



Ente per le Nuove tecnologie,
l'Energia e l'Ambiente

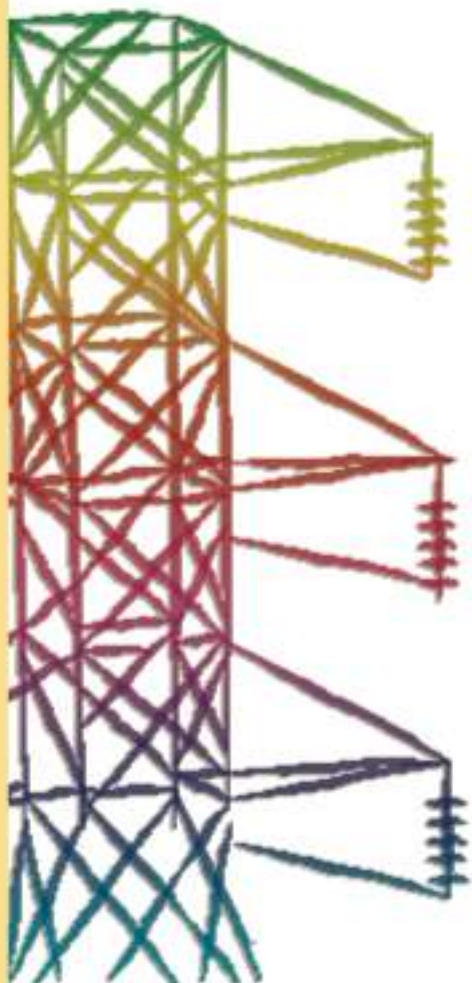


Ministero dello Sviluppo Economico

RICERCA SISTEMA ELETTRICO

Attività relative alla caratterizzazione dei rifiuti radioattivi da conferire al sito di smaltimento e di deposito

N. Cherubini, A. Dodaro, M. Ferrando, L. Silvi, N. Sparacino, F. Troiani





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ATTIVITÀ RELATIVE ALLA CARATTERIZZAZIONE DEI RIFIUTI RADIOATTIVI DA CONFERIRE AL
SITO DI SMALTIMENTO E DI DEPOSITO

N. Cherubini, A. Dodaro, M. Ferrando, L. Silvi, N. Sparacino, F. Troiani (ENEA)

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INTRODUZIONE

La Caratterizzazione dei Rifiuti Radioattivi è uno degli elementi fondamentali della gestione dei rifiuti stessi, per motivi quali valutazioni di sicurezza durante le fasi di trasporto o durante l'immagazzinamento, determinazione di metodi di trattamento e condizionamento dei rifiuti, nonché miglioramento della qualità dei controlli durante le suddette operazioni.

Una adeguata progettazione del sito di smaltimento, temporaneo o definitivo, dei residui radioattivi condizionati obbliga, inoltre, gli organi ad esso preposti ad essere a conoscenza delle caratteristiche chimico – fisiche e del grado di pericolosità radiologica associato ai rifiuti, il che implica l'uso di dati provenienti dalle operazioni di caratterizzazione.

Infine, una corretta gestione dei rifiuti radioattivi che tenga conto delle necessarie salvaguardie di protezione sanitaria e di tutela dell'ambiente pone l'esigenza della definizione e della classificazione dei rifiuti radioattivi, nonché quella della determinazione legale di limiti al di sotto dei quali i rifiuti possono essere allontanati incondizionatamente senza vincoli sulla destinazione o limitazioni al loro utilizzo.

Il presente rapporto tecnico si prefigge i seguenti obiettivi:

- proporre processi e metodologie per la caratterizzazione dei rifiuti radioattivi durante il loro intero ciclo di vita;
- contribuire a garantire condizioni di sicurezza durante i diversi stadi del ciclo di vita di un rifiuto radioattivo: generazione, manipolazione, trasporto, deposito e smaltimento;
- dimostrare che i criteri di accettabilità siano conseguiti e basati sul performance assessment per il concetto di deposito;
- fornire input tecnico per:
 - identificare le necessarie e sufficienti richieste di caratterizzazione;
 - classificare il rifiuto radioattivo e identificare le norme di regolamentazione associate;
 - identificare i requisiti per la garanzia della qualità e le azioni collegate;
 - contribuire alla selezione delle migliori “forme” del rifiuto radioattivo (in vista del deposito);
 - dimostrare che la “forma” scelta del rifiuto sia congruente con le specifiche.

Le attività legate alle azioni di caratterizzazione sono effettuate durante diversi stadi del ciclo di vita di un rifiuto radioattivo: durante la generazione, durante la manipolazione (trattamento, condizionamento), e durante le fasi di smaltimento e deposito. Il tipo e l'importanza delle azioni di caratterizzazione dipendono da molti fattori, quali:

- il tipo o la forma del rifiuto;
- il concetto di deposito;

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- il regime di regolamentazione;
- la quantità di conoscenza del processo di cui si dispone;
- il tipo di caratteristiche e grandezze da misurare.

Si ritiene fondamentale che la caratterizzazione del rifiuto radioattivo venga considerata parte integrante della strategia di gestione del rifiuto.

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1 CRITERI DI ACCETTABILITA' DEI RIFIUTI

1.1 GENERALITÀ

In tutti i tipi di impianti nucleari la minimizzazione, la manipolazione, lo smaltimento e il trattamento di rifiuti radioattivi deve essere gestito seguendo standard di sicurezza e qualità molto elevati. In particolare, il trasporto, il deposito temporaneo e lo smaltimento definitivo devono essere gestiti in modo tale da assicurare la protezione dell'uomo e dell'ambiente in concordanza con le raccomandazioni ICRP e gli standard nazionali e internazionali, minimizzando carichi e obblighi alle generazioni future. Un programma di Quality Assurance (QA) inteso come programma di gestione è e dovrà essere fortemente applicato nell'area di gestione per il "pre-deposito" dei rifiuti ad alta attività e sarà ugualmente necessario nella pianificazione, progettazione, realizzazione, gestione e chiusura di un deposito.

L'efficienza di un sistema può dipendere da un determinato numero di componenti quali la forma del rifiuto, il contenitore, l'overpack, il materiale di backfill, e l'ambiente circostante. Questi componenti dovrebbero essere scelti e progettati per essere compatibili e raggiungere un accettabile grado di isolamento.

Nel lungo periodo, la capacità di isolamento di un sistema per il deposito di rifiuti dipenderà dalla combinazione dei suoi componenti. Poiché la forma del rifiuto e il contenitore sono componenti importanti durante le fasi di trasporto, deposito temporaneo e manipolazione dei campioni, le loro performances saranno specificate nei criteri di accettabilità.

1.2 RIFIUTI DI I E II CATEGORIA

I criteri di accettabilità dei rifiuti radioattivi di I e II categoria (secondo la definizione presente nella Guida Tecnica 26) definiscono una serie di principi o standard che devono essere osservati per rendere i rifiuti idonei per un deposito superficiale. Questi criteri devono essere seguiti per assicurare una gestione sicura dei rifiuti in modo da proteggere la salute umana e l'ambiente in concordanza con le raccomandazioni ICRP e le norme legislative senza imporre carichi e obblighi indebiti alle generazioni future.

Criteri di accettabilità dei rifiuti dovrebbero essere sviluppati per assicurare condizioni di sicurezza (safety) durante il trasporto, la manipolazione, lo smaltimento e il deposito dei rifiuti radioattivi. Essi sono generalmente specifici per il sito e per il deposito in oggetto e possono comprendere molti tipi di rifiuto. La ratifica di questi criteri è responsabilità della direzione del deposito temporaneo o definitivo in unione con le autorità nazionali preposte alla sicurezza e alla regolamentazione.

I criteri di accettabilità dei rifiuti dovrebbero essere derivati da considerazioni provenienti sia da requisiti di natura operativa (es: manipolazione, ecc.), sia da requisiti contenuti nel "safety assessment" per il deposito necessari per raggiungere la sicurezza (safety) nello smaltimento del rifiuto. Questi criteri dovrebbero essere quantitativamente o qualitativamente stabiliti in modo tale che la conformità possa essere stabilita sia con misure dirette sia mediante l'applicazione di adeguati metodi di gestione e controllo durante il processo di condizionamento.

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La conformità con i criteri di accettabilità dei rifiuti richiede generalmente un approccio a due stadi, definiti come:

- definizione delle caratteristiche e degli attributi del rifiuto radioattivo, inclusi dati di natura fisico-chimica (resistenza alla compressione, resistenza all’impatto, corrosione, resistenza al fuoco, ecc.) e identificazione dei parametri ad essi correlati che devono essere controllati al fine di fornire assicurazione sulla conformità ai criteri di accettabilità identificati;
- convalida della conformità dei singoli rifiuti radioattivi ai requisiti specificati per i rifiuti.

Informazioni sulle caratteristiche e attributi dei rifiuti radioattivi sono generalmente contenute nella specificazione del rifiuto radioattivo in oggetto preparata dall’operatore dell’impianto di condizionamento del rifiuto.

Una lista delle principali informazioni che dovrebbero essere fornite per i singoli campioni è definita di seguito:

- Numero o altra identificazione del campione;
- Tipo e variante;
- Nome del sito e dell’impianto di condizionamento;
- Data di condizionamento;
- Contenuto del rifiuto grezzo e dettagli su:
 - categoria (I o II);
 - sorgente;
 - descrizione;
 - caratteristiche radiologiche;
 - caratteristiche fisiche;
 - caratteristiche chimiche;
 - caratteristiche biologiche;
 - peso del rifiuto per contenitore (kg)
- Dettagli del contenitore:
 - tipo e variante;
 - specificazione di fabbricazione.
- Dettagli sulla matrice immobilizzante;
- Dettagli sulla matrice “capping”;
- Contenuto in attività:
 - totale attività alfa (Bq);
 - totale attività beta/gamma (Bq)
- Rateo di dose

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- a contatto (Sv/h);
- a 1 metro (Sv/h)
- Calore di decadimento
- Contaminazione superficiale:
 - totale alfa (Bq);
 - totale beta/gamma (Bq).
- Peso totale del package (kg).

In Appendice viene riportata la Tabella 1 che elenca i criteri di accettabilità chiave che devono essere seguiti sia dalla specificazione del rifiuto radioattivo (per dimostrare una generale conformità con i criteri di accettabilità dei rifiuti per un tipo specifico di package che deve essere consegnato ad un particolare deposito temporaneo o definitivo) sia dai certificati di accompagnamento (data sheet) del rifiuto (per dimostrare conformità del singolo campione con i requisiti della specificazione del rifiuto radioattivo).

Un programma di Q.A. sulla gestione dei rifiuti radioattivi dovrebbe porre attenzione ai seguenti punti:

- organizzazione e responsabilità;
- addestramento e qualifica del personale;
- procedure ed istruzioni operative;
- controllo di tutti i documenti;
- ricerca e sviluppo dei processi;
- controllo del progetto e costruzione delle installazioni per il condizionamento;
- approvvigionamento dei materiali;
- controllo del processo;
- ispezioni delle installazioni per il condizionamento durante il funzionamento;
- controllo delle non conformità e le azioni correttive;
- records
- revisioni di gestione.

1.3 RIFIUTI DI III CATEGORIA

1.3.1 Approccio generale

I criteri di accettabilità dei rifiuti radioattivi di III Categoria definiscono una serie di principi o standard che devono essere rispettati da un rifiuto per essere conforme per il deposito temporaneo in una struttura ingegneristica.

I criteri di accettabilità dei rifiuti radioattivi saranno specifici per un particolare sito e di natura qualitativa o quantitativa dipendentemente dal requisito richiesto; essi descrivono quelle proprietà che sono necessarie per il deposito temporaneo dei rifiuti ad alta attività. Dal momento che fino ad oggi nessun deposito per lo smaltimento di

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rifiuti ad alta attività è stato autorizzato, sono stati formulati soltanto criteri di accettabilità di natura qualitativa.

Criteri di accettabilità di natura quantitativa, per depositi temporanei esistono in paesi con strutture di condizionamento e smaltimento di rifiuti vetrificati (e.g. Francia, Regno Unito). Per il trasporto esistono regolamentazioni internazionali che sono stati adottate in legislazioni nazionali. Specificazioni quantitative sono state elaborate per rifiuti ad alta attività vetrificati liquidi da operatori del settore per ottenere approvazioni per il trasporto e il deposito temporaneo (e.g. Francia, Regno Unito).

1.3.2 Criteri di accettabilità

Al fine di ottenere totali obiettivi di sicurezza (SAFETY), le seguenti richieste e i seguenti criteri dovranno essere soddisfatti:

- la forma del rifiuto, il container, l'overpack e l'eventuale materiale di backfill dovranno essere compatibili con il deposito e il suo ambiente;
- il rifiuto radioattivo dovrà soddisfare le norme per il trasporto di materiale radioattivo;
- il rateo di dose superficiale e la contaminazione superficiale dovranno essere commisurate alle procedure di manipolazione del rifiuto in condizioni di sicurezza;
- il rifiuto radioattivo non dovrà contenere materiali che potrebbero portare a eventuali rilasci di attività o interagire con barriere o altri materiali nel deposito (liquidi liberi, esplosivi, materiali piroforici o altamente infiammabili, agenti corrosivi);
- materiali fissili eventualmente presenti nel rifiuto devono essere in quantità limitata per prevenire situazioni di criticità;
- il confezionamento del rifiuto (package) dovrebbe fornire completo contenimento per un periodo di tempo ragionevolmente lungo.

Di seguito vengono forniti i parametri e le caratteristiche per i quali saranno definiti i criteri di accettabilità per rifiuti radioattivi ad alta attività; essi sono di natura sufficientemente generica per coprire la maggior parte di possibilità esistenti per depositi di rifiuti radioattivi ad alta attività.

- Inventario dei Radionuclidi
- Calore di decadimento ed effetti termici
- Condizioni di criticità nucleari
- Effetti delle radiazioni, danno da radiazioni e controllo della contaminazione
- Stabilità meccanica, resistenza meccanica e resistenza allo stress
- Carico termico e resistenza termica
- Generazione di gas
- Liquidi liberi

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- Materiali esplosivi o piroforici, rischio di incendio o esplosione
- Gas compressi
- Materiali tossici e/o corrosivi
- Durabilità chimica
- Dimensioni fisiche e peso
- Identificazione unica ed esclusiva
- Organizzazione e responsabilità
- Controllo di qualità
- Record
- Conformità con codici e standard.

Inventario dei Radionuclidi

Criterio: Il tipo, le caratteristiche e il contenuto di radionuclidi, presenti nel rifiuto dovrebbero essere noti con sufficiente accuratezza in modo da assicurare la conformità con i limiti autorizzati e dovrebbero, conseguentemente, essere documentati.

Calore di decadimento ed effetti termici

Criterio 1: la produzione di calore dei rifiuti dovrà conformarsi con i limiti applicabili al deposito, trasporto e manipolazione prima della sistemazione.

Criterio 2: la produzione di calore dei rifiuti sarà tale che qualsiasi associato cambiamento di proprietà fisiche, chimiche e meccaniche del rifiuto, di altre barriere ingegneristiche comprese le strutture di deposito non varino in modo tale da compromettere la sicurezza del sistema complessivo.

Condizioni di criticità nucleari

Criterio: i rifiuti saranno progettati per precludere qualsiasi condizione di criticità nucleare sia del singolo involucro che del sistema.

Danno da radiazioni e controllo della contaminazione

Criterio 1: i valori di rateo di dose esterna dei rifiuti condizionati dovranno essere conformi ai limiti imposti nelle installazioni nelle quali i rifiuti saranno manipolati, immagazzinati e trasportati prima della collocazione in un deposito.

Saranno stabiliti limiti sui valori di rateo di dose beta-gamma e neutronica.

Criterio 2: la contaminazione radioattiva trasferibile sulla parte esterna dei rifiuti dovrebbe essere mantenuta entro i limiti stabiliti per il trasporto, lo smaltimento e per gli impianti di condizionamento dove i rifiuti devono essere manipolati. Criterio 3: i Valori di rateo di dose saranno tali da non permettere o minimizzare processi indotti

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da radiazione (come radiolisi) e processi di degradazione delle proprietà dei materiali costituenti il rifiuto.

Stabilità meccanica, resistenza meccanica e resistenza allo stress

Criterio: I rifiuti radioattivi devono essere in grado di resistere a stress insorgenti senza deterioramento delle proprietà preposte alle funzioni correlate alla sicurezza (safety).

Il contenitore di rifiuto dovrebbe essere progettato per resistere adeguatamente a stress possibili durante la fabbricazione, il trasporto e il deposito.

Carico termico e resistenza termica

Criterio: I rifiuti radioattivi ad alta attività (HLW) non conterranno materiali combustibili che potrebbero bruciare in condizioni normali o per incidenti prevedibili.

Il processo di condizionamento dovrebbe essere progettato e controllato per prevenire l'introduzione di materiali combustibili nel rifiuto.

Generazione di gas.

Criterio: La generazione di gas nel rifiuto o in zone circostanti non dovrebbe mettere in pericolo le performance del sistema di deposito.

I radionuclidi volatili e la generazione di gas radioattivi, associati al rifiuto, saranno determinati. L'interazione dei gas con i componenti del sistema sarà stimata per dimostrare l'adeguatezza del deposito.

Liquidi liberi

Criterio: La quantità di liquidi liberi nel rifiuto dovrebbe essere sufficientemente bassa per assicurare che il deposito non sia messo in pericolo.

Materiali esplosivi o piroforici, rischio di incendio o esplosione

Criterio: Rifiuti radioattivi contenenti materiali che potrebbero causare esplosione o rischio di ignizione non saranno accettati nel deposito..

Gas compressi

Criterio: Contenitori di gas compressi non dovrebbero essere accettati nel deposito.

Materiali tossici e/o corrosivi

Criterio: La quantità di materiali tossici e/o corrosivi non-radioattivi all'interno di un rifiuto dovrebbe essere nota con sufficiente accuratezza in modo da assicurare la conformità con i limiti autorizzati.

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I rifiuti non dovrebbero contenere materiali che corroderanno i contenitori o le altre barriere nel sistema del deposito.

Durabilità chimica

Criterio: La durabilità chimica del rifiuto dovrebbe essere sufficiente per offrire il contenimento richiesto dei radionuclidi nell'ambiente del deposito.

Dimensioni fisiche e peso

Criterio: Le dimensioni fisiche e il peso del rifiuto dovrebbero essere compatibili con provvedimenti per il trasporto, la gestione e collocazione.

Identificazione Unica

Criterio: Ciascun rifiuto, per la collocazione in deposito, dovrebbe essere contrassegnato con un'identificazione unica (eseguita con codici a barre o alfanumerici).

Il metodo di identificazione non danneggerà l'integrità del rifiuto e dovrà essere leggibile almeno fino alla collocazione in deposito.

Conformità con codici e standard

Criterio: Le competenti autorità nazionali determineranno la legislazione applicabile, codici e standard per il condizionamento dei rifiuti radioattivi, per il deposito temporaneo e per lo smaltimento definitivo. I criteri di accettabilità dei rifiuti e l'assicurazione di qualità saranno formulate in conformità con la legislazione nazionale, codici e standard.

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2 CARATTERIZZAZIONE RADIOLOGICA E CHIMICO FISICA DEI RIFIUTI RADIOATTIVI

2.1 CARATTERIZZAZIONE RADIOLOGICA

2.1.1 Generalità

Da un punto di vista radiologico, la caratterizzazione dei rifiuti viene eseguita tramite diversi metodi, distruttivi e non distruttivi.

Le tecniche distruttive consistono in analisi di campioni effettuate in laboratorio con metodi chimici. Esse sono più accurate e precise delle tecniche non distruttive, ma necessitano di una maggiore quantità di tempo e richiedono che i campioni analizzati siano uniformi e sufficientemente rappresentativi di tutto il materiale.

La complessità e la durata del trattamento preliminare del campione limitano il ricorso a queste tecniche solo a quelle situazioni in cui si debbano determinare radionuclidi difficilmente misurabili o sia richiesto un livello di accuratezza altrimenti non raggiungibile.

Le tecniche non distruttive consistono nella misura dell'intensità delle radiazioni nucleari, spontanee od indotte, ai fini dell'analisi qualitativa e quantitativa del materiale nucleare. Esse non alterano l'aspetto fisico e la composizione chimica del materiale, ma sono caratterizzate da accuratezze più modeste e, spesso, sono condizionate da forti effetti della matrice.

Di seguito vengono elencate e descritte le principali tecniche impiegate, suddivise nelle due categorie.

Le caratteristiche descrittive e operazionali dei principali sistemi commerciali sono riportate negli allegati al presente documento.

2.1.2 Tecniche di Misura Distruttive

Lo schema generale di una analisi di tipo distruttivo prevede le seguenti fasi:

- Campionamento;
- Omogeneizzazione del campione;
- Solubilizzazione del campione (digestione acida o mineralizzazione);
- Aggiunta al campione solubilizzato di un tracciante del radionuclide di interesse;
- Purificazione del radionuclide di interesse da eventuali interferenti mediante trattamenti chimico-fisici (precipitazione, estrazione selettiva con resine).

I rifiuti in forma liquida invece presentano una procedura piuttosto complessa che in molti casi va valutata a seconda dell'origine del rifiuto e del contenuto in sostanze organiche, inorganiche, materiali solidi dispersi o insolubili. Le sostanze solide e disperse possono essere allontanate previa filtrazione e destinate ad un'analisi separata (mineralizzazione acida); le sostanze organiche eventualmente presenti sono separate in genere mediante estrazione. Il liquido restante, prevalentemente costituito da costituenti inorganici, può essere destinato all'analisi strumentale previa

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acidificazione del campione laddove la tecnica analitica lo preveda (AAS, ICP-MS, HPIC-LS).

2.1.2.1 Tecniche Chimiche Analitiche

Le principali tecniche strumentali di chimica analitica, impiegate per la caratterizzazione radiologica di un rifiuto radioattivo, sono le seguenti:

a) Spettrofotometria ad assorbimento atomico

La **spettrofotometria ad assorbimento atomico AAS** (Atomic Absorption Spectroscopy) è una tecnica analitica impiegata per la determinazione sia quantitativa che qualitativa di ioni metallici in soluzione.

Il principio chimico-fisico su cui si basa questa tecnica è il seguente: i livelli energetici atomici sono discreti, pertanto le transizioni elettroniche permesse per eccitazione radiativa ($h\nu$) sono caratteristiche per ogni atomo. A differenza delle molecole però, gli atomi non contengono sottostrutture rotazionali o vibrazionali e pertanto l'assorbimento di una radiazione elettromagnetica per eccitazione ad un livello energetico superiore non avviene in una banda di frequenze ma ad una e una sola frequenza e lunghezza d'onda. Tutto ciò implica che ogni atomo avrà il suo spettro di assorbimento caratteristico e per ogni lunghezza d'onda a cui corrisponde una transizione sufficientemente probabile è possibile effettuare misure quantitative applicando la legge di Lambert-Beer.

Il **sistema di atomizzazione** è il sistema mediante il quale il campione in analisi e i metalli da ricercare vengono ridotti allo stato di gas monoatomico, condizione necessaria per la misura in quanto questa avviene misurando la differenza di intensità della radiazione elettromagnetica prima e dopo il passaggio attraverso il campione atomizzato il quale assorbe energia mediante gli elettroni del guscio più esterno.

Esistono vari tipi di sistemi di atomizzazione, dai cui prendono origine le diverse tecniche AAS nonché il nome identificativo dello strumento:

- Atomizzazione mediante **fiamma (AAS-Flame o FAAS)**, che sfrutta la temperatura di una fiamma aria-acetilene o protossido di azoto-acetilene, o aria-idrogeno, in cui viene nebulizzato il campione.
- Atomizzazione mediante **fornetto di grafite (AAS-GF)**, che sfrutta le alte temperature raggiunte da un tubo di grafite alle cui estremità viene applicata una forte differenza di potenziale.
- Atomizzazione mediante **vapori freddi (AAS-FIAS o CVAAS)**, ovvero mediante la reazione del campione con determinati reagenti che formano idruri volatili che vengono poi posti sul cammino della radiazione elettromagnetica.

I migliori sistemi di Spettrofotometria ad assorbimento atomico disponibili commercialmente sono i seguenti:

- Perkin Elmer AAnalyst 800;
- Varian AA 280Z Zeeman AAS.

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b) Spettrometria di massa con Plasma ad Accoppiamento Induttivo (ICP-MS)

La tecnica **ICP-MS (Inductively Coupled Plasma-Mass Spectrometry)** è una tipologia di spettrometria di massa altamente sensibile e in grado di determinare diverse sostanze inorganiche metalliche e non-metalliche presenti in concentrazioni inferiori a una parte per bilione (ppb - 10^{12}). Sfrutta l'utilizzo di una torcia al plasma ICP per produrre la ionizzazione e di uno spettrometro di massa per la separazione e la rivelazione degli ioni prodotti. Lo spettrometro di massa sfrutta solitamente un analizzatore di massa a quadrupolo. Gli ioni sono separati in base al loro rapporto massa/carica e si produce un segnale proporzionale alla concentrazione. La concentrazione può essere determinata tramite taratura con standard o tramite diluizione isotopica.

Altri analizzatori di massa utilizzati nella ICP-MS includono sistemi a doppia focalizzazione magnetico-elettrostatica, sia con collettori singoli che multipli, e sistemi a tempo di volo con acceleratori assiali o ortogonali.

Con la ICP-MS è anche possibile effettuare l'analisi isotopica.

La tecnica ICP-MS può essere utilizzata per l'analisi elementale, con un intervallo di elementi chimici determinabili compresi tra la massa atomica del litio fino a quella dell'uranio (in teoria tra 7 e 250 unità). Si possono rivelare concentrazioni dell'ordine dei ng/l. Diversamente dall'assorbimento atomico, che può misurare un solo elemento per volta, la ICP-MS consente invece la determinazione simultanea degli elementi con il conseguente vantaggio di velocizzare tale tipo di analisi.

I migliori sistemi di Spettrometria di massa con Plasma ad Accoppiamento Induttivo disponibili commercialmente sono i seguenti:

- Perkin Elmer ELAN DRC II;
- Varian 820-MS;
- Agilent 7500CX ICP-MS.

c) Spettrometria di Massa a Ionizzazione Termica (TIMS)

La **Spettrometria di Massa a Ionizzazione Termica TIMS** (Thermal Ionization Mass Spectrometry) è uno spettrometro di massa a settore magnetico in grado di effettuare misure estremamente precise (precisione compresa tra 0.01 e 0.001%) di rapporti isotopici tra elementi che possono essere ionizzati per via termica.

La ionizzazione termica è effettuata mediante un nastro sottile in metallo, scaldato da resistenze attraversate da una opportuna corrente, il tutto sotto vuoto spinto. Gli ioni della sostanza da analizzare, creati sul nastro metallico sono prima accelerati da un gradiente di potenziale elettrico (fino a 10 kV) e poi collimati in uno stretto fascio grazie ad una serie di slit e piatti carichi elettrostaticamente. Il fascio di ioni passa attraverso un campo magnetico che separa il fascio collimato in ingresso in molteplici fasci secondari caratterizzati da un preciso rapporto

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massa/carica. Questi fasci secondari, separati in base alla massa degli ioni, sono raccolti da collettori e trasformati in segnale elettrico. Dal confronto tra i vari segnali elettrici dei singoli fasci ionici ottenuti, si ottengono i valori dei rapporti isotopici tra gli elementi presenti nel campione.

Una tra le applicazioni di particolare rilevanza che coinvolge la spettroscopia di massa a ionizzazione termica è la determinazione di Uranio ($^{234,235,236,238}\text{U}$) e Plutonio ($^{238,239+240}\text{Pu}$), nonché ^{135}Cs , con una accuratezza molto elevata, in diversi materiali di origine nucleare.

I migliori sistemi di Spettrometria di Massa a Ionizzazione Termica disponibili commercialmente sono i seguenti:

- Thermo Finnegan TRITON-VG 354 Multicollector MS.

d) Cromatografia Ionica con Rivelazione a Scintillazione Liquida (HPIC-LSC)

La **cromatografia ionica** è una tecnica analitica per la separazione e la determinazione qualitativa e quantitativa di anioni e cationi inorganici e organici.

Il principio su cui si fonda questa tecnica è lo scambio ionico fra gli ioni presenti in una fase mobile e i gruppi funzionali acidi o basici covalentemente legati ad una fase stazionaria, generalmente costituita da una resina ad alta stabilità di polistirene reticolato con di-vinil-benzene.

La soluzione da analizzare viene iniettata all'interno di una colonna contenente la resina scambiatrice; si raggiunge una situazione di equilibrio nella distribuzione degli ioni fra la fase mobile e quella stazionaria.

All'interno della stessa colonna viene continuamente pompata un'opportuna soluzione di elettrolita, detta eluente, i cui ioni abbiano un'affinità per la fase stazionaria comparabile con quella degli ioni del campione, così che, essendo quantitativamente più abbondanti, sia favorita la loro reazione di scambio con i gruppi funzionali della resina.

Di conseguenza questa soluzione porta fuori dalla colonna (eluisce) in modo selettivo gli ioni da analizzare: ciascuno di essi esce in tempi differenti, a seconda della propria costante di equilibrio della reazione di scambio. Si ha quindi una distribuzione a bande (picchi) degli ioni eluiti.

Fissate le condizioni operative, per una data colonna e per un preciso eluente è possibile individuare i singoli ioni presenti in una soluzione conoscendo i tempi che essi impiegano per uscire dalla colonna. Per ottenere un'analisi qualitativa e quantitativa, il flusso in uscita dalla colonna di separazione viene inviato ad un sistema di rivelazione.

I metodi di rivelazione più comuni in cromatografia ionica sono quello conduttimetrico e quello spettrofotometrico. Inoltre è possibile accoppiare ad un tale strumento cromatografico un rivelatore a scintillazione liquida (vedere paragrafo successivo) per determinare direttamente in uscita dallo strumento, la radioattività dei radionuclidi separati.

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I migliori sistemi di Cromatografia Ionica disponibili commercialmente sono i seguenti:

- Dionex ICS-3000.

e) LIQUID SCINTILLATION COUNTING

Il processo secondo il quale l'energia dovuta al decadimento radioattivo è convertita in luce visibile e misurata in un ambiente liquido organico viene indicato con LIQUID SCINTILLATION COUNTING (LSC).

La tecnica LSC, Liquid Scintillation Counting, viene impiegata per la rivelazione e la quantificazione di radionuclidi presenti in soluzioni liquide.

Nella tecnica LSC la luce prodotta è proporzionale alla radiazione presente nel campione e l'energia della luce prodotta è proporzionale all'energia della radiazione presente nel campione.

Il metodo LSC consiste nel dissolvere il campione che deve essere analizzato direttamente nel liquido scintillatore e, essendo caratterizzato da un'alta efficienza di conteggio, rappresenta la tecnica più adatta per la misura di radionuclidi beta emettitori e gamma emettitori di bassa energia non rivelabili mediante tecniche di analisi non distruttive.

I rivelatori a scintillazione sono basati sulla capacità di alcune sostanze, detti scintillatori, di convertire in luce parte dell'energia assorbita da una particella.

La tecnica prevede di mescolare il campione solubilizzato con la miscela scintillante (costituita da un solvente organico, generalmente aromatico, e da una sostanza scintillante, anch'essa organica) in modo da ottenere una soluzione omogenea o emulsione finemente dispersa.

Nel caso della scintillazione liquida l'energia emessa in un decadimento radioattivo viene raccolta da un solvente aromatico, in cui sono solubilizzati il radioisotopo stesso e lo scintillatore anch'esso organico.

Le molecole di solvente eccitate si diseccitano per collisione con le molecole di scintillatore che hanno un'alta probabilità di decadere per emissione di impulsi luminosi la cui intensità è proporzionale all'energia di decadimento.

La radiazione luminosa che esce dalla cella di misura ('vial') contenente il campione viene quindi convogliata ad un fotomoltiplicatore, cioè un dispositivo che permette la conversione di un segnale luminoso in un segnale elettrico e l'amplificazione di quest'ultimo.

In realtà il campione viene posto fra due fotomoltiplicatori posti a 180°, al fine di ridurre il rumore di fondo generato dagli elettroni emessi per effetto termico e da eventi che comportano l'emissione di un singolo fotone. I segnali generati giungono ad un circuito, detto di coincidenza, vengono sommati tra loro e quindi l'impulso analogico è trasformato in un valore digitale (corrispondente all'energia della particella) solo se al circuito di coincidenza arrivano due segnali contemporanei dai due fotomoltiplicatori.

I segnali ottenuti sono trasferiti ad un analizzatore multicanale, che ha lo scopo di inserirli in vari registri di conteggio (canali) in funzione della loro ampiezza. Il

risultato è un istogramma che riporta il numero di conteggi registrati in funzione del numero di canali. Essendo l'analizzatore calibrato in modo che ad ogni canale corrisponda una ben precisa energia, lo spettro delle altezze degli impulsi coincide con lo spettro di distribuzione delle energie.

Lo spettro digitalizzato viene accumulato, in modo che su di esso sia possibile effettuare operazioni matematiche, per valutazioni qualitative e quantitative.

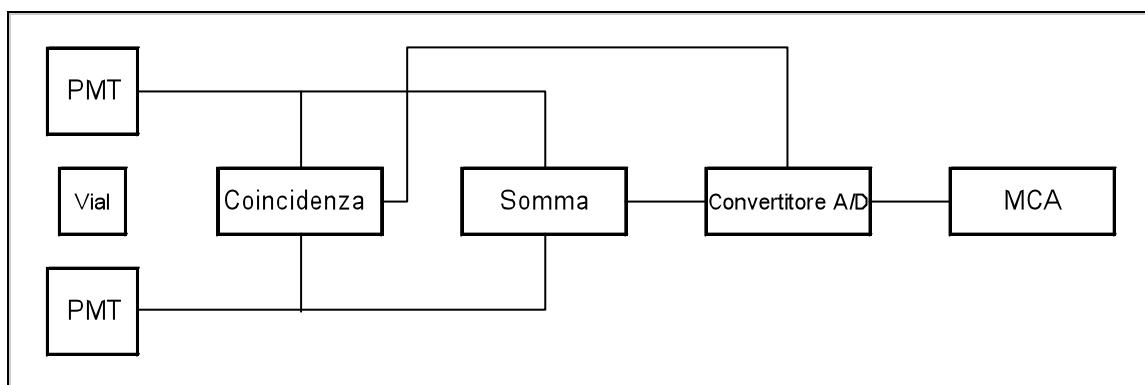


Figura 1 - Schema scintillazione liquida

La scintillazione liquida è particolarmente vantaggiosa perché non richiede una complicata preparazione del campione e presenta un'elevata efficienza di conteggio, soprattutto per particelle a bassa energia e a scarsa penetrabilità (radiazioni di bassa energia come le particelle β emesse dal Trizio e dal ^{14}C).

Questo risultato è ottenuto grazie all'intima miscelazione fra isotopo da analizzare, sostanza scintillante e solvente, condizione che ha anche il pregio di eliminare i problemi legati ai fenomeni di retrodiffusione e di autoassorbimento all'interno del campione.

I principali componenti hardware e software del sistema di rivelazione sono:

- 'radiodetector' + software che analizza quantitativamente l'eluato in uscita dal cromatografo e fornisce il segnale analogico alla scheda multicanale per l'analisi spettrale;
- scheda multicanale + software installato all'interno del personal computer gestionale, acquisisce il segnale analogico proveniente dal radiodetector e lo analizza dal punto di vista energetico;
- software di analisi degli spettri registrati dal software della scheda multicanale ed esegue sugli stessi valutazioni quantitative e qualitative;
- personal computer per la gestione delle componenti hardware, cioè il 'radiodetector' e la scheda multicanale, e per l'esecuzione della parte analitica.

Il conteggio del campione è effettuato mentre questo risiede nella cella di flusso compresa fra due fotomoltiplicatori, aventi diametro di circa 5 cm.

Le celle per la scintillazione liquida consentono un conteggio di tipo omogeneo,

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grazie alla miscela uniforme e stabile fra cocktail di scintillazione e campione.

I vantaggi legati alla scintillazione liquida sono:

- alta efficienza per gli emettitori β ad alta energia (75-95%), ma anche per quelli a bassa energia (15-55%);
- scarsa rilevanza dei fenomeni di adsorbimento o di contaminazione della spirale in Teflon.
- Gli svantaggi sono invece:
- il miscelamento con il cocktail di scintillazione rende necessario l'uso di una 'splitter valve' per conservare una frazione di campione intatta per ulteriori analisi o controlli;
- il cocktail di scintillazione costituisce un rifiuto organico generalmente tossico.

Il cocktail di scintillazione ottimale va scelto in base alle caratteristiche del sistema.

Si deve ottenere una miscela stabile e omogenea che non dia origine a precipitati, a incrementi della viscosità o alla formazioni di gel, che provocherebbero intasamenti nelle linee. Inoltre il cocktail deve garantire alte rese di scintillazione anche se aggiunto in piccole quantità, in modo che sia possibile mantenere flussi limitati: flussi troppo alti infatti abbasserebbero eccessivamente i tempi di permanenza nella cella di detezione, provocando un peggioramento della sensibilità.

I migliori sistemi per la tecnica di Scintillazione Liquida disponibili commercialmente sono i seguenti:

- Perkin Elmer Radiomatic 625TR System Analyser
- LS 6000 e LS 6500 Liquid Scintillation Counting (Beckman Coulter);
- 300 SL Automatic TDCR liquid scintillation counter (HIDEX);
- Triathler LSC counter (HIDEX).

2.1.2.2 Spettrometria ALFA

L'identificazione e la quantificazione di radionuclidi alfa-emettitori ha un ruolo fondamentale nell'ambito della caratterizzazione di materiali nucleari e nella radioprotezione, in generale.

I radioisotopi alfa-emettitori producono spontaneamente particelle alfa a energie caratteristiche comprese fra 4 e 6 MeV.

Le tecniche di spettrometria alfa hanno l'obiettivo di determinare l'attività per unità di massa dei radioisotopi α emettitori presenti in campioni di suolo, materiali vari (cementizi, ferrosi), o campioni liquidi. L'obiettivo della misura può essere raggiunto mediante la misura diretta delle particelle alfa, oppure determinando la massa dell'elemento di interesse per unità di massa del campione, mediante tecniche di

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chimica analitica, ricavando la massa dei radionuclidi sulla base della composizione isotopica dell'elemento stesso.

In entrambi i casi il campione deve essere preparato alla misura e la preparazione preliminare, dipendente dal tipo di misura da effettuare, costituisce la fase fondamentale della procedura adottata.

Da un punto di vista operativo, il campione deve essere quanto più possibile sottile e il percorso delle particelle alfa fra il campione e il rivelatore deve avvenire in una camera in cui siano state realizzate condizioni di vuoto spinto. Il ridotto valore di range che caratterizza l'interazione delle particelle alfa con la materia comporta, infatti, una significativa attenuazione sia all'interno del campione sia all'interno di ogni materiale interposto fra il campione e il rivelatore. Da un punto di vista spettrometrico ciò si traduce in una deformazione dei picchi che assumono una forma asimmetrica caratterizzata da una coda di bassa energia, che limita le prestazioni strumentali ottenibili.

Trattamento preliminare del campione

La preparazione del campione trasforma il campione stesso in uno strato sottile, in una forma chimicamente isolata che può essere posta in uno spettrometro e analizzata con interferenze e autoassorbimento minimo.

Le fasi principali per il trattamento preliminare del campione nella spettroscopia alfa sono le seguenti:

- omogeneizzazione e preparazione del campione per successivi processi chimici;
- separazione chimica: usata per isolare gli elementi di interesse;
- produzione della sorgente sottile.

La preparazione del campione consiste dunque in:

- estrazione dell'analita dalla matrice (es: co-precipitazione, estrazione liquido-liquido, scambio ionico, cromatografia);
- separazione dell'analita da nuclidi potenzialmente interferenti;
- produzione della sorgente sottile, mediante elettrodeposizione o distillazione.

La rivelazione delle particelle alfa provenienti dalla sorgente sottile viene effettuata tramite rivelatori di radiazioni a semiconduttori a barriera superficiale oppure rivelatori PIPS: Passivated Implanted Planar Silicon.

Rivelatori a barriera superficiale

In questi rivelatori a semiconduttore la barriera è ottenuta facendo ossidare spontaneamente la superficie intaccata chimicamente di un cristallo di silicio di tipo n.

Questo processo di ossidazione ha luogo in un periodo di uno o due giorni, trascorso il quale la superficie viene ricoperta con una sottile lamina d'oro (20-50 mg/cm²), ottenuta per evaporazione sotto vuoto. La giunzione è poi montata su un anello isolante con superfici metalliche per assicurare i contatti elettrici.

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A causa dei differenti livelli di Fermi dei due materiali la giunzione crea un abbassamento dei livelli delle bande del semiconduttore e la regione di svuotamento si estende lungo tutto il semiconduttore. Uno degli svantaggi di questi rivelatori è la loro sensibilità alla luce. Le sottili finestre d'ingresso sono otticamente trasparenti, e fotoni che colpiscono la superficie del rivelatore possono raggiungere il volume attivo. Il sottile strato di oro, infatti, è insufficiente a "assorbire" la luce visibile, che avendo una energia di 2-4 eV (contro 1,1 eV del gap energetico del silicio), produce un segnale di una certa ampiezza che contribuisce all'aumento del rumore di fondo.

Rivelatori PIPS: Passivated Implanted Planar Silicon

In questo tipo di rivelatori a semiconduttore si combinano le tecniche della impiantazione ionica e fotolitografia per produrre rivelatori con correnti di fuga molto basse, finestre d'ingresso molto sottili e caratteristiche operazionali eccellenti.

La sottile finestra d'ingresso dei rivelatori PIPS fornisce una aumentata risoluzione nonché la riduzione della distanza rivelatore-sorgente necessaria per avere alte efficienze. La bassa corrente di fuga contribuisce a minimizzare la deriva del picco con la variazione della temperatura. Il rateo di conteggio di fondo è tipicamente minore di 0.05 conteggi/hr cm² nel range di energia da 3 a 8 MeV.

Spettroscopia delle particelle alfa

Come illustrato nei paragrafi precedenti, rivelatori al Silicio che operano a temperatura ambiente sono rivelatori quasi ideali per particelle α e altri ioni leggeri. Data l'ampia disponibilità di sorgenti monoenergetiche di particelle alfa, le performances dei suddetti rivelatori sono convenzionalmente testate registrando lo spettro in altezza degli impulsi da tali sorgenti la più comune delle quali è ²⁴¹Am. Con particelle alfa di questa energia (5.486 MeV), il contributo del rumore dovuto al preamplificatore e ad altri componenti elettronici è normalmente più piccolo della risoluzione energetica del rivelatore stesso. Risoluzioni energetiche tipiche per rivelatori al Silicio vanno da 10 – 11 keV, per piccole dimensioni, a 15 – 20 keV per rivelatori più grandi.

Esistono diversi contributi addizionali che possono, però, produrre allargamenti del picco, molto frequenti in questi sistemi. Uno di questi è dovuto al fatto che una piccola porzione dell'energia della particella alfa è trasferita a nuclei di rinculo piuttosto che a elettroni. Se la frazione di energia persa fosse costante per ciascuna particella alfa, non ci sarebbe effetto sulla risoluzione energetica. Questa perdita di energia è soggetta, invece, a grandi fluttuazioni poiché è influenzata da un gran numero di eventi. E' stato stimato che il contributo FWHM dovuto a queste fluttuazioni ammonta a circa 3.5 keV per particelle alfa aventi energia di 6 MeV.

Altri significativi contributi all'allargamento del picco sono dovuti agli effetti dell'incompleta raccolta di carica, variazioni nella perdita di energia in strati morti alla superficie del rivelatore, nonché, per particelle cariche di più bassa energia, al rumore elettronico.

I migliori sistemi di spettrometria alfa disponibili commercialmente sono i seguenti:

- sistema di spettrometria alfa CANBERRA

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- sistema di spettrometria alfa ORTEC.

2.1.2.3 Spettrometria GAMMA

Le tecniche di spettrometria gamma hanno l'obiettivo di determinare l'attività totale o l'attività per unità di massa dei radioisotopi gamma-emettitori presenti in campioni di suolo, materiali vari (cementizi, ferrosi), e campioni liquidi. Il campione deve essere preparato alla misura con modalità analoghe a quelle descritte nel paragrafo relativo alla spettrometria alfa. La misura può essere effettuata anche direttamente su soluzioni liquide.

Le tecniche di analisi distruttive di spettrometria gamma sono utilizzate per particolari radionuclidi emettitori di radiazioni X e gamma di bassa energia. Il sistema di rivelazione a semiconduttore è analogo a quello descritto nell'ambito delle tecniche non distruttive di spettrometria gamma.

2.1.2.4 Spettroscopie di Raggi-X (XRS)

Quando un atomo di un qualsivoglia elemento viene colpito da raggi X, generati dal bombardamento della materia con particelle ad alta energia quali elettroni oppure con particelle alfa o fotoni di raggi X, emette un elettrone da uno dei suoi gusci interni. La vacanza così prodotta viene immediatamente riempita da uno degli elettroni dei gusci a più alta energia, creando in quel guscio un'altra vacanza che verrà a sua volta riempita da un elettrone proveniente da un guscio ancor più elevato. In questo modo, mediante una serie di transizioni, $L \rightarrow K$, $M \rightarrow L$, $N \rightarrow M$, ciascuna vacanza creata viene ad essere nuovamente riempita fino a che l'atomo eccitato non ritorna nel suo stato fondamentale. Ciascuna transizione elettronica (escludendo le transizioni non radiative) è accompagnata dall'emissione di una riga spettrale di raggi X caratteristica, la cui energia $h\nu$ è uguale alla differenza tra le energie di legame dei due elettroni che prendono parte alla transizione. Solo alcune transizioni elettroniche sono permesse dalle regole di selezione della meccanica quantistica.

Esistono di versi metodi di analisi con i raggi X:

- Assorbimento di Raggi X (XAS): La spettroscopia XAS (X-ray Absorption Spectroscopy) studia l'andamento del coefficiente di assorbimento di una sostanza in funzione dell'energia della radiazione incidente nella regione dei raggi X, da prima di una soglia di assorbimento fotoelettrico a circa 1000 eV dopo la soglia. Per gli spettri XAS, le energie coinvolte vanno da poche centinaia di eV (raggi X molli) a svariate decine di migliaia di eV (raggi X duri). Per esempio, la soglia K dell'ossigeno si trova a 543 eV, quella del gallio a 10367 eV, quella del renio a 71676 eV. Visto che bisogna cambiare l'energia della radiazione in maniera continua su un largo intervallo, e dato che il segnale utile è tipicamente un millesimo del segnale totale, è richiesta una sorgente di raggi X ad alta brillantezza su una larga banda energetica, ovvero una sorgente di luce di sincrotrone. La necessità di usare queste installazioni di larga scala, e l'estrema difficoltà di realizzare analisi XAS in laboratorio, limita molto l'utilizzo di questa tecnica.
- Emissione di Raggi X (XES): Il campione viene bombardato con un fascio di

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elettroni in un tubo a raggi X e vengono misurati i fotoni di raggi X emessi. Le misure sono generalmente ristrette a determinazioni qualitative, o nel migliore dei casi, semiquantitative, a causa del riscaldamento e della volatilizzazione selettiva di elementi diversi, causata dal fascio di elettroni incidenti.

- **Fluorescenza di Raggi X (XRF):** In questa tecnica si opera attraverso l'irradiazione di un fascio di fotoni X ad alta energia, che eccitano gli elettroni presenti nelle orbite interne agli atomi degli elementi che compongono il campione da analizzare. Le lunghezze d'onda caratteristiche emesse sono separate attraverso un sistema di cristalli e rivelatori, l'intensità dei singoli elementi viene memorizzata ed elaborata, fornendo dei risultati in concentrazione degli elementi presenti nel campione analizzato, in riferimento a curve di calibrazione costruite con standard internazionali. Questa tecnica è quella più diffusa per l'analisi quantitativa. La tecnica XRF (Fluorescenza a Raggi X) mediante l'impiego di appropriati standard di riferimento, permette l'analisi elementare non distruttiva di un'ampia gamma di materiali con un elevato livello di precisione specialmente ad alte concentrazioni. I punti di forza di un'analisi di questo tipo sono la facilità di preparazione del campione e la possibilità di analizzare sia materiali conduttivi (metalli) ed anche materiali non conduttivi (ossidi, vetro, ceramica, plastica, cemento etc.), nonché l'analisi di liquidi, (olio, acqua, idrocarburi, etc.) con limiti di rilevabilità nell'ordine di parti per milione (ppm). La XRF è in grado di rivelare tutti gli elementi chimici compresi tra il Sodio e l'Uranio.

I migliori sistemi di Spettroscopia a raggi X disponibili commercialmente sono i seguenti:

- Thermo Fisher Scientific NORAN System SIX;
- SPECTRO XEPOS;
- Shimadzu EDX 900HS;
- Bruker S2 PICOFOX o S2 RANGER.

2.1.2.5 Spettrometria di Emissione di Raggi-X a Bassa Energia (LEXES)

La **Spettrometria di Emissione di Raggi-X a Bassa Energia LEXES** (Low Energy X-ray Emission Spectrometry), è una tecnica di superficie che utilizza un fascio di elettroni ad alta energia quale sorgente di eccitazione. Analogamente alla spettrometria di emissione, la LEXES misura l'energia dei raggi X emessi, i quali sono caratteristici di ciascun elemento presente nella superficie del campione analizzato. Poiché la corrente del fascio elettronico può essere strettamente controllata, ne consegue una elevata precisione nelle misure, nell'ordine dell'1-5%. Con l'utilizzo di standard di riferimento, l'accuratezza delle misure può raggiungere il 5% ed oltre. E' possibile regolare l'energia del fascio di elettroni incidenti in modo tale da poter analizzare spessori sottili fino a 10 Angstrom. Il limite di rivelazione della tecnica è di circa $5 \cdot 10^{13}$ atomi/cm².

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2.1.3 Tecniche di Misura Non Distruttive

La caratteristica principale di tale tipologia di analisi consiste nel lasciare il campione da caratterizzare così come è stato prodotto, senza alcuna alterazione fisica o chimica apprezzabile.

La caratterizzazione avviene tramite la rivelazione della radiazione gamma o neutronica emessa spontaneamente dal campione o ivi indotta mediante una sorgente esterna.

2.1.3.1 Spettrometria gamma a scansione

Rientrano in questa categoria diverse tipologie di misura a seconda nel numero e tipo di scansioni, i componenti fondamentali sono sempre uno o più rivelatori gamma, spesso una sorgente di radiazione gamma (sorgente di trasmissione), una catena di acquisizione ed analisi spettrometrica, e sistemi di movimentazione del campione da analizzare e dei sistemi di rivelazione.

Le principali tipologie sono:

- Segmented Gamma Scanning (SGS).

La collimazione e la distanza fusto – rivelatore sono tali che solo una “fetta” del fusto può essere vista dal rivelatore mentre il fusto sta ruotando. La procedura di misura consiste in **n** misure in trasmissione (con il fusto ruotante e il rivelatore e la sorgente di trasmissione che si spostano alla fine di ciascuno step) per calcolare il fattore di attenuazione gamma per ciascun segmento (una curva logaritmica della trasmissione in funzione dell'energia fornisce il fattore di trasmissione per ciascuna energia dello spettro di emissione) e **n** misure in emissione (con il fusto rotante e il rivelatore che si sposta alla fine di ciascuno step) per calcolare l'attività (corretta per l'attenuazione) per ciascun segmento: la somma di tutti i contributi dà l'attività totale nel fusto. Le ipotesi di base sono: distribuzione uniforme di attività e distribuzione omogenea di densità per ciascun segmento in cui il fusto è diviso.

- Transmission e Emission Computerised Tomography (TCT-ECT).

La Transmission Computerised Tomography, per mezzo di movimenti assiali e rotazionali combinati del fusto rispetto alla direzione rivelatore – sorgente di trasmissione, fornisce la distribuzione spaziale dei coefficienti di assorbimento gamma μ nel fusto. La procedura prevede **n** passi lungo l'asse perpendicolare alla direzione rivelatore – sorgente di trasmissione, ciascuno suddiviso in **m** spettri rotazionali; tale procedura è ripetuta per ciascuno degli **s** segmenti lungo l'asse del fusto, per un totale di **n x m x s** misure (tipicamente circa 2000).

La ricostruzione della distribuzione spaziale dei coefficienti di assorbimento è effettuata tramite l'implementazione dell'Antitrasformata di Radon mediante diversi metodi, quali quello di convoluzione o i metodi basati sulle trasformate di Fourier.

La procedura descritta si basa sull'ipotesi “single pencil beam” caratterizzata dall'uso di un solo rivelatore ad alta risoluzione; avendo a disposizione una schiera di rivelatori ed una sorgente sufficientemente intensa si può utilizzare la tecnica “fan beam” e fare solo le **n x m** misure longitudinali e rotazionali (quindi circa 200).

La distribuzione tridimensionale dell'attività del nuclide viene ricostruita mediante la procedura Emission Computerised Tomography. La procedura di misura è la

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medesima della tecnica TCT, con l'esclusione della sorgente di trasmissione ed utilizza i dati forniti dalla TCT per utilizzare la corretta distribuzione spaziale dei coefficienti di assorbimento.

La distribuzione tridimensionale dell'attività si ottiene mediante il metodo della Massima Verosimiglianza, usando l'algoritmo della "expectation maximisation".

I migliori sistemi per le tecniche di Spettrometria gamma a scansione disponibili commercialmente sono i seguenti:

- WM 2200 Series Segmented Assay System - CANBERRA;
- WM 2900 TGS Tomographic Gamma Scanner - CANBERRA;
- Series 3800 Tomographic Gamma Scanner - ANTECH;
- Model 3200-320 Segmented Gamma Scanner – ANTECH;
- Series 3610 Universal Gamma Scanner – ANTECH;
- DrumScan HRGS – Modular Segmented Gamma Scanner – BIL Solutions.

2.1.3.2 Sistemi di spettrometria gamma in situ ("one shot")

Si tratta di sistemi di misura costituiti da un singolo rivelatore che viene calibrato sperimentalmente (usando sorgenti certificate) o matematicamente (con l'ausilio di codici di calcolo di tipo Monte Carlo). Il più utilizzato fra questi sistemi è I.S.O.C.S. (In Situ Object Counting System) sviluppato dalla Canberra Inc.

Esso opera con un rivelatore al Germanio, la cui risposta ad una serie di sorgenti puntiformi o distribuite all'interno di matrici predefinite è stata caratterizzata usando un codice Monte Carlo. I risultati della caratterizzazione dello specifico rivelatore sono inseriti come parte del software di taratura. Dal punto di vista operativo, l'utente deve descrivere la configurazione di misura ed il software calcola automaticamente l'efficienza di rivelazione.

I migliori sistemi di Spettrometria gamma in situ disponibili commercialmente sono i seguenti:

- ISOCS - CANBERRA;
- ISOCART - ORTEC;

2.1.3.3 Tecniche neutroniche passive

Le tecniche neutroniche passive hanno come obiettivo la determinazione quantitativa del materiale fertile (^{238}Pu , ^{240}Pu , ^{242}Pu) presente nel rifiuto a partire dai neutroni rivelati.

I componenti fondamentali di tale sistema sono:

- rivelatori di neutroni a ^3He o BF_3 ;
- sistema di moderazione dei neutroni (tipicamente polietilene ad alta densità);
- liner di Cd per il taglio dei neutroni termalizzati dalla matrice;

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- software che implementi una delle analisi NCC e/o NMC.

I neutroni rivelati possono essere dovuti a fissione spontanea, reazioni (a,n) su materiali leggeri causate dalle particelle alfa prodotte dal decadimento dei nuclei pesanti, fissione indotta sul materiale in esame dai neutroni provenienti da fissione spontanea o da reazioni (a,n).

Il rateo di neutroni dovuti a fissione spontanea, proporzionale alla massa di materiale fertile, viene misurato tramite le Tecniche di correlazione temporale (Neutron Coincidence Counting, NCC, e/o Neutron Multiplicity Counting, NMC): tali tecniche sono in grado di discriminare la provenienza dei neutroni e quindi attribuire il giusto peso alla componente di fissione spontanea caratteristica nei nuclei fertili.

La caratteristica principale della tecnica NCC è costituita dall'utilizzo di un registro a scorrimento (Shift Register) collegato alla testa di rivelazione: per questo motivo, nell'ambito delle tecniche di misura neutroniche, i termini Neutron Coincidence Counting e Shift Register sono considerati sinonimi.

Si hanno due registri il cui contenuto indica il numero di impulsi contati nel relativo intervallo di ispezione: uno, R+A, è relativo all'intervallo aperto subito dopo l'arrivo di un impulso, l'altro, A (detto delle coincidenze accidentali) è relativo all'intervallo aperto dopo T_d dall'attivazione del primo intervallo.

Per ogni impulso che si presenta all'input si esegue una doppia lettura di un contatore up-down: una istantanea, il cui risultato viene riversato nell'accumulatore R+A, ed una ritardata di un tempo T_d , il cui risultato passa nell'accumulatore A.

I dati che lo Shift Register fornisce sono, dunque: conteggi totali (T), conteggi in coincidenza reali e accidentali (R+A) e conteggi in coincidenza accidentali (A).

La differenza fra i contenuti dei registri R+A ed A dipende esclusivamente dai conteggi correlati e quindi è un indice della attività di fissione spontanea presente nel campione.

La tecnica NMC rappresenta un'estensione dell'analisi tipo NCC in quanto permette di considerare, oltre ai doppietti correlati, anche i triplette di neutroni correlati.

Ciascun segnale di neutrone rivelato apre un set di intervalli di ispezione di durata sempre più grande; alla fine della misura viene costruita una tavola di distribuzione di molteplicità che dà la frequenza di avere 0, 1, 2, ...segnali in ciascun intervallo di ispezione. Il calcolo del primo e del secondo momento di tale distribuzione di molteplicità fornisce rispettivamente i conteggi dei doppietti e dei triplette correlati, dai quali è possibile ricavare il rateo di fissione spontanea (o la quantità di fissile presente nel campione), l'efficienza di rivelazione e il rateo di reazione (a,n).

I migliori sistemi per le tecniche neutroniche passive disponibili commercialmente sono i seguenti:

- WM 3100 Series Passive Neutron Coincidence Waste Drum Assay System - CANBERRA;
- High Efficiency Passive Neutron Counter (HENC) - CANBERRA;
- Model 2203 Very High Efficiency Neutron Counter (VHEnC) - ORTEC;

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- Model 2300-Combined Passive Neutron/Gamma Drum Monitor – ORTEC;
- Series 2200 Passive Neutron/Gamma Multiplicity Drum Monitor – ANTECH;

2.1.3.4 Tecniche neutroniche attive

Le tecniche neutroniche attive hanno come obiettivo la determinazione quantitativa del materiale fissile (^{239}Pu , ^{241}Pu , ^{235}U) presente nel rifiuto a partire dai neutroni rivelati.

Il campione da misurare viene interrogato periodicamente con un fascio pulsato di neutroni, che, opportunamente termalizzati, generano fissioni indotte sul materiale fissile.

Il sistema di rivelazione viene attivato alla fine di ogni impulso, per ridurre il contributo dei neutroni di sorgente.

La discriminazione dei neutroni di sorgente da quelli di fissione indotta (metodo Differential Die-away Time), si basa sui diversi tempi di decadimento dei neutroni di interrogazione e di fissione indotta.

I componenti fondamentali sono uguali a quelli delle tecniche passive con l'aggiunta di una sorgente di neutroni che può essere un generatore di neutroni, o un acceleratore di elettroni accoppiato ad opportuni target.

I migliori sistemi per le tecniche neutroniche attive disponibili commercialmente sono i seguenti:

- Integrated Waste Assay System (IWAS) - CANBERRA;
- IPAN GEA - BNFL;
- Model 4200-600 Differential Die Away Active/Passive Neutron System- ANTECH;
- Model WM 3210 Passive/Active Neutron Cf-252 Shuffler System- CANBERRA;

2.1.3.5 Tecniche gamma attive

La Tecnica di Interrogazione Gamma, usata per determinare la massa totale degli attinidi presenti nel fusto, si basa sulla reazione di fotofissione che viene indotta sui nuclei fertili da radiazione X ad alta energia e sulla conseguente rivelazione dei neutroni ritardati emessi.

Il rifiuto viene irraggiato con radiazione elettromagnetica di alta energia in modo da produrre reazioni di fotofissione sugli elementi fertili presenti.

La misura è basata sulla rivelazione dei neutroni di fotofissione pronti o ritardati per stabilire la quantità di materiale “fotofissile” presente:

- irraggiamento a bassa energia (< 7 MeV) seguito dal conteggio dei neutroni pronti di fotofissione;

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- irraggiamento ad alta energia (> 15 MeV) seguito dal conteggio dei soli neutroni ritardati.

I componenti fondamentali sono uguali a quelli per l'interrogazione neutronica attiva salvo che la sorgente deve essere una macchina acceleratrice accoppiata ad un target (ad es. tungsteno) per poter ottenere radiazione X di frenamento sufficientemente energetica.

2.1.3.6 Sistemi radiografici

I sistemi radiografici sono impiegati, nell'ambito della caratterizzazione radiologica, per verificare la presenza o meno di liquidi all'interno del rifiuto o del manufatto.

Il prodotto, posto su un nastro trasportatore, è inserito fra un generatore di raggi X e un rivelatore. Il rivelatore è composto, generalmente, da un array lineare di fotodiodi a stato solido sensibile ai raggi X. I foto diodi rivelano il livello di raggi X che passa attraverso il prodotto; più spesso o più denso è il prodotto, minore sarà il livello di raggi X ad attraversarlo. Ad ogni misurazione del singolo fotodiode, tradotta in pixels, corrisponde un diverso livello di grigio. I pixel vengono poi combinati, riga per riga, in un'immagine formattata che viene analizzata da un computer apposito.

I migliori sistemi radiografici disponibili commercialmente sono i seguenti:

- FEP ME 990 - GILARDONI;
- FEP ME 1000 - GILARDONI;
- FEP ME CARGO - GILARDONI;
- AUTOCLEAR 100100T o 100100B – EB elettronica;
- POWERx – THERMO Scientific.

2.1.3.7 Sistemi di imaging

I sistemi di imaging gamma sono sistemi portatili progettati per effettuare misure di radionuclidi emettitori gamma "in situ" al fine di localizzare la radioattività presente presso siti nucleari in tempi brevi. Essi possono essere impiegati per fornire mappe di intensità di radiazione gamma durante le normali operazioni di routine, per individuare e valutare eventuali concentrazioni di radionuclidi emettitori gamma durante operazioni di decommissioning o situazioni incidentali.

Tali sistemi forniscono, quindi, dati in tempo reale su posizioni e livelli di concentrazione impiegando analisi di spettroscopia gamma per identificare isotopi su qualsiasi hot spot automaticamente individuato dal sistema sia nel campo dei rifiuti radioattivi condizionati sia per misure di radioattività in situ.

I sistemi di imaging gamma sono generalmente composti da una piccola testa di rivelazione e da un computer portatile; l'acquisizione, l'analisi dell'immagine e la memorizzazione dei dati vengono effettuati tramite specifici software.

Dopo aver selezionato l'area di interesse e la modalità di acquisizione, alla fine del tempo di esposizione si ottiene una immagine della mappa di radiazione gamma sovrapposta alla immagine visibile dell'area stessa.

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La possibilità di effettuare operazioni in remoto a distanze relativamente grandi comporta una significativa riduzione dell'esposizione dell'operatore in accordo con il principio ALARA.

I migliori sistemi di imaging gamma disponibili commercialmente sono i seguenti:

- CARTOGAM - CANBERRA;
- RADSCAN 800 4pi Gamma Imager – BIL Solutions;
- GAMMA CAMERA - BNFL;
- GAMMACAM LT27 – EDO Corporation.

2.1.3.8 Sistemi per la misura della composizione isotopica (MGA)

Il decadimento di nuclidi radioattivi è spesso accompagnato dall'emissione di uno o più fotoni la cui energia è caratteristica del nuclide stesso. Uno spettro gamma può essere utilizzato per identificare gli isotopi emettitori gamma in un materiale correlando i fotopicchi alle energie caratteristiche di ciascun nuclide. Inoltre, il confronto fra le diverse intensità dei picchi può essere impiegato per derivare e calcolare le relative abbondanze isotopiche.

Multi-Group Analysis (MGA) Software determina le abbondanze isotopiche relative del Plutonio in misure di carattere non distruttivo nell'ambito della gestione dei rifiuti radioattivi e in applicazioni di salvaguardia.

Il codice MGA sfrutta la regione complessa XK (94-104 keV) dello spettro gamma del Plutonio per l'analisi isotopica. Dal momento che questa regione spettrale contiene la maggior parte dei gamma e raggi X del Plutonio rivelabili in uno spettro gamma in presenza di Americio, l'uso del codice MGA consente la determinazione delle abbondanze isotopiche relative da spettri gamma accumulati in tempi relativamente brevi (15 – 30 minuti).

Nella modalità "single detector" MGA utilizza informazioni da diverse regioni dello spettro di energia che giacciono entro un range 0 – 300 keV. Nella modalità "two detector", MGA sfrutta lo spettro a bassa energia (0 – 300 keV) e quello ad alta energia (0 – 1000 keV); in entrambi i casi l'analisi principale è effettuata, comunque, usando la regione 94 – 104 keV. MGA automaticamente effettua e calcola la taratura in energia e la forma del picco usando le energie caratteristiche del Plutonio a 59, 129 e 208 keV. Per tenere conto di processi fisici quali l'efficienza di rivelazione in funzione dell'energia, e l'autoassorbimento dei gamma da parte del Plutonio, MGA sviluppa internamente una curva di efficienza intrinseca considerando 10 picchi da 3 isotopi diversi.

Il codice MGAU determina l'arricchimento dell'Uranio in applicazioni di carattere non distruttivo, sfruttando i picchi dell' ^{235}U e ^{238}U nel range di energia fra 88 – 100 keV.

I migliori sistemi di misura di composizione isotopica disponibili commercialmente sono i seguenti:

- Multi Group Analysis Software - CANBERRA;
- Multi Group Analysis for Uranium – CANBERRA;
- FRAM - CANBERRA;
- U – Pu Inspector – CANBERRA ;
- MGA++ Safeguards Software – ORTEC ;
- PC/FRAM – B32 V4.3 – ORTEC.

2.1.3.9 Limiti di rivelazione per le tecniche di misura attualmente utilizzate.

Per quanto riguarda le tecniche di misura gamma, quasi tutti gli strumenti presenti nel panorama europeo hanno limiti di attività di pochi kBq, quindi, assumendo matrici di contenimento di massa superiore ad 1 kg e fatte salve alcune considerazioni relative alla “reliability” delle misure gamma, tali limiti di rivelazione permetterebbero anche il rilascio incondizionato.

Discorso diverso per le tecniche neutroniche, dove i limiti di rivelazione sono molto più alti rispetto alle tecniche gamma: da 2 a 20 mg di $^{240}\text{Pu}_{\text{eff}}$ per le tecniche neutroniche passive, e da 0.5 a 5 mg di $^{239}\text{Pu}_{\text{eff}}$ per le tecniche neutroniche attive.

In Tabella sono riportati i range di Minima Concentrazione di Attività Rivelabile (MDAC) raggiungibili dai sistemi di misura commerciali, relative ai singoli isotopi del plutonio ed all'uranio, considerati come se ciascun isotopo fosse l'unico presente in un rifiuto. Gli estremi dei range sono stati calcolati a partire dai dati assoluti dichiarati dai produttori ed assumendo matrici **omogenee** con un range di massa pari a 25 (Low Density) e 400 kg (High Density).

Concentrazione di Minima Attività Rivelabile effettiva

Isotopo	MDAC (Bq/g)	
	LD (25 kg)	HD (400 kg)
^{238}Pu	$1.3 \cdot 10^4$	$1.2 \cdot 10^5$
^{239}Pu	$5.5 \cdot 10^2$	$8.6 \cdot 10^1$
^{240}Pu	$4.4 \cdot 10^2$	$4.2 \cdot 10^3$
^{242}Pu	4.5	$4.3 \cdot 10^1$
^{235}U	$3.2 \cdot 10^{-2}$	$3.0 \cdot 10^{-4}$

I valori di tabella si riferiscono al singolo radioisotopo come se fosse l'unico presente nel rifiuto. In realtà, all'interno di un manufatto sono presenti tutti gli isotopi del plutonio, e considerando le composizioni isotopiche più comuni utilizzate dai

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laboratori afferenti al ciclo del combustibile, le Minime Concentrazioni di Attività Rivelabili relative al plutonio totale risultano oscillare nell'intervallo 1500-15000 Bq/g, cioè ben al di sopra di quanto richiesto per la distinzione fra rifiuto di II e III categoria della GT26.

2.2 CARATTERIZZAZIONE CHIMICO FISICA DELLE MATRICI DI CONDIZIONAMENTO DEI RIFIUTI RADIOATTIVI

2.2.1 Generalità

Il processo di condizionamento si fonda su una preventiva qualificazione con caratterizzazione chimica e radiochimica dei rifiuti radioattivi primari e conseguentemente sulla scelta di idonee matrici di condizionamento. Il processo di condizionamento selezionato deve essere opportunamente qualificato prima dell'attuazione.

La qualificazione prevede la determinazione di quelle variabili di processo da controllare per garantire la forma finale voluta e la determinazione dei metodi più adeguati per il controllo di queste variabili. Un adeguato programma di confezionamento e condizionamento dei rifiuti radioattivi prevede che vengano provate varie formulazioni cementizie, ed eseguite prove chimico, fisico, meccaniche, ai sensi della G.T. 26, mirate a stabilirne: compatibilità della matrice con il rifiuto, omogeneità, densità, stabilità chimica, lisciviabilità, presenza di gas e di liquidi liberi, stabilità dimensionale, resistenza al fuoco, resistenza alla compressione, resistenza al calore ed all'irraggiamento, degradabilità biologica ed eventuali altre proprietà peculiari.

2.2.2 Formulazione e preparazione di manufatti cementizi contenenti rifiuti radioattivi

La tipologia e la concentrazione di rifiuto da condizionare determinano la scelta della ricetta cementizia. Le restrizioni per i rifiuti condizionati in termini di dose superficiale e rischio contaminazione limitano la quantità di attività che può essere inglobata nella matrice.

Per la preparazione si mescolano i costituenti per un tempo sufficiente ad avere un impasto il più possibile omogeneo, messo poi in contenitori dove permane fino a che non abbia fatto presa. Particolari additivi possono essere utilizzati per migliorare la compatibilità rifiuto-cemento o per aumentare la fluidità e la lavorabilità dell'impasto. Disposto l'impasto in apposite casseformi cubiche si procede per alcuni minuti con una vibratura meccanica per l'allontanamento dell'aria inglobata durante la miscelazione e facilitare il raggiungimento di una maggiore coesione. Tale operazione consente anche di allontanare accumuli di acqua di risalita sulle superfici, causa di incrementi locali del rapporto acqua/cemento (a/c) e di riduzioni di risposta meccanica.

Le prove per determinare inizio e fine presa vengono eseguite con l'apparecchio di Vicat, che viene utilizzato anche per individuare la quantità di acqua che mescolata con il legante idraulico fornisce l'impasto. Appareati automatici per effettuare la determinazione del tempo di inizio presa e fine presa sono disponibili commercialmente da aziende quali ANGELANTONI IND. oppure TECNOTEST.

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Dopo la presa si procede con la maturazione in un ambiente saturo di umidità (RH >95%) per un periodo di 28 giorni, successivamente il campione può essere sottoposto a vari test.

Per la maturazione dei provini sono disponibili commercialmente varie tipologie di camere climatiche secondo le caratteristiche richieste dalla GT 26. Si può citare come riferimento la Camera Climatica di Maturazione CHALLENGE 500 ACS della ANGELANTONI INDUSTRIE.

Caratteristiche morfologiche e strutturali

La caratterizzazione morfologica e strutturale è condotta, in maniera classica, con apparecchiature per l'analisi di immagine, come microscopia ottica, microscopia elettronica a scansione (SEM) e spettroscopia IR. L'uso di un sonda EDX congiunta all'analisi al SEM consente la determinazione qualitativa e quantitativa delle specie presenti nel materiale e sulle pareti dei pori.

Resistenza alla lisciviazione

Un manufatto solido contenente rifiuti di vario genere venendo a contatto con soluzioni acquose od organiche in generale, può rilasciare parte delle sostanze immobilizzate in seguito alla migrazione delle stesse nel mezzo liquido. Nel caso di manufatti di cemento inglobanti rifiuti radioattivi a contatto con acqua, si può verificare tale fenomeno di rilascio quale risultante di una serie di meccanismi quali diffusione, dissoluzione, erosione, solubilizzazione, scambio ionico, che possono avvenire in modo concomitante, parziale, sequenziale e comunque sempre dipendenti dal tempo di contatto, dalla temperatura, dalla tipologia di materiale, dalla porosità e altri fattori. Il risultato di questo possibile complesso meccanismo di migrazione dei radionuclidi nel mezzo acquoso comporta la dispersione di parte dei contaminanti nell'ambiente. A tal proposito si è definito un *Indice di Lisciviabilità* per la valutazione del grado di contenimento del manufatto e quindi della capacità a contenere i radionuclidi in situazioni di contatto con acqua. Tale Indice di Lisciviabilità viene misurato mediante l'analisi degli elementi chimici rilasciati da provini cilindrici sospesi in contenitori con un volume definito di acqua demineralizzata.

La determinazione degli elementi rilasciati, nelle soluzioni tenute a contatto con i campioni, viene effettuata mediante spettrofotometria di assorbimento atomico e spettrofotometria di emissione atomica (AES). Indipendentemente dal metodo di lisciviazione utilizzato, molti laboratori adottano diverse tecniche di analisi chimica multielementale sul lisciviato, e misure di perdita di peso, microscopia elettronica o altre indagini di superficie sul campione tenuto a contatto con la soluzione. Misure di pH e di conducibilità sul lisciviato permettono di evidenziare ulteriormente l'attacco ai danni del cemento. Validi pHmetri da laboratorio, integrati da Titolatori automatici e Sonde per la Conducibilità sono disponibili dalla MetrOhm Italia.

Le caratteristiche di lisciviabilità possono essere migliorate con l'utilizzo di particolari formulazioni cementizie opportunamente additivate.

Resistenza chimica

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I rifiuti contenenti metalli o composti chimici potenzialmente reattivi devono essere opportunamente trattati per eliminarli o minimizzarli. Sostanze reattive, quali composti ossidanti come clorati, permanganati o perossidi organici, in grado di liberare ossigeno, oppure nitrati, solfati, potrebbero innescare reazioni esotermiche o liberare fumi tossici.

I rifiuti sono considerati reattivi se interagiscono facilmente con acqua, formando miscele esplosive, gas tossici, fumi o vapori dannosi alla salute dell'uomo. Eventuali costituenti tossici e nocivi devono essere noti e limitati.

Composti chimici in grado di complessarsi con metalli pesanti e renderli solubili in acqua, come l'EDTA (un agente complessante utilizzato nelle operazioni di decontaminazione), devono essere limitati in quanto facilitano la migrazione di radionuclidi e di metalli tossici nell'ambiente.

In particolare il pH, il cui valore è governato essenzialmente dalla fase C-S-H della matrice, può influenzare la reattività all'interno del rifiuto condizionato.

Resistenza alla biodegradazione

Una elevata resistenza alla biodegradazione è un requisito fondamentale per l'isolamento a lungo termine dei radionuclidi dall'ambiente. La degradazione biologica ad azione di microrganismi, può avvenire sia per attacco diretto con crescita sulla superficie del substrato solido sia per crescita supportata dalla lisciviazione di nutrienti, preventivamente infiltrati attraverso un mezzo acquoso, dal substrato solido. Date le condizioni alcaline e la mancanza di nutrienti i microbi non possono vivere all'interno del cemento.

La degradazione microbica può incrementare la mobilità dei radionuclidi aumentando la lisciviazione in vari modi quali, la trasformazione dei radionuclidi stessi in forme o in complessi organici maggiormente mobili. La degradazione microbica può comportare un aumento della generazione di gas, e perdita delle proprietà meccaniche.

L'esperimento di attacco microbiologico viene condotto immergendo i campioni in un mezzo inoculato da colture di funghi o batteri. L'esperimento si protrae per molti giorni durante i quali, a scadenze prefissate, si sottopongono le soluzioni a contatto ad analisi chimica (liberazione di acidi organici, Si, Al, Ca), misure di pH e conducibilità ed i campioni di cemento ad analisi fisico chimica (analisi della porosità, diffrazione a raggi X, microscopia ottica, SEM). Alla fine della fase di attacco dei campioni viene valutata la resistenza a compressione residua.

Stabilità termica

Gli incrementi di temperatura riscontrabili nei fusti possono causare combustione, decomposizione del manufatto, perdita di proprietà meccaniche e dispersione di radionuclidi in forma di gas, fumi o aerosol. Forti gradienti termici innescano degradazioni piuttosto rapide, al contrario se la temperatura viene fatta variare gradualmente non si osservano danni termici visibili.

In generale l'esposizione a temperature elevate compromette la durabilità nel tempo del manufatto. Le basse temperature possono altresì costituire degli agenti

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aggressivi per il cemento. Al di sotto di 0°C i fenomeni di congelamento, in superficie o nei pori, dell'acqua contenuta proveniente dall'atmosfera o dal materiale stesso, sono associati ad espansioni, stress e lesioni.

Si effettua allora una misura della resistenza ai cicli termici (più in generale nota come saggio di gelività), sottoponendo dei campioni ad un certo numero di cicli termici in condizioni termo-igrometriche specifiche (secondo la G.T. 26): umidità relativa del 90% e temperatura tra -40 °C e +40°C. In fine si sottopongono alla prova di resistenza alla compressione che deve risultare non inferiore all'80% del valore iniziale.

Per le prove di resistenza ai cicli termici le camere climatiche disponibili commercialmente possono essere le seguenti:

- Camera Climatica MKF della BINDER
- Camera Climatica DISCOVERY DY1200 (Versione C) della ANGELANTONI IND.
- Camera Climatica Cicli Termici CHALLENGE 250 ACS della ANGELANTONI IND.

Resistenza alla fiamma

La prova di resistenza alla fiamma viene effettuata allo scopo di predire il comportamento dei rifiuti in caso di esposizione al fuoco per incidenti durante il trasporto o il deposito.

In seguito alla esposizione al fuoco, l'effetto più osservato è la formazione di fratture superficiali; i campioni mostrano delle aree carbonizzate ma non bruciano.

Le analisi termogravimetriche (TGA) risultano utili per comprendere i fenomeni indotti dal riscaldamento. Vengono condotte portando la temperatura fino a 1000°C, con un percorso del tipo riportato:

20-200 °C → perdita dell'acqua capillare adsorbita o cristallizzata

200-300 °C → perdita dell'acqua dagli idrossidi di ferro

350-450 °C → decomposizione degli idrossidi di calcio

200-800 °C → continuo rilascio di acqua dal C-S-H e dall'alluminato di calcio idrato (C-A-H)

900 °C → decomposizione del carbonato di calcio.

Alla fine dell'esposizione al fuoco viene valutata la resistenza a compressione e confrontata con quella ottenuta dopo il processo di cura.

Resistenza meccanica: compressione ed impatto

La stabilità meccanica del rifiuto condizionato è un requisito primario per le operazioni di trasporto, manipolazione e stoccaggio temporaneo e finale: in condizioni di buona resistenza meccanica, i rischi di rilascio associati ad incidenti del tipo impatto o incendio, risultano notevolmente ridotti.

Con la prova di resistenza a compressione monoassiale, di solito, si valuta il carico di rottura su provini dopo la stagionatura e dopo l'esposizione ad agenti aggressivi. In

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tutti i casi il limite di carico deve rispettare le richieste della normativa vigente in materia. La resistenza a trazione, che di solito non viene misurata direttamente per questo tipo di materiale ma attraverso correlazioni con la resistenza a compressione, consente di prevedere il comportamento a fessurazione.

La reazione del manufatto ad un impatto accidentale dipende dalla tipologia di contenitore, scelto per resistere ad un certo carico, dalla resistenza intrinseca del manufatto, dalla omogeneità o uniformità globale del prodotto condizionato, dalla orientazione e dall'energia dell'urto.

La Pressa necessaria per l'effettuazione delle prove di resistenza alla Compressione deve soddisfare le caratteristiche della GT 26. Un prodotto commercialmente disponibile risulta essere la Pressa TECNOTEST KC 150 con relativo software di gestione tramite postazione PC.

Resistenza all'immersione

La resistenza all'immersione consente di valutare anche la capacità di resistere ad agenti chimici aggressivi presenti nelle acque.

Il test di immersione viene condotto essiccando il campione fino a peso costante, immergendolo in acqua per un tempo prefissato (solitamente 90 giorni) e sottoponendolo a misure di peso e di dimensioni prima e dopo il trattamento. In 90 giorni si registra una crescita asintotica del contenuto di acqua immagazzinata con un inizio veloce e le fasi successive più lente. La quantità di acqua inglobata dipende esclusivamente dalla permeabilità del mezzo.

La valutazione di variazioni di dimensioni deve evidenziare rigonfiamenti e deformazioni permanenti riportate durante l'immersione.

Stabilità dimensionale

Modifiche dimensionali possono svilupparsi lentamente, a partire dalla fine del processo di cura di 28 giorni (durante il quale si osserva ritiro plastico o igrometrico per effetto dell'evaporazione e dell'idratazione), per effetto della continua idratazione del cemento, delle interazioni chimico-fisiche fra i costituenti, o dell'*ageing* spontaneo dei manufatti. Il ritiro che si manifesta progressivamente nel tempo, dopo la stagionatura, aumenta all'aumentare del rapporto acqua/cemento, al diminuire dell'umidità dell'ambiente e al diminuire del rapporto tra aggregati e cemento. La compresenza di vincoli interni o esterni e di fenomeni di ritiro genera degli sforzi di trazione nel cemento, che qualora superino la resistenza a trazione del materiale inducono fratture.

I fenomeni di degradazione spinta, da agenti esterni, sono, invece, responsabili di variazioni di dimensione e di volume anche in tempi relativamente brevi. Essi inducono principalmente alterazioni della porosità iniziale, rigonfiamenti, cracking.

I manufatti, sottoposti a costante e prolungata osservazione devono rivelare variazioni dimensionali minime, sotto l'azione di sollecitazioni meccaniche, fisico, chimiche e biologiche, al fine di garantire una integrità durevole in tutti i processi di trasporto, stoccaggio e deposito.

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Presenza di liquidi liberi

La quantità di acqua libera dipende dal rapporto iniziale acqua/cemento e dal progredire dell'idratazione. Porosità, fessurazioni in presenza di rilevanti flussi idrici, percolazioni nel terreno contribuiscono all'immissione di liquidi nei moduli di confinamento del deposito fino alle matrici primarie.

La presenza di liquidi liberi deve essere fortemente limitata (inferiore all'1%) per il rischio di rilascio incontrollato di attività attraverso solubilizzazione e migrazione.

Un test per evidenziare la presenza di liquidi liberi si effettua praticando un foro in fondo al recipiente, o meglio sul fondo di un fusto di prova e misurandone l'acqua di drenaggio.

Studi termogravimetrici sui campioni di cemento consentono di ottenere informazioni relative allo stato fisico-chimico dell'acqua contenuta nei pori.

Con la tomografia o la tomodensitometria è possibile misurare la densità assoluta dei fusti di rifiuti cementati e le relative variazioni di densità con grande precisione (2-6%). Data la più bassa densità delle soluzioni interstiziali ($\approx 1.2-1.3 \text{ g/cm}^3$) rispetto a quella della matrice solida ($\approx 1.8 \text{ g/cm}^3$), i liquidi liberi, nel manufatto finale, possono essere rilevati grazie alla loro densità.

Resistenza all'irraggiamento

Durante il loro ciclo di vita i rifiuti condizionati sono sottoposti all'irradiazione dai radionuclidi in essi contenuti e da parte di rifiuti condizionati stoccati nello stesso deposito. Le radiazioni possono influenzare fortemente sia l'assetto chimico-fisico del rifiuto stesso che quello dell'ambiente circostante.

Gli effetti dell'irraggiamento esterno vengono studiati, ad alte dosi (10^6 Gy per irraggiamento gamma secondo la G.T. 26), attraverso l'analisi della stabilità dimensionale, la resistenza meccanica, l'evoluzione di gas, la lisciviazione.

L'irraggiamento induce dei microdifetti strutturali per effetto principalmente della temperatura. Il fenomeno preponderante, causato dall'irraggiamento, è il rilascio di gas.

Altri possibili effetti sono: rigonfiamenti o/ritiro, fessurazioni, interazioni tra rifiuto e matrice, ossidazione radiolitica, variazioni di solubilità degli elementi radioattivi, riscaldamento, *ageing* del cemento.

La temperatura ha un effetto sinergico sulla generazione radiolitica di gas dalle matrici di inglobamento. Dove si possono generare gas è necessario predisporre sistemi di ventilazione costituiti da valvole di sfogo e di particolari filtri dell'aria ad elevata efficienza per prevenire il rilascio di particolato.

Effetti dei composti organici sulla matrice di inglobamento

I costituenti organici del rifiuto, spesso provenienti da processi di estrazione o di precipitazione degli attinidi, sono suscettibili di attacco chimico in ambiente fortemente alcalino, microbico e radiolitico. Alcuni composti di natura organica,

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inoltre, possono generare complessi che incrementano la solubilità di certi radionuclidi facilitandone la migrazione all'esterno del deposito. Gli effetti principali delle interazioni matrice-rifiuto in presenza di organici consistono nella generazione radiolitica di gas.

Possibili conseguenze di tali effetti radiolitici in presenza di organici sono: incremento della solubilità degli attinidi come risultato della formazione di complessi solubili in acqua ed in seguito ad abbassamento di pH dovuto a liberazione di specie acide quali SO_2 , CO_2 , deterioramento della matrice per interazione dei prodotti acidi con i prodotti di idratazione del cemento, maggiori rischi di corrosione dei contenitori per abbassamenti locali di pH e per azione di alcuni prodotti di decomposizione dei costituenti organici.

Bisogna tener presente, inoltre, che molti costituenti organici hanno effetti ritardanti sull'idratazione del cemento ed alterano alcune proprietà peculiari del prodotto finale, quale la microstruttura.

Meccanismi di corrosione

Processi corrosivi ai danni della matrice possono essere indotti dalla radiolisi. I prodotti di corrosione possono costituire degli agenti chimicamente attivi ed aggressivi.

L'attacco corrosivo può provenire da clorati, carbonati e solfati (CO_2 , Cl^- , SO_4^{2-}) spesso presenti in quantità rilevanti nelle acque di falda.

Inoltre il pH fortemente alcalino (>12.5) delle soluzioni disperse nei pori del materiale rende le matrici suscettibili alla corrosione. Al contrario questo ambiente ad elevato pH risulta protettivo contro la corrosione dei contenitori, prevalentemente in acciaio. La potenziale corrosività deve essere eliminata per salvaguardare l'integrità dei contenitori, poiché la loro perforazione comporterebbe forte rischio di rilascio di contaminanti. Il contenitore della matrice deve essere realizzato in materiali (acciaio inossidabile, acciaio al carbonio, al titanio) compatibili con il rifiuto e tali che la loro integrità non venga compromessa dal rilascio di gas o dalla produzione di calore.

Una tecnica in grado di monitorare la degradazione dei manufatti cementizi indotta dalla corrosione dall'esterno dei contenitori è l'emissione acustica. In alternativa è possibile effettuare misure di impedenza in corrente alternata (spettroscopia di impedenza elettrochimica) su sezioni di campioni e vedere come varia la resistenza del materiale, oppure attraverso potenziodinamiche e seguire l'evoluzione del potenziale di corrosione.

Prove Ausiliarie

In aggiunta alle prove prescritte dalla G.T. 26 per la elaborazione di una dettagliata campagna di caratterizzazione, si effettuano prove per la determinazione di alcune proprietà strutturali, fisiche chimiche e meccaniche di particolare interesse, comunemente chiamate "sottoprobe" o "prove ausiliarie". La conduzione di dette sottoprobe viene generalmente indicata qualora sia necessario fornire ulteriori informazioni circa la possibilità o meno di concomitanti effetti di degradazione oltre quelli espressamente indicati dalla GT 26, oppure completare il quadro informativo

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sulle proprietà del cemento utilizzato e/o del manufatto risultante. Questo in particolar modo quando condizioni climatiche singolari dell'ambiente in cui verrà costruito il deposito, geomorfologiche del terreno e strutturali del deposito, ne necessitano lo studio. Alcune delle suddette prove, di comune interesse per le motivazioni appena descritte, possono essere elencate qui di seguito:

- calore di idratazione del cemento
- tempo di presa
- porosità
- permeabilità all'acqua sotto pressione
- finezza e porosità di Blaine.

Alcuni tra gli apparati commercialmente disponibili per l'effettuazione di suddette prove possono essere:

- Calorimetro C390 della TECNOST
- Porosimetro a Mercurio AUTOPORE IV della MICROMERITICS
- Permeabilmetro AT 315 della TECNOST
- Porosimetro di Blaine C378 della TECNOST

2.2.3 Determinazione di proprietà dei manufatti cementizi in scala reale

I fusti prodotti su scala reale devono essere sottoposti ad alcuni test, essenzialmente fisico-meccanici, per verificare la rispondenza ai requisiti previsti dalla normativa. La correlazione tra le proprietà dei provini da laboratorio e quelle dei provini ricavati da manufatti, preferibilmente non radioattivi, prodotti in scala reale, va determinata prima di applicare integralmente il processo di solidificazione scelto. Il campionamento viene effettuato per carotaggio in due steps:

- un campionamento in diversi punti della superficie esposta, sullo stesso raggio ma in più punti, alla stessa quota, della circonferenza oppure a diverso raggio ma sempre alla stessa quota;
- un campionamento a differenti altezze ma lungo uno stesso asse longitudinale.

Le proprietà da misurare sui manufatti reali sono: densità, temperatura massima raggiunta durante l'idratazione, resistenza a compressione, modulo di Young, modulo di Poisson, resistenza all'impatto. Gli ultimi tests mirano a verificare robustezza e deformazione opportuna per evitare la rottura del manufatto.

La valutazione di alcune proprietà fisiche avviene attraverso la rilevazione della temperatura raggiunta al centro e sulla superficie dei fusti.

I test meccanici a cui i fusti vengono sottoposti sono la prova di accatastamento o compressione, penetrazione, caduta ed impatto allo scopo di determinare i parametri critici per la salvaguardia della loro integrità durante il trasporto e lo stoccaggio. Il primo test viene effettuato sottoponendo il fusto ad un carico corrispondente a cinque volte il suo peso e misurandone la conseguente deformazione (standard IAEA). La prova di impatto viene condotta in modo da concentrare l'impatto in un'area corrispondente ad un bordo del coperchio. I danni dell'impatto devono risultare

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limitati ad un'area ristretta del bidone e la deformazione del coperchio insufficiente a separarlo dal resto del contenitore per evitare il rilascio del materiale. La prova penetrometrica viene condotta con una sbarra di 6 kg, diametro circa 3 cm, bordo rotondo, fatta cadere da circa 2 m sulla superficie del bidone.

L'integrità della sigillatura viene valutata attraverso test di perdita o percolamento da ogni singolo fusto in un prefissato tempo di osservazione.

La dose a contatto dei fusti viene misurata in modo empirico attraverso l'impiego di dosimetri e può essere confrontata con il valore teorico ricavato da una analisi matematica del fenomeno.

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3 PROPOSTA DI PROCEDURA DI CARATTERIZZAZIONE DEI RIFIUTI RADIOATTIVI

Obiettivo della caratterizzazione radiologica è l'individuazione e la quantificazione dei radionuclidi emettitori presenti in un rifiuto o in un manufatto al fine di effettuare una corretta gestione dei rifiuti radioattivi e per la verifica del rispetto dei criteri di accettazione del deposito definitivo in ottemperanza ai limiti imposti dalla Guida Tecnica n. 26 dell'ENEA-DISP (edizione 1987).

La caratterizzazione radiologica viene effettuata utilizzando tutte le informazioni deducibili da misure dirette e indirette sul manufatto e/o dalla storia del rifiuto prima del suo condizionamento.

La presente procedura di caratterizzazione radiologica si applica a tutti i manufatti ricevuti dal sito di smaltimento e di deposito e riguarda le fasi relative all'accettazione, identificazione, manipolazione, caratterizzazione ed immagazzinamento dei manufatti ricevuti.

3.1 RICEZIONE E ACCETTAZIONE MANUFATTI

A cura del trasportatore i manufatti vengono scaricati in lotti non superiori a **X** unità presso l'area ricevimento della unità "Sito di Smaltimento e Deposito".

Il Responsabile e l'Operatore di turno effettuano le operazioni di accettazione, consistenti nelle seguenti attività:

- a) verifica ed esame visivo dell'integrità e chiusura fusto-manufatto;
- b) verifica della conformità del manufatto alla scheda identificativa di accompagnamento;
- c) verifica della identificazione ed etichettatura del manufatto come definite dal produttore;
- d) controllo a vista dell'integrità del fusto-manufatto per rilevare eventuali ammaccature o crepe superficiali o incrostazioni di materiale comportanti contaminazioni residue;
- e) acquisizione di immagini fotografiche del manufatto da allegare al fascicolo caratterizzazione dedicato al fusto-manufatto in esame;
- f) acquisizione della eventuale documentazione fornita dal produttore del manufatto: informazioni dettagliate sulle origini, sulla descrizione storica e sui processi di trattamento subiti dal manufatto sono necessarie per assicurare una corretta caratterizzazione per la determinazione del contenuto dei radionuclidi emettitori;
- g) misura delle dimensioni e del peso del manufatto;
- h) misura del rateo di dose beta/ gamma e neutronica (quando richiesto o applicabile) a contatto e ad un metro;
- i) misura della contaminazione superficiale mediante "smear test";
- j) acquisizione e misura con sistemi di imaging gamma delle mappe di intensità di radiazione gamma e valutazione di eventuali concentrazioni di radionuclidi

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sulla superficie esterna del fusto: l'immagine della mappa di radiazione gamma sovrapposta alla immagine visibile dell'area consente di individuare eventuali hot spots presenti sulla superficie esterna del manufatto e caratterizzare i suddetti in tempi relativamente brevi;

- k) identificazione del manufatto tramite iscrizione nell'apposito registro indicante produttore, natura, specifiche e conseguente attribuzione del relativo codice identificativo;
- l) annotazione del predetto codice su etichetta di identificazione contenente anche griglia stato prove da compilare successivamente in base all'avanzamento dello stato prove ed applicazione della stessa etichetta al manufatto.

Successivamente il Responsabile o l'Operatore di turno procede a documentare i dati acquisiti nel foglio di caratterizzazione/rapporto di misura, che segue il manufatto per tutto il ciclo prove.

Il foglio di caratterizzazione/rapporto di misura in particolare contiene indicazioni relative a:

- data ricezione;
- codice identificativo;
- operatori coinvolti in prova;
- produttore del manufatto;
- identificazione fornita dal produttore;
- risultati controllo visivo;
- risultati della misura del rateo di dose;
- risultati della misura della contaminazione superficiale;
- risultati della misura effettuata con sistemi di imaging gamma;
- dati dichiarati dal produttore o proprietario in relazione alle caratteristiche del manufatto;
- eventuale indicazione dell'urgenza a procedere alle prove.

Il Responsabile e gli Operatori in relazione alla manipolazione dei manufatti devono adottare le necessarie precauzioni per evitare danni, contaminazione, corrosione, ecc., in ottemperanza alla vigente legislazione ed alle norme di buona tecnica.

3.2 AVVIO AL CICLO PROVE ED EVENTUALE IMMAGAZZINAMENTO.

Il Responsabile e l'Operatore di turno dispongono il trasporto dall'area ricevimento all'area laboratorio dei manufatti. Il primo in ordine di identificazione in base all'etichetta apposta è sottoposto alle misure, seguito dagli altri in ordine di identificazione.

I manufatti non ancora sottoposti a prove o al termine del ciclo prove, presenti nell'area laboratorio, sono segregati a cura degli Operatori nel magazzino area prove.

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3.3 CICLO PROVE.

Il Responsabile e l'Operatore di turno avviano il ciclo prove procedendo al caricamento del fusto in esame sul nastro trasportatore.

La caratterizzazione radiologica del manufatto inizia con l'invio del fusto ai **Sistemi di Radiografia Digitale** al fine di verificare la presenza o meno di liquidi all'interno del rifiuto o del manufatto.

I) Caso di assenza di liquidi nel rifiuto o manufatto.

Nel caso di assenza di liquidi, il rifiuto o il manufatto viene inviato, tramite l'apposito nastro trasportatore, ai sistemi di analisi di misura **NON DISTRUTTIVI (NDA, Non Destructive Assay)**, basati sulla rivelazione di un flusso fotonico o neutronico proveniente dal rifiuto, al fine di determinare e quantificare il contenuto di radionuclidi emettitori.

La caratterizzazione radiologica mediante analisi non distruttive viene eseguita secondo le seguenti modalità e successioni:

1) caratterizzazione del rifiuto tramite **spettrometria gamma a scansione**:

- Segmented Gamma Scanning;
- Transmission e Emission Computerised Tomography (TCT-ECT) usata per rifiuti e manufatti con distribuzione di densità non omogenea e distribuzione di attività non uniforme.

2) caratterizzazione del rifiuto tramite **misure neutroniche**:

- Tecniche Neutroniche Passive il cui obiettivo è la determinazione quantitativa del materiale fertile (^{238}Pu , ^{240}Pu , ^{242}Pu) presente nel rifiuto a partire dai neutroni rivelati;
- Tecniche Neutroniche Attive il cui obiettivo è la determinazione quantitativa del materiale fissile (^{239}Pu , ^{241}Pu , ^{235}U) presente nel rifiuto a partire dai neutroni rivelati.
- Tecniche Gamma Attive usate per determinare la massa totale degli attinidi presenti nel fusto.

3) caratterizzazione del rifiuto tramite **sistemi per il calcolo della composizione isotopica**:

- MGA e MGAU per determinare le abbondanze isotopiche relative del Plutonio e l'arricchimento dell'Uranio qualora il manufatto in oggetto sia alfa-emettitore o costituito da elementi di combustibile esauriti.

II) Caso di presenza di liquidi nel rifiuto o manufatto.

Nel caso di presenza di liquidi, il rifiuto o il manufatto viene inviato, tramite l'apposito nastro trasportatore, ai sistemi di analisi di misura **DISTRUTTIVI (DA, Destructive Assay)**, i quali conducono ad una accurata e completa determinazione dell'inventario dei radionuclidi presenti nel manufatto. L'attendibilità di tale determinazione dipende dalla rappresentatività del campione e dalla omogeneità del rifiuto da caratterizzare.

Lo schema generale di una analisi di tipo distruttivo prevede, quindi, le seguenti fasi:

- Campionamento;

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- Manipolazione e Omogeneizzazione del campione;
- Solubilizzazione del campione (digestione acida o mineralizzazione);
- Aggiunta al campione solubilizzato di un tracciante del radionuclide di interesse;
- Purificazione del radionuclide di interesse da eventuali interferenti mediante trattamenti chimico-fisici (precipitazione, estrazione selettiva con resine).

L'applicazione delle suddette fasi richiede l'uso di celle calde o scatole a guanti per il campionamento, pretrattamento e dissoluzione del campione. La scelta dell'adeguato metodo di dissoluzione per ottenere un campione omogeneo dipende dalla natura chimico-fisica del rifiuto e dalle proprietà chimiche degli elementi da isolare.

Il passo finale di una analisi DA consiste nella misura della concentrazione di attività dei radionuclidi, con le tecniche strumentali già descritte.

Questo processo può essere applicato direttamente al campione dissolto o dopo il processo di separazione, a seconda della complessità della miscela e della risoluzione della tecnica strumentale usata per la determinazione.

A supporto delle tecniche di analisi DA, sul campione rappresentativo del materiale da caratterizzare può essere effettuata una **misura di spettrometria gamma NDA con sistemi in situ**, "one shot", sistemi di misura costituiti da un singolo rivelatore calibrato sperimentalmente o matematicamente.

Importanti fattori da considerare nel definire una procedura di caratterizzazione radiologica.

Metodologia dei fattori di correlazione ("Scaling Factor").

L'inventario dei radionuclidi rilevanti per lo smaltimento dei rifiuti radioattivi è numeroso e vario (alfa e/o beta emettitori). Alcuni di questi radionuclidi sono facili da misurare (ETM, easy to measure) tramite tecniche di analisi non distruttive (NDA) o distruttive (DA), ma molti di loro sono difficili da misurare (HTM, hard to measure) e necessitano di analisi DA in laboratorio o calcoli utilizzando speciali codici (emettitori beta puri). Alcuni di essi sono impossibili da misurare (ITM, impossible to measure) anche in laboratorio.

La metodologia dei fattori di correlazione (scaling factor) può determinare la radioattività dei radionuclidi HTM e ITM usando correlazioni fra loro e nuclidi chiave (KN, key nuclides) scelti fra i radionuclidi facili da misurare, ETM. Essa fornisce un approccio di tipo semiempirico nella valutazione delle concentrazioni dei radionuclidi presenti in correnti di rifiuto specifiche.

L'idea alla base del metodo è che radionuclidi aventi origine dalla medesima sorgente e caratterizzati dallo stesso comportamento chimico-fisico nella diffusione in precisi contesti dell'impianto, mantengano un rapporto costante nelle loro concentrazioni finali.

In maniera specifica, i nuclidi HTM sono determinati da un radionuclide gamma facilmente misurabile moltiplicando la concentrazione di questo nuclide chiave per il

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fattore di correlazione fra i due nuclidi, fattore di correlazione derivato da risultati di adeguate analisi radiochimiche o codici di calcolo.

I nuclidi ITM sono determinati anch'essi da un emettitore gamma facile da misurare, utilizzando per il calcolo dei fattori di correlazione codici quali ORIGEN o MCNP.

Ciascun manufatto può essere misurato, quindi, con un sistema NDA, che fornisce le concentrazioni dei nuclidi chiave, KN. Usando i fattori di correlazione, gli associati HTM e ITM nuclidi sono calcolati e dichiarati per ciascun manufatto.

Ciascuna tecnica di misura, non distruttiva o distruttiva, facente parte del Ciclo Prove di Caratterizzazione Radiologica di un manufatto deve essere eseguita secondo una Procedura di Misura approvata, finalizzata a determinare in termini documentali le fasi operative e le responsabilità relative alle attività di prova per caratterizzazione di rifiuti radioattivi. La Procedura di Misura sarà preceduta, se necessario, da una adeguata Procedura di Taratura, finalizzata a definire responsabilità e modalità operative per la taratura delle apparecchiature strumentali.

Al termine di ciascuna misura deve essere elaborato un Rapporto di Misura in cui sono riportati i seguenti dati e informazioni:

- Tipo di misura eseguita sul manufatto;
- Condizioni di misura e riferimento alla procedura utilizzata;
- Caratteristiche degli strumenti di misura e apparecchiature utilizzate;
- Esito della misura con le relative incertezze di misura;
- Data di esecuzione della misura;
- Firma dell'operatore e del responsabile.

Al termine del ciclo prove e delle attività di caratterizzazione, il manufatto deve essere dotato delle seguenti caratteristiche documentali:

- foglio di caratterizzazione contenenti informazioni relative alla documentazione storica del manufatto nonché informazioni relative alle caratteristiche dimensionali e dosimetriche del fusto;
- procedure applicate nel corso delle attività di caratterizzazione;
- rapporto di misura con i risultati relativi a ciascuna tecnica di misura impiegata nella caratterizzazione radiologica, con le relative incertezze di misura.

La documentazione deve essere conservata e conferita al deposito assieme al manufatto.

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4 INSIEME INTEGRATO DI INFRASTRUTTURE, TECNOLOGIE E SERVIZI PER LA CARATTERIZZAZIONE DEI RIFIUTI

Le necessità del Sistema Paese nell'ambito della caratterizzazione dei materiali nucleari, specie in riferimento al waste management, attualmente non possono essere soddisfatte appieno, vista la limitata capacità di intervento delle strutture operanti sul territorio nazionale (principalmente Enea e Nucleco).

Si ritiene necessario costituire un parco tecnologico di infrastrutture, eventualmente integrato alle strutture già presenti, impegnato nelle attività di controllo dei materiali nucleari e di caratterizzazione dei rifiuti radioattivi primari e condizionati, nello sviluppo dei processi di trattamento e condizionamento, e nella salvaguardia dell'ambiente.

Il Parco Tecnologico che qui si ipotizza deve essere in grado di rispondere a tutte le esigenze del Paese, dalla caratterizzazione non distruttiva alle tecniche analitiche, e dovrà costituire un punto di eccellenza nel campo della R&S, realizzando anche sistemi prototipali.

Di seguito sono descritte le principali infrastrutture che dovranno esservi inserite.

4.1 LABORATORIO DI CARATTERIZZAZIONE RADIOLOGICA MATERIALI E RIFIUTI RADIOATTIVI

Il laboratorio di caratterizzazione deve essere attrezzato sia per fare misure di tipo non distruttivo a campione sui rifiuti in arrivo al deposito, sia per misure di radiochimica analitica sugli eventuali effluenti liquidi e aeriformi. Le aree previste sono:

Aree di ricezione, smistamento e stoccaggio temporaneo

L'area di ricezione, smistamento e stoccaggio temporaneo è costituita da:

- una Zona di Ricezione e Controllo in cui vengono effettuati l'identificazione, il controllo della dimensione e del peso, il rapporto fotografico, e la registrazione di tutte le informazioni relative al rifiuto (in particolare dell'attività totale dichiarata dei rifiuti). Sono necessari strumenti di misura di peso (bilance, ecc.) e di dimensione, eventualmente un portale "radiologico", ed un sistema informatico di registrazione dati collegato all'archivio generale del deposito.
- Una Zona di Smistamento Diretto verso i locali deposito ed una Zona di Stoccaggio Temporaneo dove tenere i rifiuti che sono destinati a caratterizzazione in loco. Queste zone dovranno essere dotate di adeguati mezzi di movimentazione dei rifiuti (muletti, carro ponte, nastri trasportatori, ecc).

Laboratori caldi

In particolare, per la caratterizzazione non distruttiva, sono necessari:

- Sistema radiografico, per verificare l'assenza di liquidi nel rifiuto;

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- Sistema di imaging gamma, per determinazione quali-quantitativa del profilo di attività del rifiuto;
- Sistemi basati sulla spettrometria gamma: tomografia in emissione e in trasmissione per i rifiuti contenuti in fusti di tipo petrolifero, sistema di analisi in situ ISOCS per oggetti di dimensioni e geometrie differenti; sistema di misura per il calcolo della composizione isotopica (MGA);
- Sistemi basati sulle tecniche neutroniche passive e attive: sistema integrato attivo/passivo con interrogazione neutronica mediante acceleratore lineare (linac).

Per le misure di radiochimica sugli effluenti, in particolare per il controllo dei liquidi, è necessario avere un laboratorio attrezzato con:

- scintillatori α e β/γ ;
- spettrometro di massa;
- spettrometro α

Infrastrutture Ausiliarie

I servizi sono in tutto uguali a quelli di una qualsiasi installazione nucleare:

- spogliatoio caldo e freddo;
- sala di controllo;
- locali adibiti al personale della radioprotezione operativa;
- sistemi di monitoraggio personale;
- docce per la decontaminazione;
- sistemi di contenimento e controllo degli scarichi dubbi;
- sistemi di monitoraggio ambientali;
- sistemi di ventilazione;
- sistema elettrico di emergenza (UPS, motori diesel, ecc);
- sistemi di rivelazione ed estinzione incendi;
- bombolaio per gas di processo (azoto liquido, argon-metano, ecc);
- servizi igienici freddi.

4.2 SVILUPPO TECNICHE ANALITICHE INNOVATIVE PER IL CAMPIONAMENTO E LA CARATTERIZZAZIONE DEI MANUFATTI DESTINATI AL DEPOSITO

Premessa

Le operazioni di smantellamento degli impianti nucleari in Italia produrranno una notevole quantità di rifiuti radioattivi condizionati da trasferire al sito di deposito. Dovranno conseguentemente essere definite le caratteristiche ed i criteri di accettabilità dei manufatti prodotti. A tale scopo è di estrema importanza classificare

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correttamente i rifiuti radioattivi nelle tre categorie della Guida Tecnica 26 APAT, in particolare per evitare di classificare in terza categoria rifiuti che sono invece di seconda e che hanno quindi un percorso di smaltimento differente.

Analogamente è importante definire le procedure di caratterizzazione che permettano di discriminare con precisione i materiali che possono essere sottoposti a rilascio incondizionato e/o condizionato (analisi di clearance).

Si propone di realizzare nel parco tecnologico un sistema di misura integrato che, insieme alle tecniche tradizionali, comprenda anche tecniche ottimizzate per le esigenze di classificazione dei rifiuti.

Tale sistema dovrà integrare tre tecniche di misura all'avanguardia:

- interrogazione neutronica attiva tramite fissione indotta;
- interrogazione gamma attiva tramite fotofissione;
- tomografia gamma;

in modo da ottenere la completa caratterizzazione radiologica dei manufatti.

L'obiettivo principale di tali tecniche è la determinazione e la quantificazione, nei contenitori di rifiuti radioattivi, della massa di fissile, della massa di fertile nonché il contenuto totale di attinidi per la caratterizzazione completa del manufatto, soprattutto per la corretta discriminazione dei rifiuti di II e III Categoria.

Le **Tecniche Neutroniche Passive** sono utilizzate per ricavare la massa di ^{240}Pu equivalente e quindi, nota la composizione isotopica del campione, la massa totale di Plutonio.

In tali tecniche i neutroni rivelati possono essere ricondotti ai seguenti due termini di sorgente:

- reazioni (α, n) su materiali leggeri, provocate dal decadimento α di isotopi di U e Pu;
- fissione spontanea di isotopi di U e Pu.

L'importante differenza tra l'emissione di neutroni da fissione spontanea e da reazioni (α, n) è dovuta al fatto che nel primo processo si ha l'emissione quasi contemporanea di neutroni (che sono quindi correlati nel tempo) mentre il secondo processo dà luogo a neutroni singoli, distribuiti casualmente nel tempo. Dalla valutazione del rateo di neutroni da fissione spontanea è possibile ricavare la massa di materiale fissile in termini di isotopi pari del Plutonio.

I componenti fondamentali di un tale sistema sono:

- moderatore per la termalizzazione dei neutroni;
- contatori proporzionali ad ^3He ;
- cavità di rivelazione.

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La **Tecnica di Interrogazione Neutronica Attiva** può essere utilizzata per determinare la quantità di materiale fissile presente entro il manufatto. I componenti fondamentali di un tale sistema sono:

- acceleratore lineare di elettroni (Linac);
- target per la produzione di fotoni da bremsstrahlung;
- target per la produzione di fotoneutroni;
- moderatore per la termalizzazione dei neutroni (già presente nel sistema passivo);
- rivelatori ad ^3He per la rivelazione dei neutroni veloci dovuti a reazioni di fissione indotta su isotopi fissili quali ^{235}U o ^{239}Pu (già presenti nel sistema passivo);
- cavità di rivelazione.

La sorgente di neutroni è realizzata mediante un fascio di elettroni accelerati dal Linac che investe un bersaglio ad alto numero atomico (generalmente W) producendo fotoni di bremsstrahlung. Il fascio fotonico investe un ulteriore target (generalmente Be) per la creazione di fotoneutroni, con conseguente produzione di neutroni per fissione indotta sul materiale fissile presente nel fusto.

Nella **Tecnica di Interrogazione Gamma Attiva**, usata per determinare la massa totale degli attinidi presenti nel manufatto, il fascio di fotoni di bremsstrahlung viene fatto incidere direttamente sul contenitore di rifiuti generando reazioni di fotofissione: la rivelazione dei neutroni ritardati relativi alle fotofissioni indotte nel fusto dà informazioni sulla presenza di materiale fotofissile (principalmente ^{238}U).

L'acceleratore lineare di elettroni viene sfruttato, altresì, per eseguire la **Tomografia gamma in trasmissione**: la sorgente di trasmissione consiste proprio nel fascio fotonico di bremsstrahlung che investe il campione da analizzare, viene rivelato da una schiera di rivelatori del tipo BGO per fornire una accurata determinazione della distribuzione del coefficiente di attenuazione (μ) della radiazione gamma nel manufatto. La **Tomografia gamma in emissione** viene eseguita con l'ausilio di rivelatori al Germanio ad alta risoluzione per la misura della distribuzione di attività spaziale all'interno del contenitore di rifiuti.

I risultati di ciascuna tecnica di caratterizzazione vengono raccolti e combinati per fornire una corretta e completa caratterizzazione del manufatto, con limiti di rivelazione abbastanza ridotti e tali da consentire una ottimale discriminazione fra rifiuti di II e III Categoria.

Il sistema dovrà essere progettato per lavorare in continuo con un sistema di nastri trasportatori che possano spostare agevolmente il campione per l'analisi con l'una o con l'altra tecnica in sequenza per un tempo di misura stabilito a priori che, data la concezione del sistema, risulterà relativamente breve (si prevede 2 ore circa per fusto).

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4.3 SVILUPPO TECNOLOGIE INNOVATIVE PER IL TRATTAMENTO E IL CONDIZIONAMENTO DEI RIFIUTI RADIOATTIVI

Premessa

Si propone di realizzare una infrastruttura attrezzata per lo sviluppo di tecnologie e per la qualificazione di processi di trattamento e condizionamento di rifiuti radioattivi, in particolare per quelle tipologie di rifiuti provenienti essenzialmente da operazioni di decommissioning e dalla ricerca scientifica, per i quali non ci sono tecniche standardizzate a livello internazionale.

Come esempi non esaustivi si possono indicare: soluzioni acquose di decontaminazione (contenenti ad es. complessanti organici), soluzioni acquose contenenti sospensioni organiche (olio, etc.), soluzioni acquose di transuranici, fanghi contaminati, resine organiche e inorganiche, etc.

La struttura dovrebbe funzionare anche in sinergia con quella dedicata alla ricerca e sviluppo di tecnologie innovative per la fabbricazione e trattamento dei combustibili nucleari dei reattori di quarta generazione.

La qualificazione dei processi di condizionamento è intesa come un complesso di attività, inquadrata in un programma documentato, volte a dimostrare che il manufatto risultante dal processo di condizionamento rispetti i requisiti minimi per il deposito temporaneo, il trasporto e lo smaltimento.

Si propone di non dedicare inizialmente risorse ai processi ad alta tecnologia dedicati ai rifiuti ad alta attività, come ad esempio la produzione di matrici di inglobamento quali vetri speciali o materiali ceramici, in quanto si tratta di processi che richiedono grandi investimenti e che sono sviluppati in altri paesi tradizionalmente più attrezzati (es. vetrificazione con cold crucible in Francia).

L'infrastruttura sarà quindi inizialmente focalizzata sullo sviluppo di processi di cementazione e di qualificazione delle relative matrici, ambito in cui esistono in Italia esperienza e competenza.

Il compito consiste nell'individuare il processo di condizionamento più appropriato per la tipologia di rifiuto di volta in volta in esame, e nello sviluppare un programma di caratterizzazione volto a mostrare la rispondenza dei manufatti ai criteri di accettabilità/stabilità approvati dall'autorità di controllo. Vengono valutate le prestazioni delle matrici cementizie, in termini di resistenza alla compressione, ai cicli termici, all'immersione, alla lisciviazione, all'irraggiamento, alla biodegradazione, ai liquidi liberi e alla fiamma, in conformità a specifici standard, verificando il rispetto dei requisiti prescrittivi vigenti in ambito nazionale (Guida Tecnica n. 26 dell' APAT) ed internazionale.

Si può prevedere successivamente di ampliare la hall tecnologica con l'inserimento di apparecchiature in scala laboratorio per lo studio di matrici vetrose, di norma più idonee di quelle cementizie per il condizionamento di rifiuti a lunga vita.

L'infrastruttura dovrà prevedere un area attrezzata con **Scatole a Guanti** e **Celle Schermate** per lo studio e lo sviluppo in scala laboratorio dei processi di trattamento e condizionamento delle varie tipologie di rifiuti radioattivi individuate.

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Un'altra area dovrà invece essere attrezzata con le apparecchiature necessarie per eseguire a "caldo" le seguenti prove tecniche su provini di matrice cementizia (tipo Laboratorio CETRA dell'ENEA Casaccia, che però può operare solo a "freddo"):

- Trattamento in cella di stagionatura
- Prova di lisciviazione
- Durimetria
- Trattamento in cella climatica
- Prova di compressione
- Prova di resistenza al fuoco
- Prova di resistenza all'irraggiamento
- Prova di resistenza all'attacco microbiologico.

Sarà poi necessario mettere a punto metodiche sperimentali per la qualificazione dei materiali impiegati in ambito nucleare, inerenti principalmente i seguenti aspetti:

- comportamento alla corrosione dei materiali;
- fenomeni di radiolisi in materiali cementizi;
- porosità e permeabilità dei materiali cementizi;
- resistenza a trazione e modulo elastico dei materiali a base cementizia.

Infrastrutture Ausiliarie

Come già descritte per l'attività precedente, e quindi possono essere in comune se opportunamente dimensionate a tale scopo.

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5 PROPOSTA DI PROSECUZIONE DELLE ATTIVITÀ

La progettazione, la realizzazione e la definizione particolareggiata dell'insieme integrato di infrastrutture, tecnologie e servizi necessari per la caratterizzazione di rifiuti sarà l'argomento principale per il lavoro da eseguire nelle prossime annualità.

In particolare dovranno essere perseguiti i seguenti obiettivi:

- **Progettazione preliminare del Laboratorio di Caratterizzazione Radiologica mediante Tecniche di Analisi Distruttive.**

Il Laboratorio dovrà in primo luogo prevedere la progettazione o l'acquisizione di celle calde o scatole a guanti per il campionamento, pretrattamento e dissoluzione del campione considerato rappresentativo del materiale da caratterizzare.

Il Laboratorio dovrà quindi potersi avvalere delle principali tecniche di chimica analitica necessarie per una completa determinazione dell'inventario dei radionuclidi presenti e per una corretta misura della concentrazione di attività degli stessi: Spettrometria di Massa con Plasma ad Accoppiamento Induttivo (ICP-MS), Spettrometria di Massa a Ionizzazione Termica, Cromatografia Ionica, Scintillazione Liquida, Spettrometria Alfa, Spettrofotometria ad assorbimento atomico.

- **Progettazione preliminare del Laboratorio di Caratterizzazione Radiologica mediante Tecniche di Analisi Non Distruttive.**

Il Laboratorio di Analisi Non Distruttive sarà fisicamente separato dal Laboratorio di Analisi Distruttive e dotato di sistemi in grado di trasportare e analizzare il rifiuto in successione e in modo completamente automatico, in maniera tale da minimizzare il rateo di equivalente di dose assunto dai lavoratori esposti.

Il campione da caratterizzare viene lasciato così come è stato prodotto, senza alcuna alterazione fisica o chimica apprezzabile e sottoposto alle principali tecniche di analisi quali Radiografia Digitale, Imaging Gamma, Segmented Gamma Scanning, Tomografia in Emissione e in Trasmissione, Tecniche Neutroniche Passive, al fine di individuare gli emettitori beta/gamma, gli emettitori alfa presenti nel materiale da caratterizzare e individuare la rispondenza alle specifiche riportate sulla scheda fornita dal produttore.

- **Progettazione preliminare del laboratorio di qualificazione e certificazione di matrici di contenimento.**

L'obiettivo del laboratorio di qualificazione e certificazione di matrici di contenimento è quello di valutare la fattibilità di una operazione di cementazione, in termini di:

- compatibilità tra matrice cementizia e rifiuto simulato;
- selezione della migliore ricetta di cementazione;
- verifica di variazioni dimensionali e di resistenza a compressione dopo immersione in acqua dolce;

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- verifica dell'assenza di alterazioni dimensionali e di resistenza a compressione in seguito a ripetute escursioni termoclimatiche;
- valutazione della velocità di combustione e classificazione in provini combustibili, non combustibili ed autoestinguenti;
- verifica dell'assenza di alterazioni dimensionali e di resistenza a compressioni in seguito ad intenso irraggiamento gamma;
- verifica della resistenza all'attacco microbiologico con ceppi fungini e batterici mediante misura della resistenza a compressione.

Il fine è quello di valutare la rispondenza tra le proprietà chimiche, fisiche e meccaniche dei manufatti ottenuti e i requisiti stabiliti dalla normativa nazionale di riferimento.

Il Laboratorio dovrà essere progettato e realizzato con la strumentazione in grado di effettuare le prove chimico, fisico, meccaniche previste dalla Guida Tecnica n. 26, mirate a stabilire: compatibilità della matrice con il rifiuto, omogeneità, densità, stabilità chimica, lisciviabilità, presenza di gas e di liquidi liberi, stabilità dimensionale, resistenza al fuoco, resistenza alla compressione, resistenza al calore ed all'irraggiamento, degradabilità biologica ed eventuali altre proprietà peculiari.

- **Progetto particolareggiato del Sistema Integrato di Caratterizzazione Radiologica Non Distruttiva.**

L'obiettivo del presente progetto è la determinazione e la quantificazione, in contenitori di rifiuti radioattivi da 200 litri, della massa di fissile, della massa di fertile nonché il contenuto totale di attinidi per la caratterizzazione completa del manufatto e per la corretta discriminazione dei rifiuti di II e III Categoria. Tale sistema dovrà integrare tre tecniche di misura all'avanguardia (interrogazione neutronica attiva tramite fissione indotta, interrogazione gamma attiva tramite fotofissione, tomografia gamma) in modo da ottenere la completa caratterizzazione radiologica dei manufatti.

I risultati di ciascuna tecnica di caratterizzazione vengono raccolti e combinati per fornire una corretta e completa caratterizzazione del manufatto, con limiti di rivelazione abbastanza ridotti e tali da consentire la discriminazione fra rifiuti di II e III Categoria.

Il sistema dovrà essere progettato per lavorare in continuo con un sistema di nastri trasportatori che possano spostare agevolmente il campione per l'analisi con l'una o con l'altra tecnica in sequenza per un tempo di misura stabilito a priori che, data la concezione del sistema, risulterà relativamente breve (si prevede 2 ore circa per fusto).

Il sistema integrato di caratterizzazione dovrà essere progettato per essere trasportabile o mobile: il sistema di misura, con tutti i suoi accessori, dovrà poter essere alloggiato su un "camion" al fine di spostarsi agevolmente per rispondere alle esigenze di qualsivoglia committente e con l'obiettivo di eseguire le misure "in loco", evitando, così, i numerosi problemi relativi al trasporto di materiali nucleari.

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- **Studio Approfondito e Analisi Critica dei criteri contenuti nelle seguenti norme UNI:**

- Norma UNI 10621 1997: Manufatti di rifiuti radioattivi condizionati. Caratterizzazione
- Norma UNI 11194 2006: Manufatti di rifiuti radioattivi condizionati – Caratterizzazione radiologica di manufatti appartenenti alla Categoria 2 ai fini del conferimento al deposito finale

L'attività dovrà preferibilmente essere eseguita con la collaborazione delle Università per le loro sfere di competenza.

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6 BIBLIOGRAFIA ESSENZIALE

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- Guida Tecnica n° 26: Gestione dei rifiuti radioattivi. ENEA/DISP
- IAEA, SAFETY STANDARD SERIES, Draft Safety Guide No. DS 390, “Classification of Radioactive Waste”, Vienna Novembre 2006
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- UNI CEI EN 45020, “Normazione e attività connesse - Vocabolario generale”, Febbraio 2006
- UNI CEI EN ISO IEC 17025, “Requisiti generali per la competenza dei laboratori di prova e di taratura”, Settembre 2005
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APPENDICE

Criteri di Accettabilità per Rifiuti Radioattivi di I e II Categoria

SPECIFICHE		CERTIFICATO DI ACCOMPAGNAMENTO
Generale		
Quality Assurance Programme	Una descrizione di tutte le attività, eventi e risorse utilizzate da un operatore di una struttura per il condizionamento dei rifiuti nucleari al fine di assicurare l’effettiva gestione e il controllo di tutti i parametri identificati come critici per raggiungere la qualità e la conformità coi requisiti richiesti per un carico di rifiuti, incluso dettagli inerenti le relative certificazioni e verifiche.	Certificazione da parte dei responsabili delle strutture per il processo di condizionamento. In alternativa certificazione di conformità di ogni rifiuto con i requisiti identificati nella specifica dell’involucro del rifiuto.
Conformità con i requisiti fissati dalla legge	Disposizioni per assicurare la conformità con le norme legislative dovrebbero essere incluse all'interno delle suddette disposizioni atte ad assicurare la qualità	
CARATTERIZZAZIONE DEI RIFIUTI		
Descrizione generale del rifiuto grezzo. Proprietà fisiche, chimiche e biologiche - Contenuto dei radionuclidi - Contenuto fissile	Una descrizione per iscritto del rifiuto dovrebbe essere fornita insieme ai dettagli su proprietario, provenienze, volume (m ³) e peso (t). Per poter determinare la conformità con i criteri di accettazione del rifiuto dovrebbero essere identificate, e dove possibile quantificate con sufficiente accuratezza, le caratteristiche e la composizione del rifiuto grezzo. Dovrebbe inoltre essere stabiliti dei limiti per quei radionuclidi e altre proprietà che potrebbero influire negativamente sulla pertinenza del rifiuto per il deposito. Laddove pertinente, (Threshold Recording Levels (TRL) possono essere utilizzati per identificare quando viene recuperata informazione quantificata sul singolo radionuclide. Per ciascun componente presente nel rifiuto dovrebbero essere definiti valori medi e valori limite per ogni singolo rifiuto insieme ad un limite massimo del contenuto fissile per prevenire situazioni di criticità.	Dovrebbe essere fornita conferma che il contenuto del rifiuto grezzo sia entro i limiti definiti nella specificazione del rifiuto. Dovrebbero essere registrati i valori effettivi per quei radionuclidi e gli altri componenti fondamentali del rifiuto che eccedono il TRL identificato. Laddove presente materiale fissile dovrebbe essere confermato che sia entro il limite di massa fissile consentito.
CONTENITORE		
Descrizione (incluse dimensioni) Proprietà Peso	Dovrebbe essere fornita, con disegni ove possibile, una descrizione del contenitore del rifiuto utilizzato per contenere il rifiuto condizionato con dettagli sulle proprietà meccaniche e fisiche. Dovrebbero essere inclusi dettagli di fabbricazione e il peso del contenitore vuoto.	Dovrebbe essere fornita conferma che il container è conforme ai requisiti della specifica di fabbrica, con riferimento ad una certificazione della fabbrica dove possibile (se necessario offrire accesso a record di fabbrica) e dettagli su eventuali concessioni di fabbrica

TRATTAMENTO E CONDIZIONAMENTO

Dettagli del processo di condizionamento, incluse disposizioni per il controllo dei seguenti:

- Liquidi liberi
- Polveri
- Esplosivi e gas compressi
- Metalli e composti tossici
- Materiali pericolosi
- Agenti complessanti
- Sostanze organiche
- Materiali fissili
- Attività

Dettagli su eventuale trattamento effettuato sul rifiuto prima del condizionamento

Dettagli su qualsiasi matrice immobilizzante (inertizzante) utilizzata includendo la specificazione della matrice nonché le disposizioni per il controllo dei parametri di qualità.

Dovrebbe essere fornita una descrizione tecnica del processo di condizionamento, illustrata da diagrammi di flusso dove possibile.

Dovrebbero essere identificati parametri importanti per il conseguimento della qualità dell' involucro del rifiuto. Dovrebbe essere fornita una descrizione delle disposizioni atte a monitorare e controllare tali parametri.

Se il rifiuto deve essere sottoposto ad un pretrattamento, lo scopo e natura di tale processo dovrebbero essere descritti.

Qualora ci sia il rischio che qualche sostanza non consentite sia presente nel rifiuto dovrebbe essere fornita una descrizione delle disposizioni per controllarne e limitarne l'inclusione secondo i limiti specificati nei criteri di accettazione dei rifiuti.

Alla stessa maniera, qualora il rifiuto includa materiale fissile, dovrebbe essere determinata la quantità che, senza rischi, può essere incorporata nel rifiuto, e dovrebbe essere dimostrato l'adeguamento ai limiti specificati nel criterio di accettazione dei rifiuti. Dovrebbero essere descritte le disposizioni per il controllo della quantità di materiale fissile nei singoli rifiuti.

Si dovrebbero specificare l'attività media e massima dei singoli package.

Le disposizioni per monitorare e limitare l'attività del singolo package dovrebbero essere descritte qualora l'attività massima prevista superi il limite specificato nei criteri di accettazione dei rifiuti o le norme di sicurezza che regolano la gestione, il deposito e il trasporto di rifiuti.

Dovrebbe essere fornita una descrizione Per qualsiasi matrice utilizzata per immobilizzare il rifiuto grezzo, o elementi in esso contenuti comprendente:

- l'identificazione del rifiuto che deve essere immobilizzato
- dettagli su qualunque pretrattamento effettuato sul rifiuto
- specifiche sulla matrice immobilizzante incluse:
 - la sua composizione;
 - rapporto a prodotto immobilizzato
 - percentuale di vuoto e grado di omogeneità con il prodotto finale
 - resistenza a compressione
- risultati dei test per la stima del prodotto finale dopo lisciviazione e rilascio dei radionuclidi inclusi

La data, il luogo e l'impianto in cui è stato effettuato il condizionamento del rifiuto dovrebbe essere registrato sul certificato di accompagnamento con la conferma che il rifiuto è stato condizionato in accordo coi requisiti del processo di condizionamento

Dovrebbe essere fornita una conferma che qualsiasi matrice immobilizzante utilizzata risponda ai requisiti della relativa specifica



- identificazione di quei parametri necessari per controllare che il prodotto finale sia conforme alle specifiche ed una descrizione delle disposizioni per il monitoraggio e il controllo di tali parametri.
Il grado di dettaglio di questa descrizione dovrebbe essere sufficiente a permettere di effettuare una valutazione tecnica della conformità della matrice coi requisiti del criterio di accettazione dei rifiuti.

MODULO DEL RIFIUTO

Tipo di modulo (package) e variante	Dovrebbero essere definiti tipologia e varianti del modulo (package)	Dovrebbe essere registrati sul certificato di accompagnamento la tipologia e varianti di modulo
Dimostrazione di integrità del modulo ivi compresi: - Resistenza meccanica - Resistenza all'impatto - Stabilità alla radiazione - Resistenza al fuoco - Grado di vuoto - Durabilità - Resistenza alla lisciviazione	Dovrebbero essere riportati i risultati del lavoro eseguito per valutare e dimostrare l'integrità del modulo di rifiuti contro ognuno dei requisiti identificati.	
Identificazione, etichettatura e marcatura del modulo	Il sistema da usare per contrassegnare ed etichettare i moduli dovrebbe essere descritto insieme ai dettagli relativi all'assegnazione a ciascun modulo di un unico identificatore (numerico, alfa-numerico o codice a barre)	L'identificatore del package dovrebbe essere marcato chiaramente su almeno due facce del contenitore registrato sul certificato di accompagnamento
Registrazioni (records)	Dovrebbero essere identificate le registrazioni essenziali a dimostrare la conformità del waste package ai requisiti contenuti nella specifica del modulo stesso. Dovrebbero inoltre essere definiti il formato e le informazioni da fornire per ogni singolo package.	Completamento del certificato di accompagnamento come definito nella specifica del waste package.
GESTIONE, DEPOSITO E CONSEGNA		
Peso del package	Il peso massimo del singolo package dovrebbe essere specificato e mostrato essere compatibile con qualsiasi limite specificato nei criteri di accettabilità di rifiuti e/o requisiti per la gestione e manipolazione dei rifiuti radioattivi. Il metodo per la	Il peso, i livelli della contaminazione superficiale e di rateo di dose di ogni package dovrebbero essere misurati e registrati nel certificato di

Contaminazione superficiale	determinazione di questo limite dovrebbe essere definito. I provvedimenti atti a determinare il peso di ogni modulo o verificare che il peso sia entro il limite specificato dovrebbero essere descritti. Dovrebbe essere definito il limite massimo per la contaminazione superficiale di un package. Tale limite dovrebbe essere dimostrato essere compatibile con qualsiasi limite specificato nei criteri di accettabilità del rifiuto e/o i requisiti per la gestione, il deposito e il trasporto del package. Il metodo per determinare il limite dovrebbe essere definito. Dovrebbero essere descritte le disposizioni per determinare i livelli di contaminazione superficiale di ogni packagee per verificare che siano all'interno dei limiti specificati.	accompagnamento alla fine del processo di condizionamento. In alternativa dovrebbe essere confermato che tali misure rientrino nei limiti indicati nella specifica del rifiuto.
Rateo di dose	Dovrebbero essere specificati il rateo di dose medio e massimo per ogni package. Questi sono solitamente valutati sia per la superficie del package sia ad una distanza di 1 metro dallo stesso. Il metodo di determinazione dovrebbe essere definito e i ratei di dose specificati dovrebbero dimostrare di essere compatibili con qualsiasi limite specificato nei criteri di accettabilità di rifiuti e/o requisiti di gestione, deposito e trasporto. Dovrebbero essere descritte le procedure per determinare il rateo di dose di ogni package, o per verificare che siano entro i limiti specificati. Se si eccede oltre il valore di 2 mSv/h per la dose superficiale, devono essere prese misure speciali.	
Manca lo “STORAGE” (perché) Trasporto	Dovrebbero essere descritte le disposizioni relative alla preparazione del package per il trasporto al deposito che dimostrino la loro conformità con le norme nazionali e, se necessario, internazionali che regolamentano il trasporto di waste packages. Dovrebbe inoltre essere identificata qualsiasi documentazione richiesta secondo tali norme, oltre al certificato di accompagnamento del package.	Dovrebbe essere confermata nella documentazione attinente la conformità alle norme nazionali (e dove necessario internazionali) che regolamentano il trasporto di materiali radioattivi.
Documentazione di spedizione	Dovrebbero essere identificati, e allegati ove necessario, tutti i documenti e le registrazioni che devono essere consegnati all'operatore del deposito quando un modulo viene consegnato. Dovrebbe essere dimostrato in che modo la relativa documentazione adempie e soddisfa i requisiti dei criteri di accettabilità del rifiuto,. Dovrebbe inoltre essere fornita una descrizione delle operazioni effettuate per il completamento di tale documentazione, unitamente a dettagli sul personale	Il completamento della documentazione di spedizione come descritto nella specifica del waste package.



Rintracciabilità e Identificazione	autorizzato a firmarla. Deve essere assicurata la rintracciabilità e l'identificazione. Possono essere usati diversi metodi quali codici a barre, codici numerici o alfa numerici impressi su carta, cartellini di metallo o sul modulo(impronta diretta)	
DEPOSITO TEMPORANEO		
Minimizzazione del deterioramento durante il deposito Sicurezza durante il deposito Rintracciabilità	Qualora un package debba essere conservato in un deposito temporaneo prima del deposito definitivo, dovrebbe essere fornita una descrizione del deposito stesso e delle disposizioni finalizzate al monitoraggio della condizione dei packages e alla minimizzazione del loro deterioramento.	Il periodo di un eventuale deposito temporaneo di un package dovrebbe essere registrato sul certificato di accompagnamento unitamente a dettagli relativi al luogo in cui è stato depositato.
RECORDS		
Dati del package Procedure di registrazione Rintracciabilità dei dati	I dati dovrebbero essere determinati e concordati con l'operatore della struttura di deposito temporaneo o definitivo. In ogni fase della produzione dei rifiuti radioattivi.	Un certificato di accompagnamento (data sheet) dovrebbe essere prodotto per ciascun manufatto. Nel certificato di accompagnamento dovrebbero essere disponibili informazioni come richiesto dall'operatore del deposito.

RFIC

S Y S T E M S

ICS-3000 System

Productivity

Capability

Performance



Passion. Power. Productivity.

Innovation

All the Advantages of Modular IC

The ICS-3000 Reagent-Free™ Ion Chromatography (RFIC™) system provides the versatility of a modular system and the convenience of an integrated system. Whatever your needs, from high-throughput routine analyses to trace detection of varied and complex analytes in high-strength matrices, choose the modules that fit your applications, and upgrade your system as your needs change.

The Modular System that Delivers Flexibility
The innovative ICS-3000 system increases your productivity and expands your capabilities, combining consistently high performance, intelligent automation, and integrated data management and control. Its modular design makes upgrading your system easy and economical, allowing your laboratory to adapt to changing demands. All ICS-3000 modules give you easy access to components, facilitating reconfiguration and maintenance.

Innovative Modules that Expand Capabilities
Innovations in all ICS-3000 modules increase productivity and improve performance. The EG Eluent Generator is the heart of the RFIC system. It generates eluents electrolytically from water, letting you run gradient IC as easily as isocratic IC, with precise concentration control. Its dual cartridge capacity supports an expanded range of eluent systems, including carbonate/bicarbonate and new chemistries for hydroxide elution.

Combined with the EG, a single isocratic pump is all you require for gradient IC. And the high-performance pump module can be upgraded easily to a dual configuration, giving you extra versatility and capacity. The dual pump module allows you to use more complex eluent systems or perform a variety of dual IC techniques such as sample preconcentration or matrix elimination. The chemically-inert pump module withstands pH extremes and protects sensitive samples from metal contamination.

The intelligent autosampler can deliver samples to two separate chromatographic systems within the same instrument, either sequentially or simultaneously, and facilitates unique automation capabilities for sample and standard preparation.



The DC Detector/Chromatography Compartment provides precise thermal control and organizes columns, detectors, valves and plumbing for decreased noise and void volume. The optional AM Automation Manager plugs directly into the DC, and increases system flexibility by providing integrated valves for the automation of complex techniques like matrix elimination and two-dimensional IC (2-D IC).

Chromeleon® Chromatography Management Software brings all the modules together, automating sample preparation and injection, eluent generation, column switching, and data collection and analysis.



Powerful Features of RFIC Systems

- Precise, accurate, and effortless eluent management—just add water!
- Superior reproducibility—lab-to-lab, system-to-system, operator-to-operator, year-to-year
- Convenient and safe, with no acidic or caustic reagents or wastes to handle
- Application versatility through support for single- and dual-component eluents

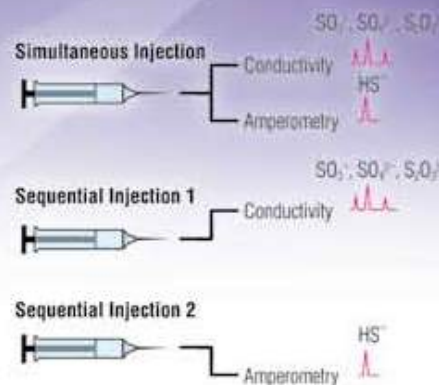


Productivity

The Power and Flexibility of Dual IC

The inherent flexibility and precise control of the system make complex applications such as 2-D IC, matrix elimination, preconcentration, and on-line sample pretreatment easier to implement.

Increase productivity with simultaneous or sequential injection. These techniques use only one autosampler in a dual system to increase throughput in your laboratory. For example, you can detect anions and cations from one injection using only one autosampler.



Flexibility—combine or separate analytical techniques.

Dual IC Provides Twice the Productivity
Dual IC describes varied techniques that utilize two distinct chromatography systems in one instrument. These systems can work in parallel or in series, running sequentially or simultaneously with the same or different samples. With the advent of column switching techniques, sample and solvent switching, and, most importantly, powerful software control, the advantages of dual applications are becoming more and more accessible.

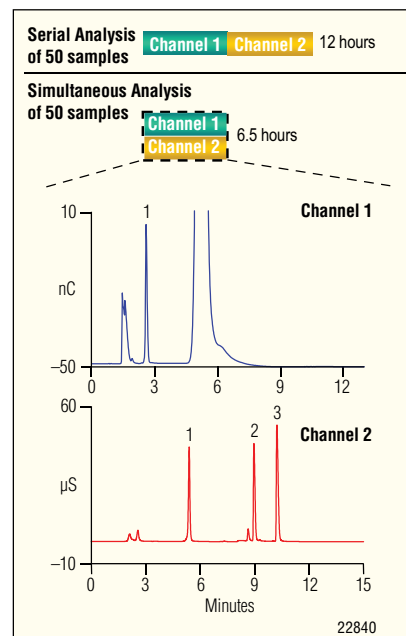
Dual IC:

- Increases productivity
- Expands flexibility
- Enhances sensitivity and selectivity
- Saves time and money

The dual ICS-3000 combines traditional instrument improvements for signal enhancement with valving and automation to increase system capability and adaptability.

The ICS-3000 system provides an effective platform for both standard techniques and multiple valve switching applications such as 2-D IC. The close proximity of the valves to the columns and detector cells in the DC provides a low-dispersion platform for multidimensional sample preparation and analysis schemes. 2-D IC is a dual-column technique to enhance sensitivity and selectivity. This technique involves loading a sample and matrix on one column in the first dimension, then transferring a fraction of interest onto a second column that further resolves the analytes. By using a 4-mm column in the first dimension and a different 2-mm column in the second dimension, 2-D IC improves selectivity and enhances the signal. This approach also allows the potential to combine two different chemistries in two dimensions, enabling a selectivity not possible using only a single chemistry dimension.

With the ICS-3000, dual IC is easy to achieve. Upgrading from a single to a dual system is a breeze due to the system design. The ICS-3000 can expand as your lab expands, and allows you to perform techniques you always wanted to try but found too cumbersome with other systems. With the ICS-3000, you get more information per sample, increased selectivity, and lower detection limits in an economical design and a single-system footprint.



Double your throughput with dual IC for greater productivity.

Single- and Dual-System Solutions

- Full range of configurations to satisfy diverse needs
- Economical single-system configurations for light to moderate workloads
- Powerful dual-system configurations for higher versatility and productivity
- Economical, field-installable upgrades to dual-system configuration



Adaptability

Interchangeable Modules to Support All Your IC Applications

Whether you need a simple analyzer for occasional IC analysis, a rugged workhorse that maximizes sample throughput, or a high-performance system that handles the most challenging applications, the modular ICS-3000 will satisfy your needs, now and into the future. Choose from a range of high-performance modules to customize a system around your current requirements, and simply add or reconfigure modules if your requirements change.

Take Advantage of New RFIC System Capabilities
If you have already used an RFIC system, you know the convenience and performance benefits of its three electrolytic technologies: eluent generation, impurity trapping, and suppression. Now, with the dual eluent generator of an ICS-3000 RFIC system, you can enjoy those benefits with a wider range of applications, including those requiring two-component eluents like carbonate/bicarbonate.

Choose a Dual Pump for Greater Versatility
With the optional ICS-3000 dual pump module, you get more than the quietest, most accurate IC eluent delivery ever. You get two complete pumping systems that can operate together or independently, both in one module. Use your second pump for sample preparation, column cleaning or conditioning, reagent delivery, or simply as a spare that you can bring on-line at any time.

Use a Dual System for Maximum Productivity
Upgrading your ICS-3000 to a dual system is easy and economical, especially if you already have a dual pump module. Simply add an injection valve, a detector, and columns, and you have two complete chromatography systems in one, for twice the productivity. Run the same application on both systems to double sample throughput. Use your second channel to simultaneously run a secondary or confirmatory analysis on each sample. You can even run two completely independent applications asynchronously on different sets of samples. And you can do all this using one autosampler and no additional bench space.



AS Autosampler

- Delivers samples to two systems, simultaneously or sequentially
- Offers unique sample preparation capabilities



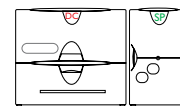
DC Detector/Chromatography Module

- Maintains highly stable temperatures for optimal IC performance
- Provides convenient access to all flow paths while minimizing dead volumes
- Supports single-system and dual-system configurations
- Offers a variety of electrochemical detection capabilities
- Simplifies complex applications with optional AM Automation Manager

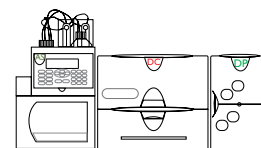
EG Eluent Generator

- Generates high-purity eluents for single or dual systems
- Supports dual-component eluents such as carbonate/bicarbonate
- Supports gradient-compatible eluents such as KOH, NaOH, and MSA

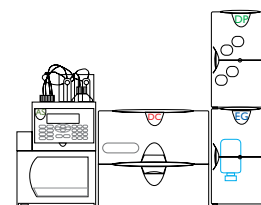
ICS-3000 Conductivity or Electrochemical System Configurations



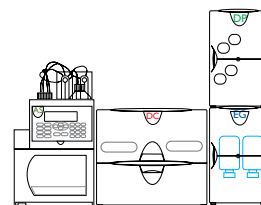
Basic system



Single system with dual pump



Single RFIC system with dual pump



Dual RFIC system

SP/DP Pump

Primary pump

- Delivers precise, accurate flow and gradient proportioning
- Automatically rinses seals and monitors their performance

Optional secondary pump

- Enables easy upgrade to a complete dual RFIC system
- Adds versatility for single-system configurations

Performance

Reach Your Laboratory's Potential with Dual Pump and Eluent Generation Technology

Discover the Optimal Metal-Free Pump

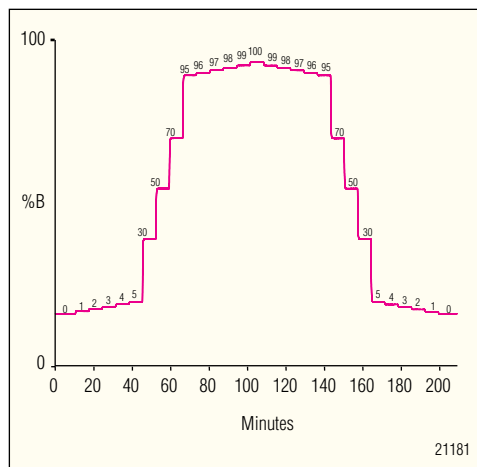
High-performance IC requires a high-performance pump made of chemically inert materials, and you won't find one better than the pump module of the ICS-3000. The metal-free pump provides the precise flow delivery and gradient proportioning that define excellent pump performance. The static mixer ensures that only homogeneous blends reach your column, even when poorly miscible liquids are combined. The result? Chromatography data that is highly accurate and reproducible.

Extend Capabilities with Optional Second Pump

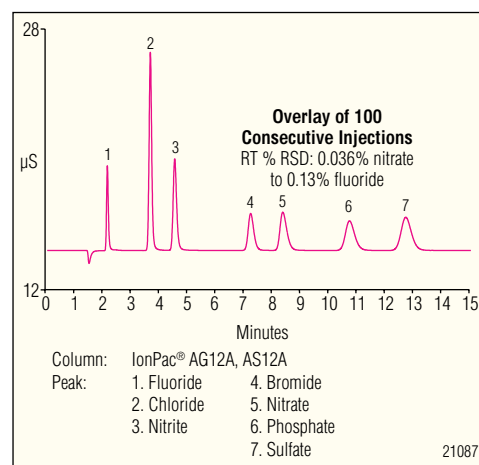
Get even more from your ICS-3000 pump by opting for the DP Dual Pump module. If you run only one chromatography system, you can use the second high-performance dual-piston pump to preconcentrate samples or deliver post-column reagents. Or use the second pump for offline tasks like cleaning columns, and switch it inline to continue operation during maintenance of your primary pump. If you need to process more samples or run a second analysis, you can easily set up a second complete chromatography system. Just add an injection valve, an economical detector, and columns.

Increase Reliability and Monitor Performance

The ICS-3000 pump's exclusive piston seal wash system regularly rinses piston and seal parts that are exposed to air. This prevents build-up of abrasive salt crystals from evaporation of eluent solutions or buffers, greatly extending piston seal life. The system also monitors the amount of eluent that seeps past the piston seals, and notifies you when the seepage rate indicates that seals are due for replacement. Thus, you get maximum life out of each set of seals, and ample notice to replace worn seals before they affect your chromatography.



The SP and DP pumps deliver exceptionally smooth proportioning and precise gradients with low void volumes.



Chromatogram showing a seven-anion separation on a 4-mm IonPac® AS12A column using the ICS-3000 and carbonate eluent generation. The DP and EG combine to give you consistent eluent for dependable and reliable results, day-to-day, month-to-month, lab-to-lab.



The SP (single) and DP (dual) pumps deliver outstanding accuracy and precision for consistent peak retention times.



The EG Eluent Generator delivers consistent eluent for reliable results, day to day, month to month, and lab to lab.



Make Your Job Easier and Get Better Results

The ICS-3000 EG Eluent Generator is the heart of your RFIC system. With the EG, you no longer have to spend time and effort mixing eluents, because the EG automatically transforms deionized water into high-quality eluent on demand, at the exact concentration needed for your application. This not only makes IC extraordinarily convenient, it also eliminates the variability that occurs with manually prepared eluents. You get reproducible results week-to-week, month-to-month, lab-to-lab.

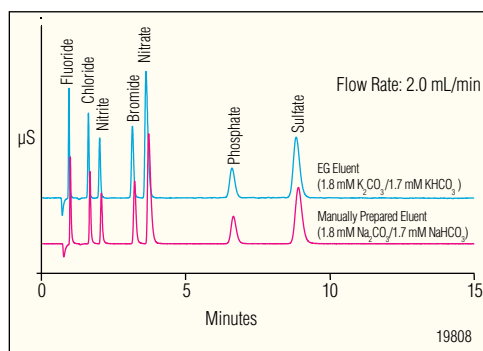
Tap Into the Power of Gradient Ion Chromatography

Your eluent generator does more than increase convenience and improve reproducibility; it also provides the eluent purity and precise control needed to run gradient IC. With a concentration gradient, you can elute strongly

retained analytes faster without compromising the separation of weakly retained analytes. Even for target analytes that can be separated under isocratic conditions, the peak focusing effect of gradient elution makes all your analyte peaks taller, sharper, and more symmetric than peaks eluted using isocratic conditions. Thus, gradient elution can deliver better resolution, higher sensitivity, and lower detection limits. And with an RFIC system, gradient elution is as easy to use as isocratic elution. You simply define the gradient profile, and the eluent generator creates it for you, using only deionized water.

Enjoy the Benefits of Eluent Generation

Now you can get the convenience and reproducibility of on-line eluent generation without having to change your methodology. The dual-cartridge capability of the ICS-3000 EG supports two-component eluent systems, such as carbonate/bicarbonate, broadening your options. Of course, you can decide at any time to switch to chemistries that are compatible with gradients—all you need to do is change EluGen® cartridges.



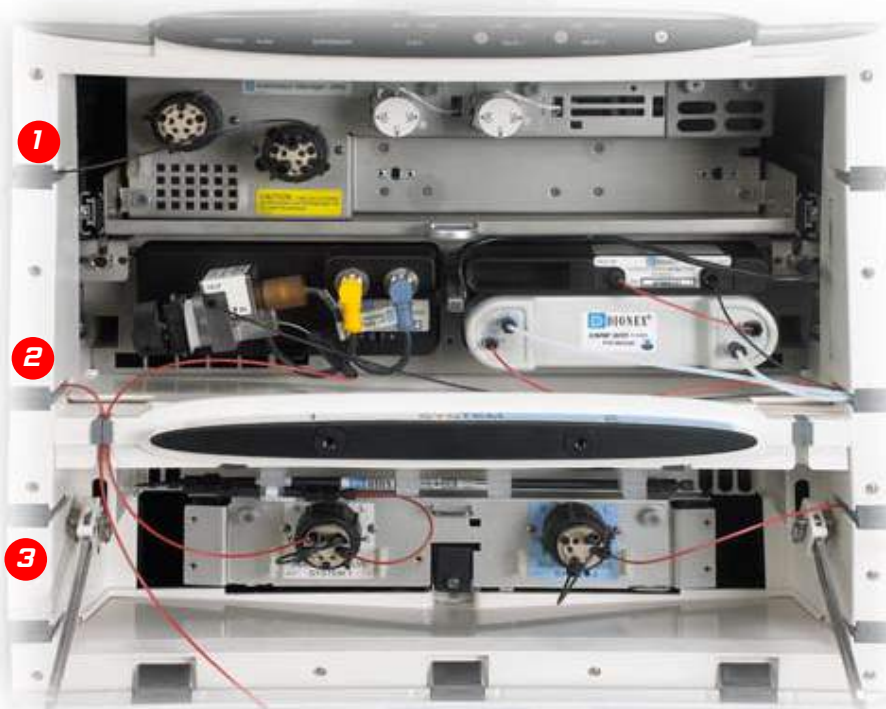
Chromatogram showing the separation of common anions on a 4-mm IonPac AS4A-SC column using $K_2CO_3/KHCO_3$ eluent generation. The ICS-3000 produces high-purity carbonate/bicarbonate eluent at a precisely controlled concentration, eliminating the labor and variability of manual eluent preparation.

Sensitivity

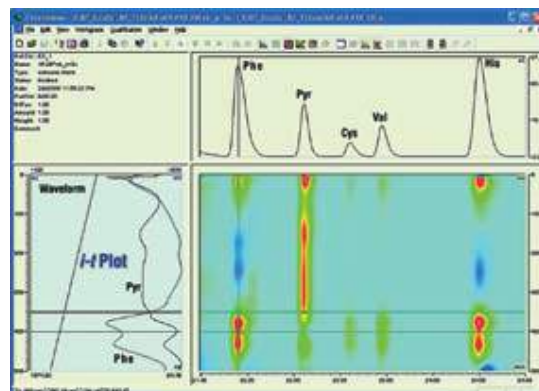
Superior Response and Reproducibility

Detector/Chromatography Module

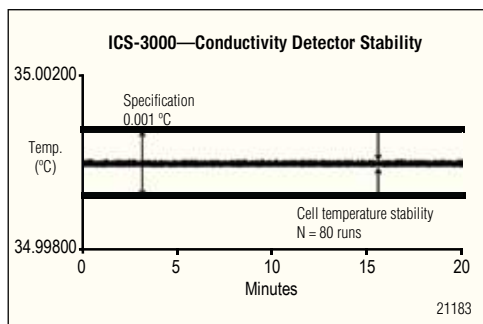
The Ideal Environment for Your Chromatography
The DC Detector/Chromatography module is a high-performance environmental chamber that precisely controls temperatures of valves, columns, suppressors, and detectors. Precise temperature control eliminates drift and minimizes noise, significantly improving sensitivity and stability. And you don't have to sacrifice convenience to gain outstanding performance. The DC gives you immediate access to all components of the flow path from the front of the instrument.



- 1 Automation 2 Detection 3 Separation



Learn more about your analytes with 3-D amperometry, an exciting new detection technology available only from Dionex.



Advanced electronics and design have resulted in a highly temperature-stable conductivity detector that delivers consistent peak areas from run to run.



Innovative, self-contained conductivity (above) and electrochemical (below) detectors easily snap into the DC module, which precisely controls their temperature and virtually eliminates baseline drift.



New ED cell design features a new one-piece reference electrode and a torque control knob that ensures consistent pressure and cell volume.

Enjoy Performance and Convenience

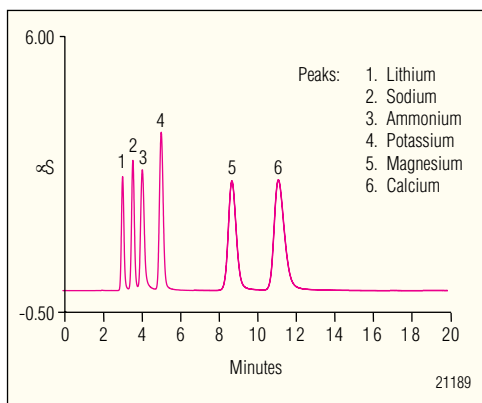
Behind the DC's clamshell doors you'll find more design features that enhance performance and convenience. The lower compartment organizes columns and valves, and equilibrates eluent to the correct temperature before it reaches the column. The upper compartment, which can maintain a different temperature, organizes detection components in its lower section and automation components in its upper section. Thoughtfully designed mounts and connectors not only make component installation and removal fast and easy, but also keep tubing and cable lengths short to minimize dead volumes. Applications requiring precolumn or postcolumn techniques are easier than ever, because Chromeleon software coordinates the additional valves, heaters, and other devices included with the optional Automation Manager.

Get Better Results and Expand Your Capabilities

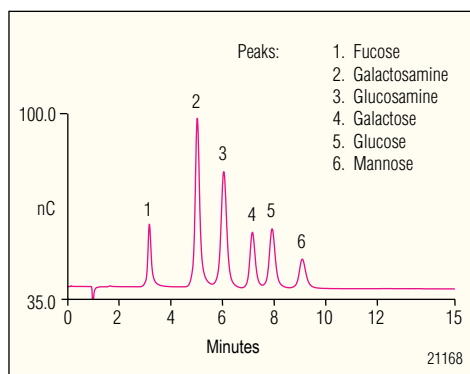
The ICS-3000 goes beyond stabilizing detector cell temperatures—it stabilizes the detector electronics too. The novel CD Conductivity Detector and ED Electrochemical Detector are compact, self-contained units that simply snap into place inside the protective environment of the DC module. You can quickly swap them out for servicing or to change applications.

The CD Conductivity Detector handles any IC application, from single-column methods with high background matrices to determinations of trace contaminants in high-purity water. Industry-leading suppressor technology provides low noise and high pressure tolerance for sensitive suppressed conductivity determinations using isocratic or gradient separations.

The ED Electrochemical Detector brings exciting capabilities to amperometry, such as waveform switching, to achieve optimal detection of different analytes in the same chromatogram. You can run cyclic voltammetry experiments right in the chromatography cell to develop an optimal waveform for each analyte. And with Chromeleon software, you can capture amperometric measurements as a rich 3-D data set that reveals subtle differences not visible in a single chromatogram. Three-dimensional amperometry also enables post-run adjustment of integration periods, so you can optimize them without having to reinject samples.



Switch between microbore and standard-bore applications, such as this separation of common cations on a 2-mm IonPac CS12A column, without changing anything more than columns, tubing, and flow rate.

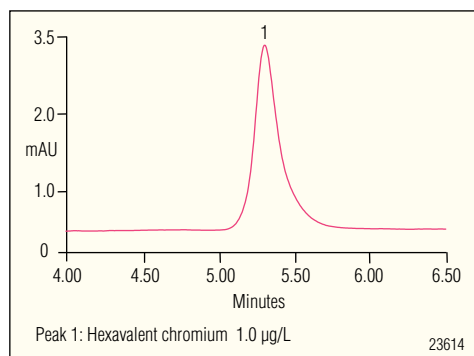


The ED Electrochemical Detector enables very sensitive detection of electroactive species such as carbohydrates, amino acids, catecholamines, and many inorganic compounds, as shown in this separation of six monosaccharides.

Corrosion Resistance

Metal-Free For IC and Biological Samples

The ICS-3000 is the optimal liquid chromatography system for IC and biomolecule analysis. With a 100% metal-free system (autosampler, pump, flow path, and detector), the ICS-3000 is able to overcome the limitations of traditional stainless steel or other metal chromatography systems affected by corrosive mobile phases. Metal flow paths can cause denaturation or absorption effects with some analytes, resulting in poor chromatography. The complete PEEK™ flow path of the ICS-3000 system eliminates the possibility of system corrosion.



The VWD Variable Wavelength Detector allows sensitive, specific detection in the ultraviolet and visible range.

Enhanced UV-Vis Detection

The VWD variable wavelength detector can be used for a variety of applications that require UV or visible detection. The VWD allows monitoring of up to four separate wavelengths at the same time. In addition, precise thermal stabilization of both the eluent and the lamp housing minimizes noise and drift in the baseline.

The VWD's dual beam detection method reduces noise, increases signal-to-noise ratio, and ensures excellent linearity. The VWD utilizes high quality deuterium and tungsten lamps to cover wavelengths from 180–900 nm. Moreover, integrated chip technology identifies detector cell and lamp properties and tracks lamp usage. System wellness and predictive performance features of Chromeleon software monitor lamp intensity and usage, and can provide warning when limits are exceeded.

Maximized Absorbance Information

The PDA provides all the advanced features that you expect from photodiode array detection. With its range-extending dual lamp configuration, the PDA provides three-dimensional information for accurate assessment of peak identity, purity, and quantitation in a single run. The Dionex PDA uses dual extended-life lamps for superior intensity and improved signal handling. Advanced logic for

the lamp power-up sequence allows the user to set the start-up parameters for both lamps. Faster spectrum calibration allows the PDA to operate on short notice. With exceptional thermal stability and calibration management, rapid analysis is just moments away.

Large Temperature Range, Ultrahigh Precision

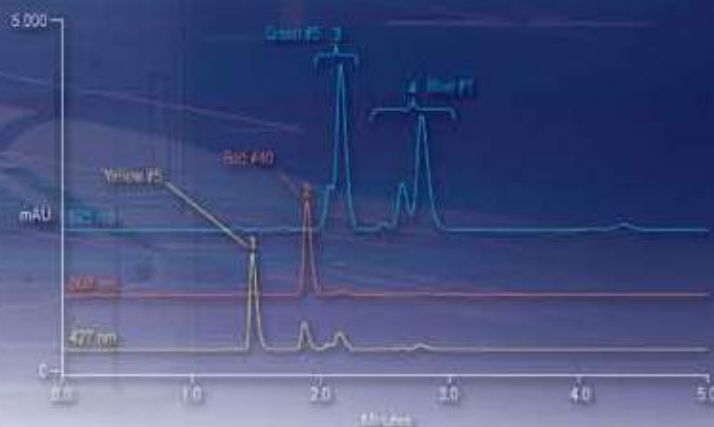
The TC Thermal Compartment module maintains very precise temperatures while allowing a large temperature range from 5 to 85 °C. Optional eluent temperature stabilizers help bring the eluent to oven and column temperature, to ensure more precise separations. The ICS-3000 TC comes configured with single or dual valves. Dual valve configurations can maximize productivity by implementing simultaneous or sequential injection or column switching techniques. In addition, the integrated column chip technology helps the user track important information regarding the operating conditions to which the column has been exposed, number of injections, and expiration date. A complete record of the column's history always accompanies the column.

MSQ™ Plus for Increased Confidence in Results

Combine IC separations with the MSQ Plus detector for positive identification of the analytes in your samples. With IC and MS together, you can determine ionic and polar compounds that other techniques can't quantify. The chromatographic separation isolates analytes from interferences, while the mass spectrometer provides structural information for each analyte. You can determine parameters such as oxidation state speciation, molecular mass identification, isotope ratios, and fragmentation patterns while avoiding coelution and background interferences.



MSQ Plus mass spectrometric detector for optimal sensitivity, specificity, and limits of detection.



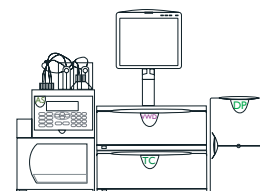
The VWD Variable Wavelength Detector allows simultaneous detection of multiple wavelengths for applications such as complex food dyes, congeners, and isomers.

VWD

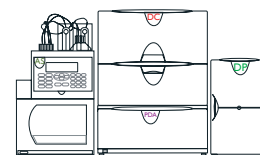
- Monitoring of up to four wavelengths simultaneously provides superior analysis of complex mixtures.
- Broad detection range, 180–900 nm, enables detection of more compounds.
- Expanded linear range delivers accurate detection of concentrated and dilute samples.
- Excellent signal-to-noise ratio improves minimum detection limits.

PDA

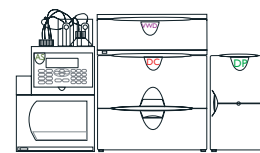
- Dual lamp configuration provides full optical range detection.
- Extended lamp lifetime increases reliability.
- Full 3-D scanning capabilities provide more information about each sample.



Basic optical system

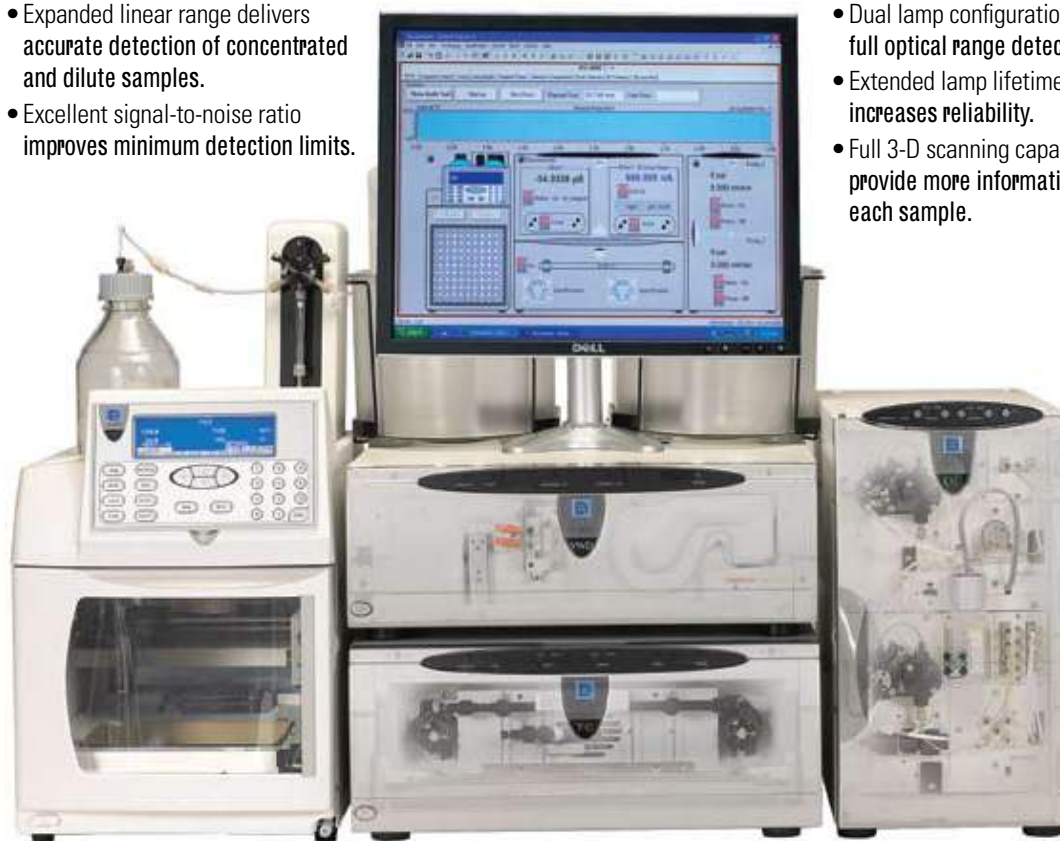


Dual system PDA and CD/ED



System with UV-VIS and CD/ED

The ICS-3000 system combines with the highly sensitive ICS-Series detectors for complete and trouble-free analysis of biomolecules.



TC

- Increased flexibility with single or dual valves supports complex applications.
- Expanded temperature range allows a wide variety of applications.
- Integrated column chip technology tracks column history for greater reliability.

Automation

Versatile Solutions to Simplify Your Applications

The Automation Manager provides integrated valve control, minimal tubing length, and consistent temperature control for greater sensitivity and robustness with complex applications. Chromeleon's graphical user interface makes programming easy.

Automation for Complex Applications

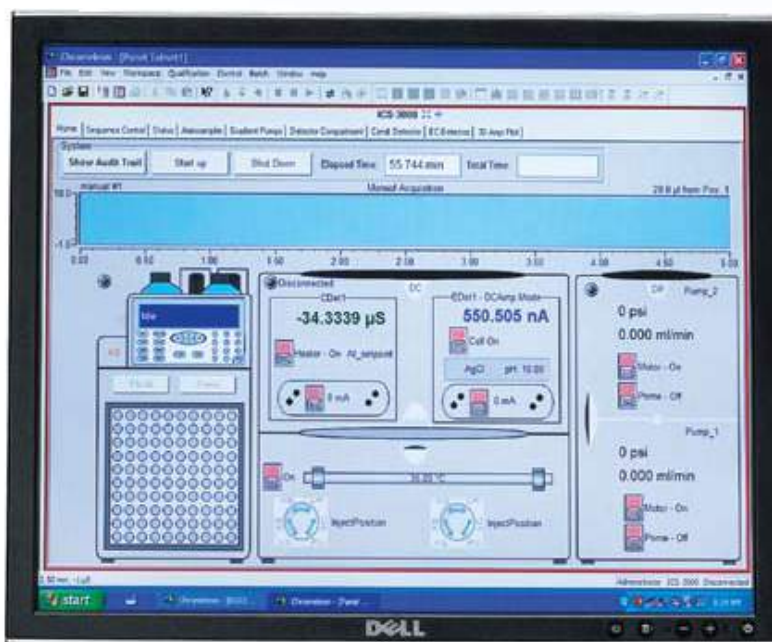
Analytical problems sometimes require complex solutions, but complex doesn't have to mean difficult. With the AM Automation Manager, you can easily perform special techniques like high-volume or high-pressure sample preconcentration, matrix elimination, column flushing, heart-cutting, and post-column treatments. The Automation Manager neatly organizes valves, concentrators, reactors, and plumbing in the top section of the DC module, protecting these accessories from laboratory temperature variations and eliminating clutter. And you no longer need cumbersome relay or TTL connection. The Automation Manager works seamlessly with Chromeleon software to orchestrate the devices, so control is easier, timing is more accurate, and communications are more reliable.

Control for Your System and Data

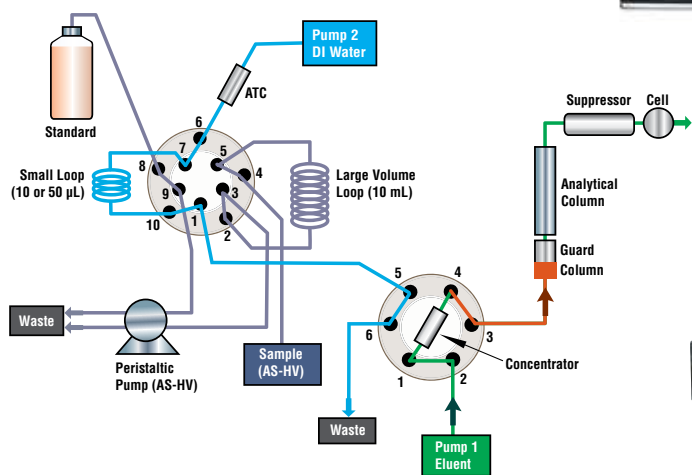
To operate most modular systems, you have to learn the front panels of various modules, then try to coordinate them through your chromatography software. But the ICS-3000 is different. Powerful Chromeleon software integrates system control and data handling into your instrument, providing a convenient command center. Run with direct control, or set up a sequence of samples and methods for your system to run automatically overnight. It's easy and convenient.



For data analysis, Chromeleon software gives you all the power and versatility of the world's most complete chromatography management system. If your lab requires third-party software for data analysis, Chromeleon Xpress provides complete ICS-3000 system control, and affords an easy upgrade path to Chromeleon.



The user friendly Chromeleon control panels show system status and allow you to access system modules with easy tab-page control.



The valves of the AM, in combination with Chromeleon software, allow you to automate tasks such as standard dilution and sample preconcentration.



The optional AM Automation Manager simplifies automation of complex applications. It plugs into the top section of the DC module, which instantly recognizes the accessories, enables their control, and keeps their temperature stable.

Autosamplers

Autosamplers Deliver Accuracy and Ease of Use

AS: Precision for Advanced IC Techniques

When there is no room for compromise and you need sample automation, the AS boasts an impressive set of features to meet the demands of any lab.

- PEEK injection needle
- Simultaneous and sequential injections
- Full loop, partial loop, limited sample-partial loop
- Concentration and matrix elimination

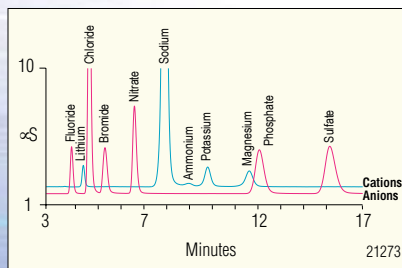
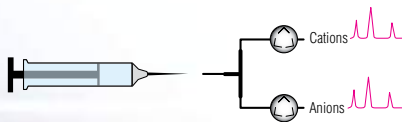
The ICS-3000 has the automation solutions you need to achieve maximum productivity with minimal effort.



Save Time and Money with Intelligent Sample Handling
The AS Autosampler delivers sample handling solutions that no other autosampler can. Your samples are protected from contamination by its metal-free flow path and chemically-inert vials. The solid-state cooling option preserves heat-sensitive samples.

With Chromeleon software and the AM Automation Manager, you can easily automate sample pretreatments, such as preconcentration or matrix elimination. You can save time by enabling sample overlap, which prepares the next sample while the current one is undergoing analysis.

To increase throughput, you no longer need to buy a second autosampler or use additional bench space. The AS delivers samples to two separate chromatography systems within the same ICS-3000 instrument, either simultaneously or sequentially. Use the simultaneous option to perform two different analyses (such as anions and cations) on every sample. Use the sequential option to double throughput for a single application, or to efficiently process separate sets of samples for two different applications. Never before has an autosampler given you so much functionality.



One AS Autosampler can inject a sample into two separate channels of the dual ICS-3000 system simultaneously. This capability allows the ICS-3000 to double your throughput, as in this simultaneous analysis of anions and cations in tap water.



AS-HV: the Solution for High Volume Samples

When higher sample volumes are required for trace analysis, matrix elimination, or automated sample preparation, the AS-HV delivers with ease of use, reliability, and flexibility.

- Rapid, precise arm motion speeds sampling time to maximize efficiency
- Sample volumes up to 250 mL with Nalgene® bottles or low-contaminant tissue culture flasks

AS40: the Solution for High Throughput

With dedicated full-loop and optional concentrator loading, the AS40 is equipped to handle your most challenging production loads. Reliable, economic, and equipped for routine analysis, the AS40 makes quick work of high sample loads.

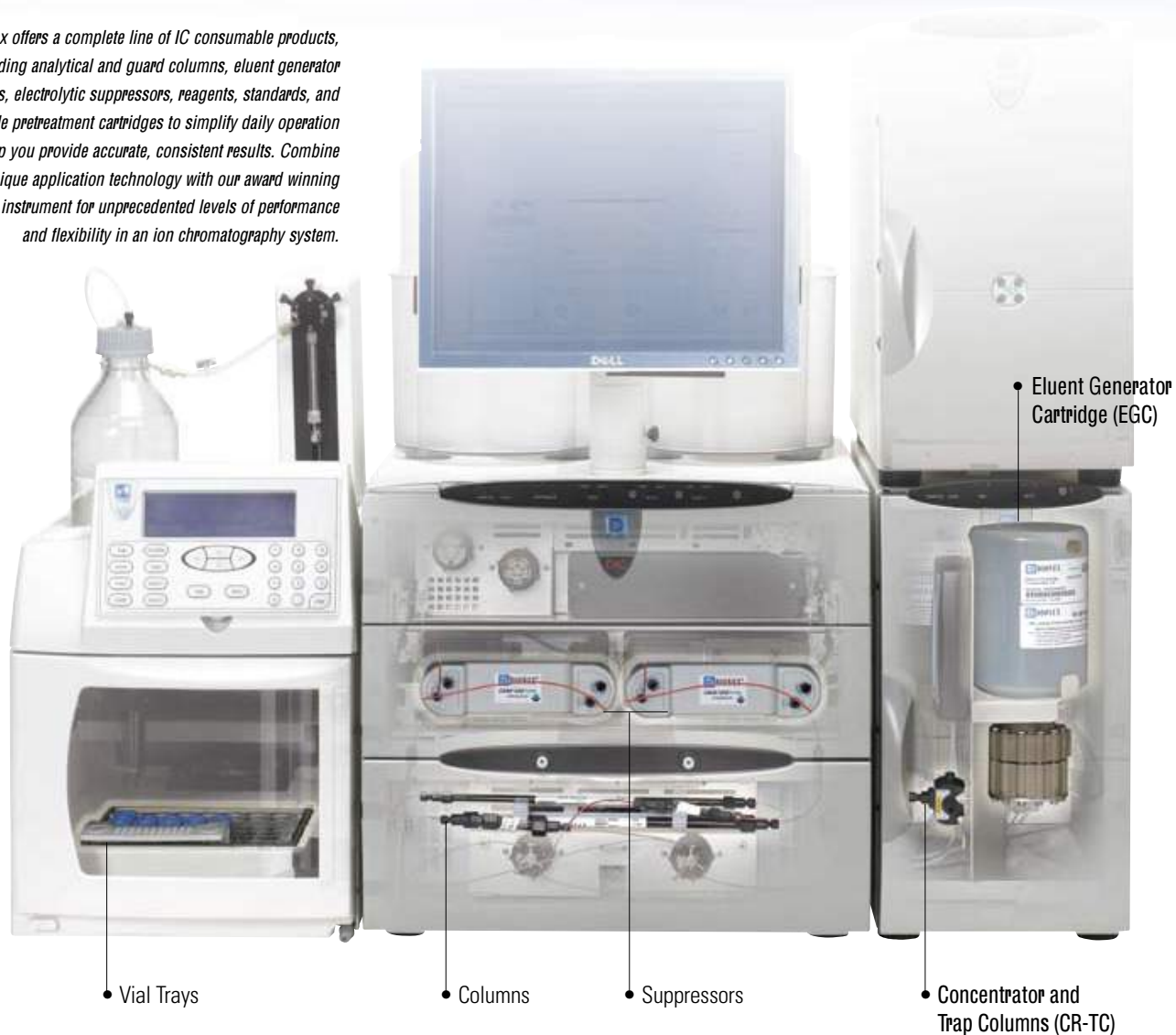
- All non-metallic flow path
- Five- and 0.5-mL sample capacity with optional filters
- Full loop and concentrator loading

All Dionex Autosamplers have completely non-metallic PEEK-based flow paths. In addition, all samplers are fully supported with Chromeleon control and up-to-date qualification protocols.

Consumables

Complement Your System with Dionex Chemistries

Dionex offers a complete line of IC consumable products, including analytical and guard columns, eluent generator cartridges, electrolytic suppressors, reagents, standards, and sample pretreatment cartridges to simplify daily operation and help you provide accurate, consistent results. Combine our unique application technology with our award winning ICS-3000 instrument for unprecedented levels of performance and flexibility in an ion chromatography system.



The ICS-3000 is the recipient of many prestigious instrumentation awards.



Dionex's goal is to provide you with solutions to your ion analysis challenges, rather than just selling you an instrument.



To meet that goal, we offer a complete line of training, service, and consulting products, installation and warranty service, and comprehensive support agreements.

What's Included with Your System?

The ICS-3000 is a complete package. Not only does it include all modules and accessories, but also complete installation and initial training to allow you to immediately start productive work. Systems come with a comprehensive set of ready-to-use guides, software, and templates.

Getting the Most from Your System

Dionex offers a variety of hardware and software training courses to help you get the most from your ICS-3000. Whether you need basic training for new operators or advanced training to further the skills of experienced operators, we have training courses to meet your needs. Courses are held regularly at Dionex facilities, and can also be held at your site. Our experienced staff is available to customize programs to your needs.

If You Need Help

It's reassuring to know that Dionex offers one of the most extensive and professional service and support organizations in the chromatography industry. Local support is close at hand, quick to respond, and provides effective solutions. For minor problems and questions, Dionex offers toll-free technical support, for rapid and competent assistance over the telephone.

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systems

ICS-3000 Ion Chromatography System



The ICS-3000 Ion Chromatography System provides an impressive combination of increased productivity, expanded capabilities, and improved performance. Innovations in all modules provide up to an order of magnitude improvement in performance—the foundation of the system. Modular versatility, functional integration, and superior performance culminate in the most advanced ion chromatography system on the market.

Modular design allows versatility in configuring a wide variety of applications

Flow rate accuracy, eluent generator electronics stability, and conductivity cell temperature control deliver high retention time reproducibility, baseline stability, and sensitivity

Hydroxide, carbonate, and MSA consumables for Reagent-Free™ Ion Chromatography systems with Eluent Generation (RFIC-EG™ systems) offer high purity and unparalleled control and reproducibility for isocratic and gradient elutions

When configured as a RFIC system with Eluent Regeneration (RFIC-ER™ system), the ICS-3000 allows the use of a single preparation of eluent for up to four weeks

Dual-system capability (within the same footprint) maximizes throughput

VWD Variable Wavelength Detector, PDA Photodiode Array, and MSQ Plus™ Mass Spectrometer Detector expand the range of applications and provide additional detail for every sample

Integrated DC Detector/Chromatography module with precisely controlled temperature zones maintains baseline stability and increases application flexibility

AM Automation Manager simplifies and automates complex applications including sample preparation, preconcentration, matrix elimination, and postcolumn reagent addition

Innovative ED Electrochemical Detector capabilities improve and expand applications: multiwaveforms in a single run and post-run 3-D data processing

Chromeleon® Chromatography Management software unifies and simplifies system control, operation, data collection, and reporting



Passion. Power. Productivity.

Modular Capabilities and Performance

The modular ICS-3000 meets a wide and ever-increasing range of application needs. From entry-level IC for routine, dedicated analysis to the high-throughput, dual RFIC system, the ICS-3000 is truly designed for versatility and productivity. The system can be upgraded to a dual system configuration—without taking up more valuable laboratory bench space.

Performance Enhancements

Significant performance enhancements make the ICS-3000 the most reproducible, stable, and sensitive ion chromatography system available today. State of the art flow rate accuracy, eluent generator electronics, and conductivity cell temperature control increase baseline stability and improve sensitivity.

Unique System Control

Instead of individual module front panels, the ICS-3000 gives you one convenient control system. Chromeleon Chromatography Management software provides a centralized panel so that all module control parameters, status, calibration, and diagnostics are easily available. A convenient home screen shows overall system status while individual module tabs provide quick access to module functions and detailed status and diagnostics. Wizards take the uncertainty out of setting up customized analyses. System Wellness features alert you to potential system issues before they become problems.

DP Dual and SP Single Pump

The DP Dual Pump and SP Single Pump are each available in multiple configurations based on application requirements. Both formats can be configured for gradient or isocratic eluent delivery. The SP pump-based system can be field-upgraded to a DP pump, depending on need. Pump assemblies slide out for easy access and serviceability. The pumps feature a variable-speed, serial-piston design to deliver consistent flow rates and quiet detector baselines. The pump offers a tenfold improvement in flow rate accuracy and precision over previous systems. The pumps are designed to support flow rates from 0.001 to 10.000 mL/min.

EG Eluent Generator

The EG Eluent Generator module provides the benefits of an RFIC system with Eluent Generation (RFIC-EG™ system) in a dual-system format. Robust electronics provide an extremely stable baseline and precise gradient generation. You can generate high-purity eluents on-line, and run gradient separations as easily as isocratic. RFIC-EG systems combine “Just Add Water” eluent generation, eluent purification, and electrolytic suppression technologies. RFIC-EG systems eliminate variability and potential contamination compared to systems with manually prepared eluents, and provide superior performance, higher sensitivity, improved resolution, and excellent reproducibility. The EG can be configured for a single system or for dual-system support, along with an expanded set of eluent chemistry options for carbonate and hydroxide applications for anion analysis. RFIC-EG systems are only available from Dionex.

Eluent Regeneration Option

With the eluent regeneration option, a single preparation of eluent can be used for up to four weeks. The RFIC-ER system uses the SRS 300 electrolytic suppressor to simultaneously regenerate returning eluent as it suppresses eluent before detection. Trap and catalytic columns purify returning eluent, assuring consistent, high quality eluent for separations.

Because it is a closed loop, the always on, always ready RFIC-ER system remains equilibrated and calibrated between eluent changes, up to four weeks. Less frequent eluent preparation reduces unintentional variations in concentration, increasing reliability and reproducibility. RFIC-ER systems are designed for high throughput analyses of anions or cations in low- to moderate-concentration matrices.

DC Detector/Chromatography

The DC Detector/Chromatography module houses and organizes chromatography components such as valves and columns, as well as conductivity and electrochemical detectors and cells. The module keeps plumbing organized and minimizes connection lengths to reduce delay volumes and improve peak efficiencies. The DC is separated into three sections for automation, detection, and separation. The DC offers up to five separate temperature zones that can be maintained simultaneously (separation section, detection section, two conductivity detector cells, and postcolumn reaction coils). This flexible and precise temperature control improves stability and enhances sensitivity. Improvements in conductivity detector temperature control and column temperature control further improve sensitivity.

TC Thermal Compartment

The TC Thermal Compartment is for UV-Vis or IC-MS applications which do not require an ED or CD detector. It provides precise temperature control over a wide temperature range with fast heat up and cool down times. The single zone oven design minimizes tubing connection lengths and reduces delay volumes, yet allows single and dual valve configurations.

CD Conductivity and ED Electrochemical Detectors

The CD and ED detectors are installed inside the DC compartment, minimizing tubing lengths and providing optimum thermal stability. The detectors are easy to install snap-in devices and can be configured in series for dual detection or as separate detectors for a dual system—all in the same enclosure.

The ED features a new cell design with an improved reference electrode. The cell is also more rugged due to an improved handle design that provides uniform torque on the working electrode. Multiple waveforms optimize detection conditions for individual analytes and signal measurements can be collected as a complete three-dimensional data set for post-run analysis and characterization of different compound classes.

Optical Detectors

The ICS-3000 can be configured with any of the optical detectors available from Dionex; the VWD, the PDA, and the RF2000, covering the visible ultraviolet, and fluorescent range of wavelengths. The ICS-Series Variable Wavelength Detector can be configured to monitor single or multiple wavelengths — up to four simultaneously. The PDA can monitor single or multiple wavelengths in addition to performing full 3-D scanning during each run. Each optical detector is configured as a separate module.

AM Automation Manager

The AM Automation Manager option can be configured in the upper compartment of the DC module. The AM includes options for two high pressure rotary valves and two low pressure solenoid valves for automated sample preparation, preconcentration, matrix elimination, and postcolumn reagent addition. Components are recognized, configured, and controlled through Chromeleon, providing complete automation for even the most complex applications.

AS Autosampler

The AS Autosampler can be configured for simultaneous or sequential sample delivery. In simultaneous delivery mode, sample is delivered through a splitter to two injection valves for dual full-loop injections. With this configuration you can perform two separate analyses on one sample (e.g., anions and cations).

For sequential delivery, valves are configured to divert the sample stream to the appropriate injection valve for loading. The AS also provides sample preparation options and variable sample size loading for preconcentration on various trap columns.

The ICS-3000 can also be configured with all other Dionex autosamplers and is compatible with many third party autosamplers.

Module Features

DP Dual and SP Single Pump

The Dionex DP and SP Pumps are each available in isocratic or gradient configurations. The pumps support standard-bore and microbore applications. Gradient configurations provide low-pressure mixing of up to four mobile phases per pump at precisely controlled proportions and flow rates.

DP and SP Features

Variable-speed, serial dual-piston design delivers consistent flow rates and quiet detector baselines

Pump flow components are chemically inert, made with high-quality PEEK heads and fittings, inert polymer seals, and sapphire pistons

Quaternary proportioning and a low-volume mixer deliver reproducible eluent mixtures

Linear, concave, and/or convex gradients are possible

Vacuum degas provides sealed, in-line degassing for flow reproducibility and protection of eluent from contamination and degradation

Automated integral piston seal wash prolongs seal lifetime by preventing eluent crystallization on the seal surfaces

The pump assemblies slide out for easy access and serviceability

User-selectable pressure limits automatically stop pump flow in the event of leaks, flow restrictions, or depleted eluent reservoirs

User-configurable alarm features in Chromeleon allow additional responses to status or alarm conditions

Front panel indicates the status of power, pump flow, priming, connectivity (Chromeleon Control), and alarms



DP Dual Pump module

Benefits of Dual Pump Configurations

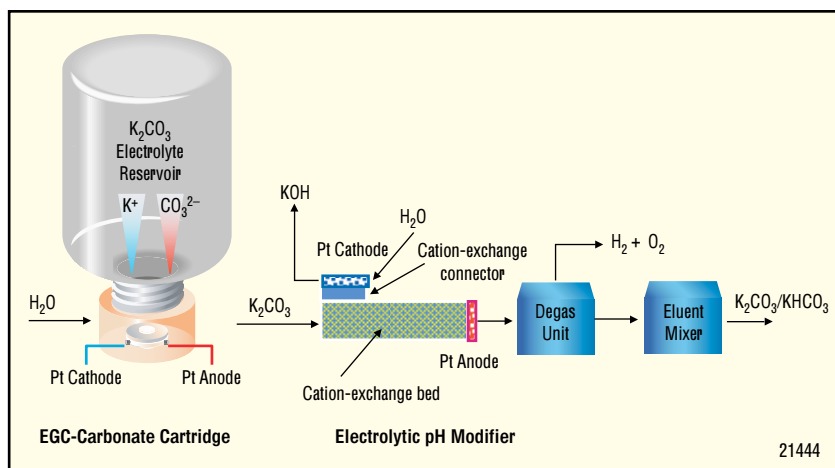
Dual configurations provide independent pumping capabilities in the same module and same space-saving footprint. Configure a DP-based system according to one of the following scenarios:

Configure the system for dual applications, either running simultaneously or independently:

- Anion and cation separations
- Two different anion or two different cation separations

Use the second pump for:

- Sample preconcentration or matrix elimination
- Postcolumn reagent delivery for postcolumn reaction (PCR) applications
- External water and chemical regenerant delivery
- A backup pump for the primary application
- Consumables cleanup or start-up preparation; preventing primary system downtime for reconfiguration



Electrolytic generation of $K_2CO_3/KHCO_3$ eluents using an EGC II K_2CO_3 cartridge and an EPM Electrolytic pH Modifier.

EG Eluent Generator module

EG Eluent Generator Module

The EG Eluent Generator module provides the benefits of an RFIC-EG system in a dual system format. The EG continues Dionex's technology leadership, allowing the user to generate high-purity eluents on-line and run gradient separations as easily as isocratic applications. Reagent-Free IC is the powerful combination of Dionex "Just Add Water" electrolytic eluent generation, purification, and suppression technologies. The EG can be configured for a single system or for dual system support.

EG Features

Eluents are generated from deionized water using an EG cartridge and then polished of contaminants using one of the Continuously Regenerating Trap Columns (CR-TCs)

Now you can enjoy the RFIC system carbonate-based eluent generation using a carbonate cartridge and EPM Electrolytic pH Modifier

In addition to KOH for anion separations, NaOH and LiOH cartridges are available for specialized applications

The EG delivers eluent concentrations from 0.1 – 100 mM

Control, status, and diagnostics are

provided with Chromeleon software

Improved EG electronics provide smoother eluent delivery with minimal noise for improved peak detection in both gradient and isocratic modes

A slide-out tray provides easy access to the EG cartridges and CR-TCs for maintenance

Using on-line eluent generation actually extends the lifetime of pump pistons and seals because the pumps only deliver water

Front panel displays the status of module power, CR-TC power, and leak functions

Benefits of an RFIC-EG System

Minimizes baseline drift

Improves retention time stability and resolution

Provides excellent run-to-run reproducibility

Supports both gradient and isocratic applications

Minimizes labor and operating costs

RFIC-ER Option

RFIC-ER systems can regenerate eluent for isocratic IC separations using carbonate, carbonate/bicarbonate, or methanesulfonic acid. These always on, always ready systems are ideal for the analysis of drinking, ground-, and surface waters, and are intended for use as systems dedicated to these analyses.

Benefits of Eluent Regeneration

used for up to four weeks, reducing labor and waste.

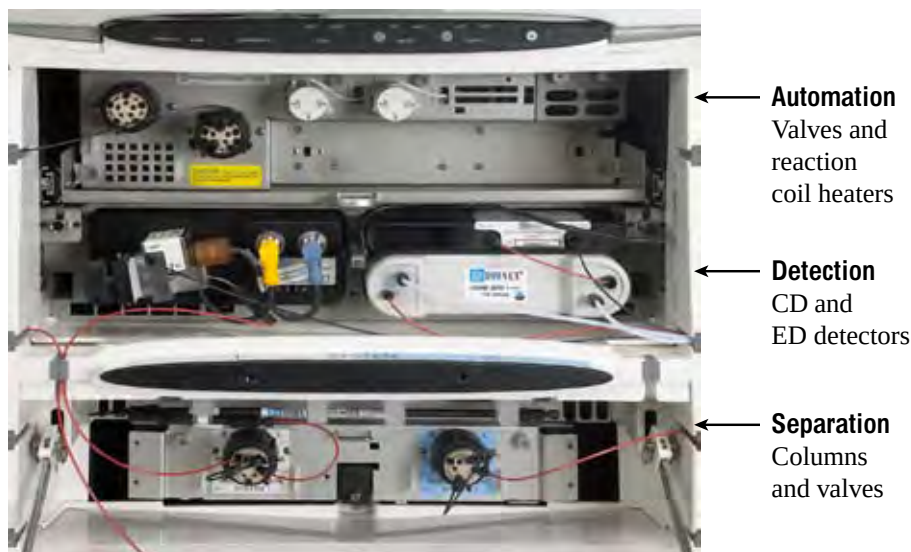
columns purify returning eluent, assuring consistent, high quality eluent for separations.

generates reproducible results.

always on, always ready RFIC-ER system remains equilibrated and calibrated between eluent changes, up to four weeks, increasing the amount of operator and system time available for analysis.

DC Detector/Chromatography Module

The DC Detector/Chromatography module houses and organizes chromatography components such as valves and columns. The DC module contains three sections: (1) separation, (2) detection, and (3) automation. The lower separation compartment holds injection valves, guard, and analytical columns, and is under independent temperature control. The conductivity and electrochemical detectors are housed above the separation columns. An Automation Manager option can be configured in the upper compartment to support switching valves and other hardware required for advanced applications.



DC Features

Three distinct sections keep plumbing organized while minimizing connection lengths, reducing delay volumes, and improving peak efficiencies

Two options for overall thermal control offer application and budgetary flexibility

- Dual temperature zone configuration controls the injection valve and column compartment separately from the upper compartments
- A single temperature zone configuration controls the temperature of both compartments at one set temperature

With either configuration, the CD cells feature temperature control independent of the other sections

In the dual temperature zone configuration, up to five separate temperatures can be maintained simultaneously (separation section, detection section, two detector cells, and reaction coil) providing maximum application flexibility

Independent compartment doors allow independent access to the separation or detector section without disturbing the other thermal section (with dual temperature zone configuration)

DC Detector/Chromatography module

Automatic detection of valves, CD/ED cells, and suppressor devices by software

Manual loading of sample is possible

Column compartment can be configured with two independent injection valves

Column/injection valve panel slides forward for easy access

Optional analog output board provides analog detection signals to data recorders

Optional analog board also includes eight user-assignable TTL inputs that are provided for basic valve and detector operation

Front panel displays the status of module power, injection valve position, and alarms

Expand Your Capabilities with Dual Detection Configurations

Easily install the CD and ED detectors as plug-in devices and have a dual system in a single system footprint

- Run anion/cation analyses simultaneously from one injection
- Run confirmatory separations in parallel to verify components
- Inject different sample loop sizes; eliminate reanalysis of samples at different dilutions

Implement innovative detection schemes by pairing conductivity and electrochemical detection techniques in series on the same system

- Determine classic anions with conductivity along with sensitive and selective ED detection of electroactive species such as iodide, sulfide, cyanide, and phenols
- Analyze cations and electroactive amines, amino acids, organic acids, and carbohydrates from a single separation

AM Automation Manager

Simplify complex applications with the AM Automation Manager option. This option, which fits in the upper section of the DC module, organizes and controls high-pressure rotary valves, low-pressure solenoid valves, the RCH Reaction Coil Heater, and a variety of reaction coils.



AM Automation Manager

Configure up to two 6- or 10-port high-pressure rotary valves for automated sample preparation, preconcentration, matrix elimination, or flow-diversion applications

Configure up to two low-pressure 2-port shut-off or 3-port switching valves for selection of reagents for postcolumn reagent addition, rinse solutions, or regenerants

Install the optional RCH for heated reactions, or simply mount non-heated reaction coils to support ambient reagent addition

Installed components are automatically recognized through Chromeleon

All valves and positions are recognized with Chromeleon

Preconcentrate samples during a run to increase throughput

Supports all IC and RFIC system applications with maximum range up to 15,000 μ S

Control through Chromeleon software or locally through TTL inputs

Mount inside the DC compartment in either of two locations

No tools are required

Minimizes noise and maximizes thermal stability

Electronics are integrated between cell and detector for greater stability

Heats CD cell independently from other chromatography components

Innovative built-in electronics allow for easy calibration and diagnostics

New detection capabilities include use of multiple waveforms and multiple integration times to optimize detection conditions for individual analytes

Three-dimensional display of the raw integrated amperometry data set similar to PDA data display, with cross-hairs on an isoamperometric plot used to select "slices" of the plot along the applied voltage axis (to render a chromatogram) and along the time axis (to render a voltammogram)

Three-dimensional wireframe rendering, printing, color selection, display of apex, and other spectra on peaks in chromatograms are echoed in the integrated amperometry implementation

The integrated amperometry mode provides complete freedom to change the waveform profile's number of segments, duration of each segment, and voltage applied at each segment

Control through Chromeleon software or locally through TTL inputs

Mounts within the DC compartment in either of two locations

No tools are required for installation

Cell and detector electronics integrated to minimize noise, maximize electrical isolation and shielding, and maximize thermal stability

Innovative, built-in electronics for easy calibrations and diagnostics

Can be used in dual-detection configuration (detectors in series or systems in parallel)



CD Detector cell with suppressor



ED Electrochemical Detector and cell

CD Conductivity and ED Electrochemical Detectors

The CD and ED detectors are installed inside the DC compartment as snap-in devices. They can be configured in series for dual detection, or as separate detectors for a dual system.

CD Features

Microprocessor-controlled digital signal processing detects high and low concentrations of analytes in the same run

ED Features

New one-piece reference electrode provides consistency and reliability

New handle design provides consistent torque to cell electrode for consistent installation and mounting of working electrode

Uses microprocessor-controlled digital signal processing

Supports DC amperometry, pulsed amperometry, or integrated amperometry detection modes



PDA Photodiode Array detector

Optical Detectors

The ICS-3000 can be configured with any of several optical IC detectors available from Dionex.

ICS Series PDA Photodiode Array Detector

The PDA is a high-resolution, 1024-element photodiode array detector with low noise and drift. Two light sources, a deuterium lamp and a tungsten lamp, provide a broad spectral range. The PDA is operated using Chromeleon software with a 3-D data processing option.

Achieve the benefits of performance and versatility of the PDA Photodiode Array detector through the following unique features:

- Photodiode array (1024-element) provides optimum wavelength resolution

- Low noise and high light intensity over the full spectral range via deuterium and tungsten lamps

- Full control and data collection through Chromeleon software with 3-D option

- USB-based digital data collection for simple installation

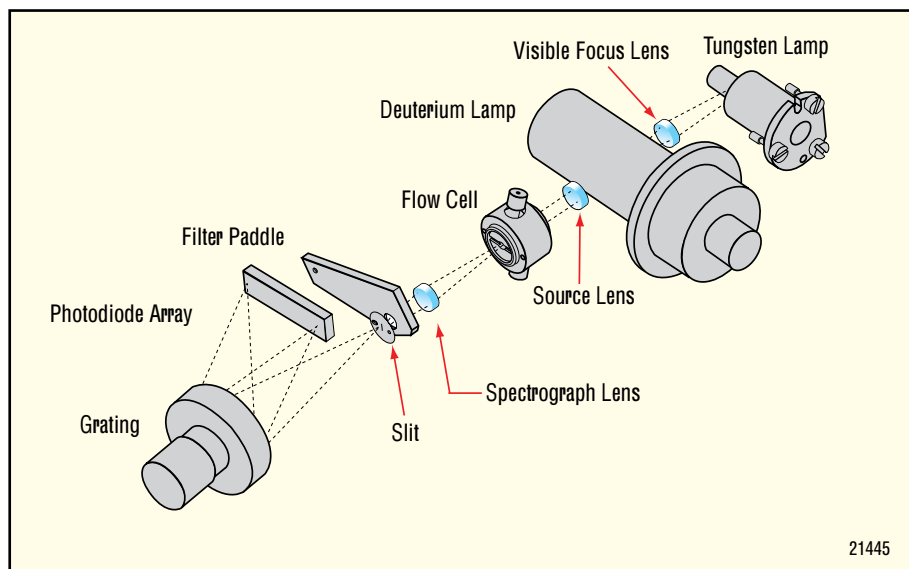
- Four analog outputs support alternate data collection

- Built-in holmium oxide filter provides verification of wavelength accuracy

- Low baseline drift for excellent reliability and reproducibility

- Front access to prealigned cells and lamps for easy maintenance

- Five front-panel LEDs that clearly indicate detector status



ICS Series PDA optical schematic



TC Thermal Compartment

TC Thermal Compartment

The TC Thermal Compartment houses and organizes the chromatography columns and valves. The TC can be configured with up to two valves. The TC can be configured on a single timebase or shared between two timebases for sequential analysis.

- Ideal for UV/VIS applications which do not require an ED or CD detector

- Single zone oven designed to minimize tubing connection lengths, reduce delay volumes, and improve peak efficiencies

- Valve configurations include no valves, one 6-port injection valve, two 6-port injection valves or one injection valve and 10-port chemistry switching valve.

- Column ID chip system for monitoring column properties and use (automatically logged to audit trail)

- Front panel displays power up status, injection valve position, and alarm status

- Wide temperature range; 5° to 85° C

- Precise temperature control

- Fast heat up and cool down times

- Optional heat exchangers for optimal eluent temperature and improved reproducibility



VWD UV-Vis detector

VWD Absorbance Detector

Get the benefits of performance and versatility of the VWD through the following features:

Deuterium and tungsten lamps that provide operation over the entire wavelength range of 190–900 nm

Compact design for optimal plumbing of liquid flow path and minimal use of bench space

Built-in holmium oxide filter for automated wavelength verification

High signal-to-noise ratio for maximum sensitivity

Data collection rate up to 100 Hz allows detection of even the sharpest peaks

Low baseline drift for reliable results

Excellent resolution that yields high linearity

Integrated flow cell heat exchanger for thermal stability

Lamp lifetime monitor to prevent downtime

Front access to prealigned lamps and flow cell to simplify detector maintenance

Identification chips integrated into lamps and flow cells (automatically logged to audit trail)

Multiple wavelength monitoring; up to 4 different wavelengths simultaneously

Autosamplers

AS Autosampler

The AS Autosampler delivers precision, reliability, ruggedness, and ease of use. Options include sample preparation, temperature control, and chemistry switching.

Configure the sampler for simultaneous injection and perform concurrent injections of a sample or standard onto two analytical systems running unique or similar applications. Improve efficiency by controlling dual ICS-3000 systems with one autosampler through sequential injections. This setup allows different applications to be run, or doubles the throughput in one application. With simultaneous and sequential injection, you can increase sample throughput, and eliminate errors associated with multiple operators and sampling locations.

New features include reagent prime, reagent flush, and concentrate. These capabilities offer additional flexibility that range from matrix elimination to concentration. Sequences can also be run in “overlap” with the previous sample to minimize overall cycle time.

Free up your schedule and lab time with automated sample handling for your IC



AS Autosampler

- Simultaneous injection
- Sequential injection
- Preconcentration
- Matrix elimination
- Automated dilutions

Eliminate complex laboratory procedures with automated standard preparation

Key AS Autosampler Features Provide Performance and Versatility

Consistent operation at RSDs of less than 0.3% provide reproducible, accurate results

Specially designed 10 mL polystyrene sample vials with wide openings that are easy to fill, easy to handle, and permit large-volume injections

Optional well plates facilitate processing large numbers of samples

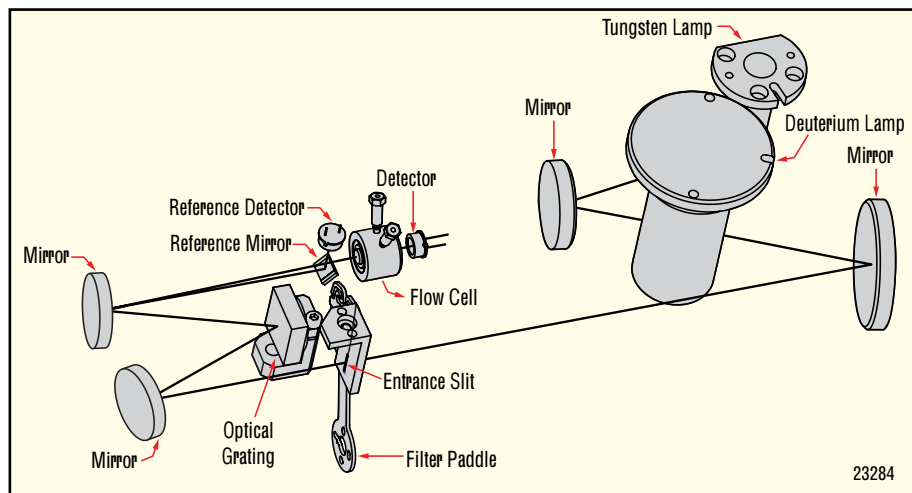
All-PEEK flow path – including the sample needle – ensures compatibility with aqueous and reversed-phase eluents and protects sensitive samples from metallic contamination

Control through Chromeleon or module front panel

Moving-needle design to guarantee reliable sampling from a variety of vial sizes

Sample preparative option that saves time and labor by automating your sample and standard preparations

Sample tray temperature control option for thermally sensitive samples that offers precise, reliable control over a temperature range of 4–60 °C



23284

ICS Series VWD optical schematic

ICS-3000 System Control

To operate most modular systems, you have to learn the front panels of various modules, then try to coordinate them through your chromatography software. The ICS-3000 is different. Powerful Chromeleon software integrates system control and data handling into your instrument, providing a convenient command center. Run with direct control, or set up a sequence of samples and methods for your system to run automatically overnight. It's easy and convenient.

For data analysis, Chromeleon software gives you all the power and versatility of the world's most complete chromatography management system. If your lab requires third party software for data analysis, Chromeleon Xpress provides complete ICS-3000 system control, and affords an easy upgrade path to the full version of Chromeleon.

Analyze

Set up and start running your routine analyses in seconds

Develop

Customize your methods for advanced analysis

Control

Take complete control of your chromatography instruments

Acquire

Get accurate results for peaks of all sizes with autoranging digital data acquisition

Diagnose

Maintain high confidence in your results with System Wellness

Interpret

Process your data quickly and accurately for dependable results

Organize

Find the data you need quickly and easily with powerful queries

Report

Produce the reports you need with an easy-to-use spreadsheet

Compliant

All with full 21 CFR Part 11 compliance



EO Eluent Organizer

The EO Eluent Organizer holds eluent containers in a liner for spill and leak containment. The EO holds and organizes eluent tubing and air lines. The EO is designed for placement on top of or adjacent to ICS-3000 modules.

A pressure regulator is available to provide an inert blanket of helium over the mobile phase.

EO Features

The flexible design of the EO Eluent Organizer accommodates:

- Four 1 or 2 L plastic containers
- Two 4 L plastic containers

Up to two EO eluent organizers stack on top of the DC or TC module.

Translucent liner contains spills and allows view of liquid levels

Constructed of corrosion-proof polypropylene and epoxy resin

Pressure regulator option available



Eluent Containers

Features

Available in 1, 2, and 4 L sizes constructed from polypropylene

Non-twist stopper with separate retaining ring prevents tubing from tangling

Graduations marked on containers in 100 mL increments

Includes custom-molded polyethylene end-line filters with 5 µm pores

ICS-3000 SP SINGLE AND DP DUAL PUMPS SPECIFICATIONS**Pump****Type:**

Dual-piston (in series),
microprocessor controlled,
constant stroke, variable speed,
patented Isokinetic Eluent
Precompression, without a
pulse damper

Construction:

Chemically inert, metal-free
PEEK pump heads and flow
path; compatible with aqueous
eluent from pH 0–14 and
reversed-phase solvents

Pressure Range:

0–35 MPa (0–5000 psi)

Flow Rate Range:

0.000–10.000 mL/min with
settable flow increments
at 0.001 mL/min, without
changing pump heads

Flow Rate Precision:

<0.1%

Flow Rate Accuracy:

<0.1%

Pressure Ripple:

<1%

Eluent Bottle Pressure:

None required

Vacuum Degasser:

Integrated, optional 1 channel
for isocratic pump or 4 channel
for quaternary pump

Piston Seal Wash:

Standard, automatic operation

Gradient Formation:

Quaternary low pressure or
electrolytic eluent generation
at high pressure and with pH
modification, optional

Gradient Profiles:

Any combination of an
unlimited number of linear,
convex, and concave positive
and negative gradient profiles

Gradient Proportioning Accuracy and Precision:

±0.5% at 2 mL/min

Gradient Mixing:

Passive mixers for 2 mm and
4 mm id columns, optional

Eluent Generation:

Optional eluent generation
(RFIC-EG) and eluent
regeneration
(RFIC-ER)

Eluent On/Off Valve:

Electrically actuated, standard

Leak Sensor:

Optical, standard

System Software**Software:**

Chromeleon Chromatography
Management Software,
supports Microsoft Windows®
2000, XP, or Vista

Automated Procedure Wizards:

Yes, standard feature

System Smart Startup and Shutdown:

Yes, standard feature

System Wellness and Predictive Performance:

Yes, standard feature

Application Templates:

Yes, standard feature

Multivendor Automation Support of 3rd Party:

Yes, fully controls over 200
different instruments from
more than 25 manufacturers,
including GC, HPLC, and MS.

Customizable System Control Panels:

Yes, standard feature

Signal Channels:

Pump pressure

Data Trending Plots:

Device numerical parameters
plotted

System Status Virtual Channels:

Yes, standard feature

Power Failure Protection:

Yes, standard feature

System Trigger Commands and Conditionals:

Yes, standard feature

Daily Audit Trail:

Yes, standard feature

Sample Audit Trail:

Yes, standard feature

System Calibration Storage:

Yes, factory, present, and
previous; completely user
selectable

Customized Reporting:

Yes, standard feature with
unlimited report workbooks

GLP Compliance:

Yes, optional

Physical Specifications**Power Requirements:**

90–265 V ac, 47–63 Hz

Dimensions (h x w x d):

36 × 21 × 48 cm
(14 × 8.25 × 19 in.)

Weight:

SP: 20.4 kg (45 lb)
DP: 24.1 kg (55 lb)

Flow Path:

All polymeric (PEEK), anion
or cation configurations

ICS-3000 EG ELUENT GENERATOR SPECIFICATIONS

Minimum and Maximum Eluent Concentrations:

0.01–100 mM

Flow Rates:

0.100–3.000 mL/min

Eluent Types:

KOH, LiOH, NaOH;
Carbonate; Carbonate/
Bicarbonate; Carbonate with
pH modifier; MSA

Maximum Operating Pressure:

21 MPa (3000 psi)

Maximum Solvent Concentration:

Cations: None
Anions: 25% methanol

Gradient Profiles:

Standard - any combination of
an unlimited number of linear,
convex and concave positive
and negative gradient profiles

Number of Cartridges Supported:

Two–dual cartridge support

System Software

Software:

Chromeleon Chromatography
Management Software,
supports Microsoft Windows®
2000, XP, and Vista

Automated Procedure Wizards:

Yes, standard feature

System Smart Startup and Shutdown:

Yes, standard feature

System Wellness and Predictive Performance:

Yes, standard feature

Application Templates:

Yes, standard feature

Multivendor Automation Support of 3rd Party:

Yes, fully controls over 200
different instruments including
GC, HPLC, and MS from
more than 30 manufacturers.

Customizable System Control Panels:

Yes, standard feature

Signal Channels:

Eluent concentration

Data Trending Plots:

Device numerical parameters
plotted

System Status Virtual Channels:

Yes, standard feature

Power Failure Protection:

Yes, standard feature

System Trigger Commands and Conditionals:

Yes, standard feature

Daily Audit Trail:

Yes, standard feature

Sample Audit Trail:

Yes, standard feature

Eluent Cartridge Information Storage:

Yes, serial number, remaining
life (ion count), remaining
lifetime (%) and expiration date

Customized Reporting:

Yes, standard feature with
unlimited report workbooks

GLP Compliance:

Yes, optional package provides
security system, modification
history, and electronic signatures

Physical Specifications

Dimensions (h × w × d):

41 × 23 × 56 cm
(16 × 8.75 × 21.5 in.)

Weight:

25 kg (40 lb)

Power requirements:

90–265 V ac, 47–63 Hz

Flow Path:

All polymeric (PEEK), anion
or cation configurations

ICS-3000 ER ELUENT REGENERATION SPECIFICATIONS

Eluents:

Carbonate and carbonate/bicarbonate combinations
up to 20 mM MSA up to 34 mM

Flow Rates:

0.01–2.00 mL/min

Continuous Operation with 4 L of Eluent:

Up to 28 days or 2000 samples, typically

Always On, Always Ready Capable:

Yes, standard feature

Remains Fully Calibrated for Extended

Periods of Time (≤28 Days):

Yes, standard feature. Results are traceable
to a single calibration.

System Wellness:

Consumables usage monitoring for predictive
maintenance

Maximum Operating Pressure:

21 MPa (3000 psi)

Operating Temperature Range:

4–40 °C

ICS-3000 DC DETECTOR/CHROMATOGRAPHY COMPARTMENT SPECIFICATIONS

DC Models:

Single or Dual Temperature
Zone Models

Single Temperature Zone Model or Dual Temperature Zone Model:

Thermoelectric cooling/heating

Temperature Range:

15 °C – 40 °C

(minimum temperature:

ambient -15 °C)

(maximum temperature:

ambient +20 °C)

Temperature Accuracy: ± 0.5 °C

Temperature Stability: ± 0.2 °C

Temperature Precision: ± 0.2 °C

Dual Temperature Zone Model:

Independent Temperature Control of Each Zone:

Upper Zone Temp. Range:

15–40 °C

(minimum temperature:

ambient -15 °C)

(maximum temperature:

ambient +20 °C)

Lower Zone Temp. Range:

10–70 °C

(minimum temperature:

ambient -15 °C)

(maximum temperature:

ambient +50 °C)

Temperature Accuracy: ± 0.5 °C

Temperature Stability: ± 0.2 °C

Temperature Precision: ± 0.2 °C

Lower Compartment: (Applies to Both Single and Dual Temperature Zone Models):

Injection Valves:

1 or 2 ea., 6 or 10 port

(upgradable, field
installable)

Up to two column sets

1–9 mm diameter

Maximum Column Length:

250 mm plus

50 mm guard column

Precolumn Heat Exchangers:

2 (2 mm or 4 mm column id
version)

Automation Manager: (Optional):

Injection Valves:

Up to 2 high pressure valves,
either 6 or 10 port, 2 position

Low Pressure Valves:

Up to 2 inert, 2- or 3-way

Reaction Coil Heater (RCH):

Holds two reaction coils

RCH Temperature Range:

5 °C above upper zone,

80 °C maximum

AutoPrep Kit:

Dual loop with sample
pre-concentration

All valves and heater

upgradable and field installable

Flow Path:

Plumbing configurations for
4 mm and 2 mm columns, fully
inert, PEEK

Detectors:

Any combination of two
conductivity or electrochemical
detectors, upgradeable and field
installable. Dual detectors can
be operated simultaneously or
independently. Optional remote
operation up to 3 m from
instrument.

Analog Signal Output:

Two analog output channels,
two 24 V relays, 2 TTL Out and
8 TTL In lines, upgradable and
field installable, optional

Leak Detection:

Optical leak sensor standard

Application Control Automation:

Yes, standard. All DC modules
come equipped with two switched
AC controllers built-in to
automate external devices and
the ability to control up to 6 low
pressure 2-way or 3-way valves
for fluidic automation.

Suppression

Non-suppressed conductivity:

Yes, supported

Suppressor wear parts:

None. No valves, pumps,
peristaltic pump tubing or
inline filters required

Chemical Suppression:

2 mm and 4 mm anion and
cation membrane suppression
bed types available

Displacement Chemical Suppression:

2 mm and 4 mm anion and
cation membrane suppression
bed types available

Electrolytic Suppression,

Self-Regenerating:

2 mm and 4 mm anion
and cation. Membrane and
MonoDisc suppression bed
types available

Electrolytic Suppression,

Self-Regenerating, External

Water Mode:

2 mm and 4 mm anion
and cation. Membrane and
MonoDisc suppression bed
types available

Salt Converter:

Available in 2 and 4 mm
versions

AMMS-ICE:

Available in 2 and 4 mm
versions

Carbonic Acid Removal for Anions:

ASRS and AMMS plus CRD
300 for 2 and 4 mm versions

ICS-3000 DC DETECTOR/CHROMATOGRAPHY COMPARTMENT SPECIFICATIONS (CONTINUED)*Suppression Capacities:*

Anion SRS 300 (4 mm): 200 µeq/min
 Cation SRS 300 (4 mm): 110 µeq/min
 Anion SRS 300 (2 mm): 50 µeq/min
 Cation SRS 300 (2 mm): 37.5 µeq/min
 Anion MMS 300 (4 mm): 150 µeq/min
 Cation MMS 300 (4 mm): 150 µeq/min
 Anion MMS 300 (2 mm): 37.5 µeq/min
 Cation MMS 300 (2 mm): 37.5 µeq/min
 Anion AES: 25 µeq/min
 Cation AES: 25 µeq/min
 AMMS-ICE: N/A

Suppressor Void Volumes:

SRS 300 (4 mm): <50 µL
 SRS 300 (2 mm): <15 µL
 MMS 300 (4 mm): <50 µL
 MMS 300 (2 mm): <15 µL
 AMMS-ICE 300 (4 mm): <50 µL
 AMMS-ICE 300 (2 mm): <15 µL
 AES (Anion or Cation): <35 µL

System Software*Software:*

Chromeleon Chromatography Management
 Software, supports Microsoft Windows® 2000,
 XP, and Vista

Automated Procedure Wizards:

Yes, standard feature

System Smart Startup and Shutdown:

Yes, standard feature

System Wellness and Predictive Performance:

Yes, standard feature

Application Templates:

Yes, standard feature

Multivendor Automation Support of 3rd Party:

Yes, fully controls over 200 different instruments
 from more than 25 manufacturers, including GC,
 HPLC, and MS.

Customizable System Control Panels:

Yes, standard feature

Signal Channels:

Detector signals, detector background signals,
 temperatures

Data Trending Plots:

Device numerical parameters plotted

System Status Virtual Channels:

Yes, standard feature

Power Failure Protection:

Yes, standard feature

System Trigger Commands and Conditionals:

Yes, standard feature

Daily Audit Trail:

Yes, standard feature

Sample Audit Trail:

Yes, standard feature

System Calibration Storage:

Yes, factory, current, and previous.
 Completely user selectable

Customized Reporting:

Yes, standard feature with unlimited
 report workbooks

GLP Compliance:

Yes, optional

Physical Specifications*Power Requirements:*

90–265 V ac, 47–63 Hz; (auto-sensing power
 supply; no manual voltage or frequency
 adjustment required)

Dimensions (h × w × d):

44.5 × 42 × 57 cm (17.5 × 16.5 × 22.5 in)

Weight:

38 kg (84 lb)

Flow Path:

All polymeric (PEEK), anion or
 cation configurations

ICS-3000 CD CONDUCTIVITY DETECTOR SPECIFICATIONS*Electronics Type:*

Microprocessor controlled
digital signal processing,
autoranging

Cell Drive:

8 kHz square wave

Linearity:

1%

Resolution:

0.00238 nS/cm

Output Range:

Digital Signal Range:

0–15,000 µS/cm,

Analog Signal Range:

0–15,000 µS/cm

Noise, Wet:

<0.2 nS at 23 µS/cm

background

<0.1 nS at 1 µS/cm

background

Filter:

Rise times 0 to 10 s,
programmable

Sampling Rate:

1 to 100 Hz, user settable
or automatic

Cell Temperature:

5 °C above DC upper
zone temperature to 60 °C
maximum. User settable,
working range is identical
to settable range.

Cell Temperature Stability:

<0.001 °C

Cell Temperature Compensation:

Default 1.7% per °C ;
programmable from 0–3%
per °C

Flow Cell Maximum Pressure:

10 MPa (1500 psi)

Flow Cell Volume:

0.7 µL

Cell Electrodes:

Passivated 316 stainless steel.
Compatible with MSA

Cell Body:

Chemically inert polymeric
material

Heat Exchanger:

Inert, tortuous-path for low
axial dispersion

System Software*Software:*

Chromeleon Chromatography
Management Software,
supports Microsoft Windows®
2000, XP, or Vista

Automated Procedure Wizards:

Yes, standard feature

System Smart Startup and Shutdown:

Yes, standard feature

*System Wellness and Predictive**Performance:*

Yes, standard feature

Application Templates:

Yes, standard feature

*Multivendor Automation Support
of 3rd Party:*

Yes, fully controls over 200
different instruments from
more than 25 manufacturers,
including GC, HPLC, and MS

Customizable System Control Panels:

Yes, standard feature

Signal Channels:

Conductivity, Total Conductivity

Data Trending Plots:

Detector numerical parameters
plotted

System Status Virtual Channels:

Yes, standard feature

Power Failure Protection:

Yes, standard feature

*System Trigger Commands and
Conditionals:*

Yes, standard feature

Daily Audit Trail:

Yes, standard feature

Sample Audit Trail:

Yes, standard feature

System Calibration Storage:

Yes, factory, present, and
previous. Completely user
selectable

Customized Reporting:

Yes, standard feature with
unlimited report workbooks

GLP Compliance:

Yes, optional

Physical Specifications*Dimensions (h x w x d):*

6.9 × 16.7 × 9.9 cm

(2.7 × 6.5 × 3.9 in)

Weight:

400 g (1.6 lb.)

ICS-3000 ED ELECTROCHEMICAL DETECTOR SPECIFICATIONS**Electronics Type:**

Microprocessor controlled
digital signal processing

Electronic Noise:

IPAD <80 pC
DC Amperometry <5 pA

Potential Range:

-2.0 to 2.0 V in 0.001 V
increments

Signal Range: Digital and Analog:

Integrated Amperometry:
50 pC to 200 μ C
DC Amperometry: 5 pA to 74 μ A

Filter:

0–10 s response time, user
settable

Control Mode:

Local or remote control using
relay closures or TTL, or
control using Chromeleon via
DC module

Cell Body:

Titanium body and inlet
tubing. Compatible with 2 mm
to 4 mm id columns

Working Electrodes:

Conventional: gold, glassy
carbon, platinum, and silver
Disposable: gold, carbon,
platinum, and silver

Reference Electrode:

pH-Ag/AgCl combination,
one piece design

Autoranging:

Yes

Analog Output:

User selectable full scale of
10, 100, or 1000 mV

Working Volume:

<0.5 μ L

Maximum Cell Operating Pressure:

0.7 MPa (100 psi)

System Software and Control**Software:**

Chromeleon Chromatography
Management Software,
supports Microsoft Windows®
2000, XP, or Vista

Detection Modes:

DC amperometry, pulsed
amperometry, integrated
amperometry, and cyclic
voltammetry.
Detection modes include use
of multiple waveforms and
multiple integration times to
optimize detection conditions
for individual analytes
Integrated amperometry
mode—unlimited changes to
the waveform profile's number
of segments, duration of each
segment, and voltage applied
at each segment

3-D Amperometry:

Three-dimensional display
of the raw integrated
amperometry data set,
with crosshairs on an
isoamperometric plot used
to select "slices" of the plot
along the applied voltage axis
(to render a chromatogram)
and along the time axis (to
render a voltammogram)
Three-dimensional wireframe
rendering, printing, color
selection, display of apex, and
other voltammograms

Automated Procedure Wizards:

Yes, standard feature

System Smart Startup and Shutdown:

Yes, standard feature

**System Wellness and Predictive
Performance:**

Yes, standard feature

Application Templates:

Yes, standard feature

**Multivendor Automation Support
of 3rd Party:**

Yes, fully controls over 200
different instruments from
more than 30 manufacturers,
including GC, HPLC, and MS.

Customizable System Control Panels:

Yes, standard feature

Signal Channels:

Electrochemical and total
electrochemical signals

Data Trending Plots:

Detector numerical parameters
plotted

System Status Virtual Channels:

Yes, standard feature

Power Failure Protection:

Yes, standard feature

**System Trigger Commands
and Conditionals:**

Yes, standard feature

Daily Audit Trail:

Yes, standard feature

Sample Audit Trail:

Yes, standard feature

System Calibration Storage:

Yes, factory, present, and
previous. Completely user
selectable

Customized Reporting:

Yes, standard feature with
unlimited report workbooks

GLP Compliance:

Yes, optional

Physical Specifications**Dimensions (h x w x d):**

6.9 × 16.7 × 9.9 cm
(2.7 × 6.5 × 3.9 in)

Weight:

400 g (1.6 lb.)

ICS-SERIES PDA PHOTODIODE ARRAY DETECTOR SPECIFICATIONS

Optics	Flow Cell	Performance	Physical Specifications
<i>Photodiode Array:</i> 1024 element	<i>Standard:</i> PEEK or SST, 13 μ L, 10 mm path length	<i>Noise:</i> ± 10 μ AU at 254 nm (flowing water, 2-s rise time)	<i>Power Requirements:</i> 90–265 V ac, 47–63 Hz
<i>Pixel Resolution:</i> 0.7 nm	<i>Semi-Prep:</i> PEEK, 0.7 μ L, 0.4 mm path length	± 15 μ AU at 520 nm (flowing water, 2-s rise time)	<i>Operating Temperature Range:</i> 4–40 °C (40–104 °F)
<i>Lamps:</i> Tungsten and deuterium	<i>Maximum Flow</i>	<i>Drift:</i> <500 μ AU/h	<i>Operating Humidity Range:</i> 5–95% relative, noncondensing
<i>Optical Resolution:</i> 1.0 nm	<i>Operating Pressure:</i> 300 psi (<2 MPa) PEEK 500 psi (<3 MPa) SST	<i>Wavelength Accuracy:</i> ± 1 nm, self- calibration with deuterium lines, verification with built-in holmium oxide filter	<i>Dimensions (h $\times$ w $\times$ d):</i> 17.4 $\times$ 44.4 $\times$ 50.3 cm 6.8 $\times$ 17.5 $\times$ 19.8 in.
<i>Wavelength Range:</i> 190–800 nm			<i>Weight:</i> 18.1 kg, 40 lb
Electronics			
<i>Analog Outputs:</i> Four, 0–3 AU, 1000 mV range		<i>Linearity:</i> >2 AU	

TC THERMAL COMPARTMENT MODULE SPECIFICATIONS

TC Models:	High-Pressure Valve Types:	General Specifications	Physical Specifications
<i>Temperature Range:</i> 5–85 °C (max 18 °C below ambient) in 0.1 °C increments	<i>Six-port/two position</i> Rheodyne PEEK (injection) valve	<i>Control:</i> Chromeleon/ Chromeleon Xpress	<i>Power Requirements:</i> 90–265 V ac, 47–63 Hz
<i>Temperature Performance:</i> Accuracy: ± 0.5 °C Stability: ± 0.1 °C Precision: ± 0.1 °C	<i>Ten-port/two position</i> Rheodyne PEEK (switching) valve	<i>Computer Connection:</i> USB	<i>Operating Temperature Range:</i> 10–35 °C (50–95 °F)
<i>Heat up / Cool down Time:</i> Typically 15 minutes 20 °C to 50 °C and 50 °C to 20 °C	<i>Column Capacity:</i> Three column sets, 1–9 mm	<i>Leak Detection:</i> Humidity and vapor sensors	<i>Operating Humidity Range:</i> 5–80% relative, noncondensing
	<i>Maximum Column Length:</i> 300 mm + 50 mm guard column	<i>TTL and Relay inputs and outputs:</i> Two digital inputs/ outputs, two relay outputs	<i>Dimensions (h $\times$ w $\times$ d):</i> 17.4 $\times$ 44.4 $\times$ 50.3 cm 6.8 $\times$ 17.5 $\times$ 19.8 in.
	<i>Precolumn Heat Exchangers (optional):</i> Two low delay volume exchangers		<i>Weight:</i> 15.4 kg, 34 lb

ICS-SERIES VARIABLE WAVELENGTH DETECTOR SPECIFICATIONS

Optics	<i>Rise Time:</i> 0.00–4.55 s	<i>Cell Volume:</i> 11 µL PEEK	Physical Specifications
<i>Optical System:</i> Dual beam forward optics design (monochromator) single or multiple (4-channel) wavelength UV/VIS detector options	<i>Full-Scale Recorder Output:</i> 1V or 10V	<i>Heat Exchanger Volume:</i> 8.8 µL	<i>Power Requirements:</i> 85–265 V ac, 47–63 Hz
<i>Light Source:</i> Deuterium lamp for UV range; tungsten lamp for visible range	<i>Data Collection rate up to 100 Hz Digital Output:</i> Full dynamic autoranging digital absorbance signal output to Chromeleon	<i>Maximum Flow Cell Operating Pressure:</i> 725 psi (5 MPa)	<i>Operating Temperature Range:</i> 10–35 °C (50–95 °F)
<i>Wavelength Range:</i> 190 to 900 nm in 1-nm increments	<i>Control Modes:</i> Software remote control through Chromeleon/ Chromeleon Xpress	Performance	<i>Operating Humidity Range:</i> 5–80% relative, noncondensing
Electronics	Flow Cell	<i>Wavelength Accuracy:</i> ±1 nm	<i>Dimensions (h × w × d):</i> 15.2 × 44.4 × 50.3 cm 6.0 × 17.5 × 19.8 in.
<i>Analog Output Ranges (optional):</i> 0.001–3.0 AU	<i>Cell:</i> PEEK	<i>Bandwidth:</i> 6 nm at 254 nm	<i>Weight:</i> 15.4 kg, 34 lb
	<i>Cell Path Length:</i> 10 mm	<i>Linearity:</i> Up to 2.5 AU	
		<i>Noise:</i> Typically <±2.5 × µAU at 254 nm	
		<i>Drift:</i> <0.1 mAU/h at 254 nm	

AS AUTOSAMPLER SPECIFICATIONS*Sample Capacity:*

10 mL vials: 49
 1.5 mL vials: 100
 Well Plates: 192 (two standard
 or deep well 96 well plates)

Injections per Vial:

1–99

Minimum Sample Volume:

10 µL can be sampled from
 a 300 µL microvial;
 20 µL can be sampled from
 a 500 µL microvial

Maximum Injection Volume:

8200 µL

Variable Volume Range:

1–100 µL in 0.1 µL
 increments;
 100–8200 µL in 1 µL
 increments

Injection Cycle Time

*(including sample prep such
 as dilution):*

15 seconds, with sample
 overlap function

Injection Modes:

Full Loop
 Partial Loop
 Limited Sample

Injection Precision:

Fixed Loop: <0.3%
 RSD at 20 µL;

Partial Loop: <0.5%
 RSD at 20 µL

Dilution:

1:1 to 1:1000

Autodilution:

With post run functionality
 and Chromeleon Purification
 License

Dilution Precision:

<1.0% RSD for a 1:100
 dilution

Dispensing Precision:

<0.2% RSD (by weight)

Carryover:

<0.01% with 500 µL flush
 volume

Sample Tray Thermostatting:

4 °C to 60 °C, optional

Dual Instrument Support:

Sequential (asynchronous)
 and Simultaneous modes, field
 upgradeable, optional

Sample Degassing:

CRD 200/300, upgradeable,
 user installable

Injection Valves:

One or two two-position
 six-port

Diverter Valve:

One two-position six-port

Sample Preparation:

Dilution, addition of internal
 standards, concentration/
 matrix elimination,
 derivatization, etc. optional

Inline Sample Filtration:

Dual filter, backflush, optional

System Software*Software:*

Chromeleon Chromatography
 Management Software,
 supports Microsoft Windows®
 2000, XP, or Vista

Automated Procedure Wizards:

Yes, standard feature

System Smart Startup and Shutdown:

Yes, standard feature

*System Wellness and Predictive
 Performance:*

Yes, standard feature

Application Templates:

Yes, standard feature

*Multivendor Automation Support
 of 3rd Party:*

Yes, fully controls over 200
 different instruments from
 more than 25 manufacturers,
 including GC, HPLC, and MS.

Customizable System Control Panels:

Yes, standard feature

Data Trending Plots:

Yes, all device numerical
 parameters

System Status Virtual Channels:

Yes, standard feature

Power Failure Protection:

Yes, standard feature

*System Trigger Commands
 and Conditionals:*

Yes, standard feature

Daily Audit Trail:

Yes, standard feature

Sample Audit Trail:

Yes, standard feature

System Calibration Storage:

Yes, factory, current and
 previous. Completely user
 selectable

Customized Reporting:

Yes, standard feature with
 unlimited report workbooks

GLP Compliance:

Yes, Optional

AS AUTOSAMPLER SPECIFICATIONS (CONTINUED)**Physical Specifications***Dimensions:*

58 x 30 x 46 cm
(23 in x 12 in x 19 in.)
65 x 30 x 46 cm
(27.5 in x 12 in x 19 in)
with sample temperature
control

Weight:

<30 kg (<65 lb)
<38 kg (<81 lb) with sample
temperature control

Power:

90–265 V ac, 47–63 Hz

Flow Path:

All polymeric (PEEK), anion
or cation configurations

Validation Services

Dionex offers a full range of validation services and kits for the ICS-3000 product line. Validation procedures include Installation Qualification (IQ) and Operational Qualification (OQ)/Performance Qualification (PQ) for the ICS-3000 system modules.

All validation kits include detailed procedures for performing the validation. Also included are calibration tools, data worksheets, methods, and validation certificates.

Ordering Information

Part numbers for ICS-3000 systems and modules are available from your local Dionex office or distributor. Please consult your Dionex representative for the system configuration and modules best suited to your needs.

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Denmark (45) 36 36 90 90 France (33) 1 39 30 01 10 Germany (49) 6126 991 0
Ireland (353) 1 644 0064 Italy (39) 02 51 62 1267 Sweden (46) 8 473 3380
Switzerland (41) 62 205 9966 United Kingdom (44) 1276 691722

Asia Pacific

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Japan (81) 6 6885 1213 Korea (82) 2 2653 2580 Singapore (65) 6289 1190
Taiwan (886) 2 8751 6655

www.dionex.com



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Agilent 1200 Series LC Systems and Modules



Agilent Technologies





Agilent 1200 Series

Pure Liquid Chromatography

Agilent Technologies has taken its world leading LC system and made it even more flexible, smarter and ultimately equipped for the future.

The new Agilent 1200 Series is finely tuned to give you a winning combination of speed, resolution and sensitivity, while the modular design ensures that you get a configuration ideally suited to meet your application requirements.

Agilent has been developing robust and reliable LC systems for over 30 years. The Agilent 1200 Series represents the latest advance in this evolution of excellent integrated solutions, designed to help you achieve uncompromised data quality and higher productivity.

Make a secure investment in the future of your lab with the scalable and open architecture of the Agilent 1200 Series.

**All the performance.
All the time.**

Sensitivity and Performance

Optimized to give you complete confidence in your results

The seamless integration of each module gives you unparalleled accuracy and precision for both quantitative and qualitative analysis. Highly sensitive detectors deliver the lowest possible detection limits for even the most demanding applications.

Spectral information from 190 to 950 nm

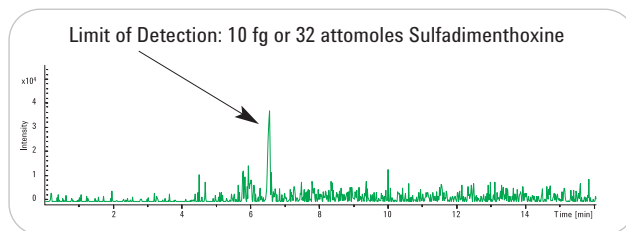
The dual-lamp design and the temperature control of the Agilent 1200 Series diode array detectors ensure outstanding sensitivity. Photodiode arrays with 1024 elements, programmable slit width (1, 2, 4, 8, 16 nm) and the selection of nine different flow cells enable optimization of resolution, linearity and sensitivity.

Mass selective detection for more confidence

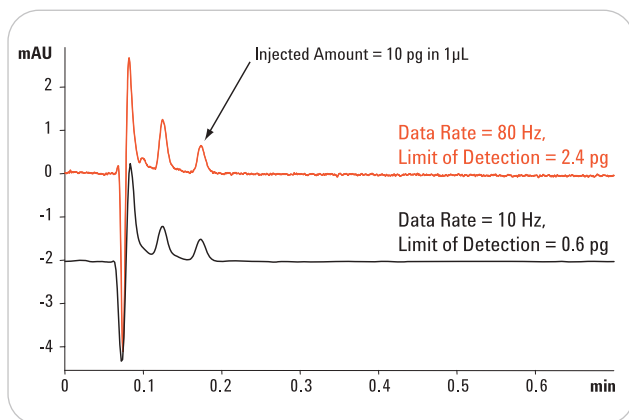
By providing molecular weight and structural information, which complements the spectral information from a diode array detector, the Agilent 6000 Series LC/MS systems are the ideal solutions for scientists who need additional selectivity and sensitivity for their chromatographic systems.

HPLC-Chip/MS for reliable high sensitivity nanospray

The easy-to-use HPLC-Chip/MS system significantly improves your nanoflow separations by eliminating all post-column dead volumes and is ideally suited for high sensitivity nanospray LC/MS with limited sample amounts.



Serum sample with HPLC-Chip/6320 Ion Trap LC/MS, EIC of 311.1 → Σ (155.9, 217.9, 245.0), 1 μ L injection.



Limit of detection of anthracene at different data rates with diode array detector.

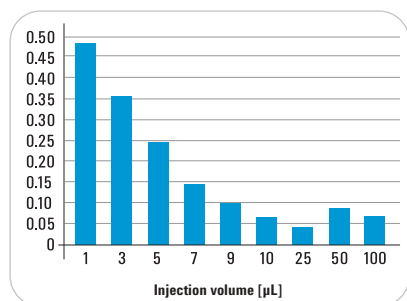


Revolutionary HPLC-Chip/MS integrates capillaries, nanocolumns and nanospray emitter on a single polymer chip.

Superior injection precision and lowest carryover

The selection of different autosamplers provides for precision levels of < 0.5 % RSD over an injection volume range from 0.01 μL to 2000 μL .

The unique flow-through design, combined with the external needle wash and optional multiple wash solvents, virtually eliminates carryover, even for highly adsorptive compounds.



Typical repeatability data for injection volumes demonstrates the high precision of the standard autosampler.

High resolution chromatography reveals more

Small particle size and long separation columns are key for higher efficiency and resolution. The Agilent 1200 Series Rapid Resolution system fully exploits the power of Agilent ZORBAX Rapid Resolution HT columns with 1.8 μm particles, providing a new dimension of information for complex samples.



High resolution chromatography of a ginseng root extract with the Agilent 1200 Series Rapid Resolution system and TOF detection, with the average peak width of 0.13 minutes giving a peak capacity of 540.

Speed and Throughput

Modular and scalable platform lets you decide just how fast you want to work

By choosing a system from the fast quaternary/binary LC system through to the ultra-fast rapid resolution system you can achieve new levels of productivity, processing more samples in less time, while maintaining and even improving data quality.

Short columns with sub-2 μm particles offer a unique opportunity to dramatically reduce analysis time by increasing the flow rate without losing separation performance. In order to take full advantage of their power, you need a system that can do more than handle high back pressure. The answer is a fully integrated solution, optimized for system volumes, cycle times, detection rates and temperature control.

Column: ZORBAX SB RRHT C18,
2.1 mm x 50 mm, 1.8 μm
Flow = 2.4 mL/min
Gradient: water/acetonitrile
0 min 35 %
0.38 min 95 %
0.46 min 95 %
0.47 min 35 %
Temperature: 95 °C
Pressure: 550 bar
Detection: DAD SL, 80 Hz data rate

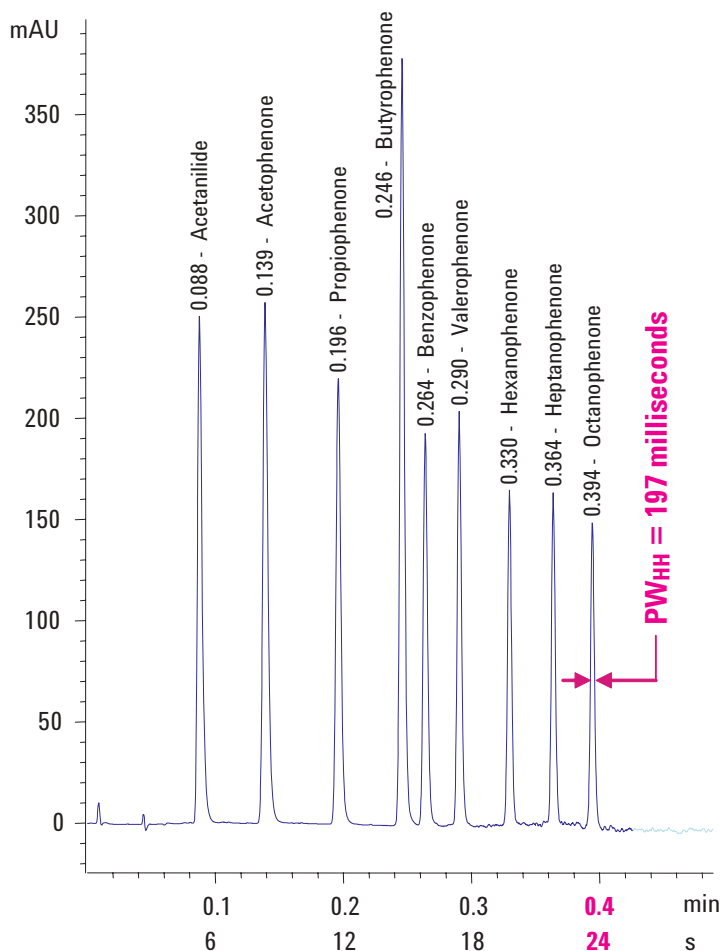
Ultra-fast separation of a phenone mix with the Agilent 1200 Series Rapid Resolution system.

Agilent 1200 Series binary pump SL

- Configurable delay volume down to 120 μL together with a flow range up to 5 mL/min provides universal applicability
- Electronic damping control for lowest baseline noise
- Perfect choice for fast and precise gradients using LC/MS, as well as UV-only systems
- Fully exploits the speed and separation potential of ZORBAX Rapid Resolution HT columns

Fast cycle time for ultra-fast analysis

- High performance autosamplers enable fast injection cycles without sacrificing lowest carryover
- Valve solutions for alternating column regeneration
- Minimized run-to-run instrument and software initialization time



Complete ZORBAX Rapid Resolution HT column portfolio

The optimized particle size distribution results in less back pressure which makes these columns the number one choice for all LC systems.

High temperature enables higher speed

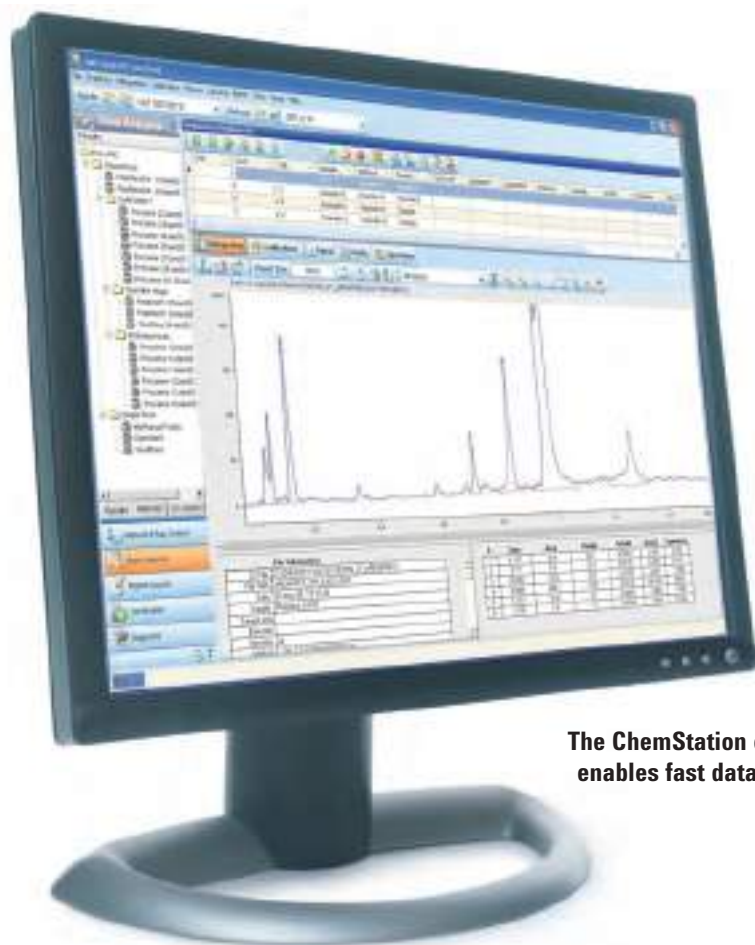
The two independently controllable low volume heat exchangers allow ultra-fast, high temperature separation with unique post-column cooling for the lowest possible UV detection limits.



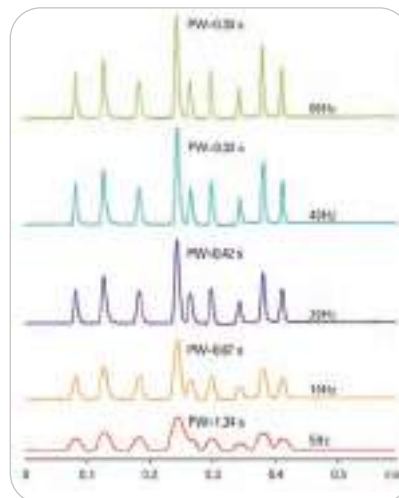
Peltier cooling/heating ranging from 10 °C below ambient up to 100 °C.

Ultra-fast detectors with uncompromised sensitivity

- Programmable variable wavelength detector VWD (55 Hz)
- Multiple wavelength detector MWD (80 Hz)
- Diode array detector for full spectral acquisition DAD (80 Hz)
- Five types of mass spectrometers, all with fast spectral acquisition that can keep up with the fastest chromatography



The ChemStation explorer enables fast data review.



80 Hz full spectral sampling rate provides resolution and peak capacity gains of 90 % relative to 10 Hz sampling rates.

Reliability and Lifetime

Easy maintenance and intelligent system monitoring for increased uptime

With an installed base of more than 60,000 LC systems, Agilent LC technology is renowned for its reliability under all operating conditions. The Agilent 1200 Series represents the next generation of LC, designed for even greater robustness and reliability together with enhanced performance.

Agilent pioneered technologies to monitor and track important system parameters with the goal of ensuring that you achieve greater productivity and keep operating costs low.

Robust components

- Long-life pistons and seals, together with active seal wash, reduce the frequency of preventive maintenance
- Deuterium and xenon lamps with a lifetime of over 2000 hours
- Patented orthogonal spray design substantially reduces ion source contamination and the need for cleaning

Easy maintenance

- Demonstration videos on a multimedia CD-ROM guide you through maintenance procedures
- Easily interchangeable ion sources
- E-Pac design significantly reduces assembly and disassembly time

Agilent system intelligence

- Early Maintenance Feedback (EMF) tracks system usage (such as lamp burn time, solvent usage) and alerts you for timely replacement of parts
- Column identification module records column parameters (such as number of injections, particle size and maximum pressure) and provides a unique column signature
- Patented RFID tracking technology in the DAD SL saves all relevant meta data from the flow cells and UV lamp
- Control Area Network (CAN) provides inter-modular, real-time communication for reliable operation, regardless of PC failures or network interruptions
- Software independent LC diagnostic tool assists users and the support experts interpreting the instrument status
- Agilent system intelligence provides a new generation of services with on-demand remote connectivity for a new level of productivity



Self-aligning, front access to replacement parts, such as lamp and flow cells.



A unique embedded data recovery card for DAD SL offers you "data-never-lost insurance".

Customer support and services

Agilent provides customer-focused products and services for all stages in an instrument's life cycle, from installation and upgrade to operation and repair. The Agilent global network of support services offers a broad range of options for customized or contract services, enabling you to choose the package which best suits your laboratory needs and budget requirements.

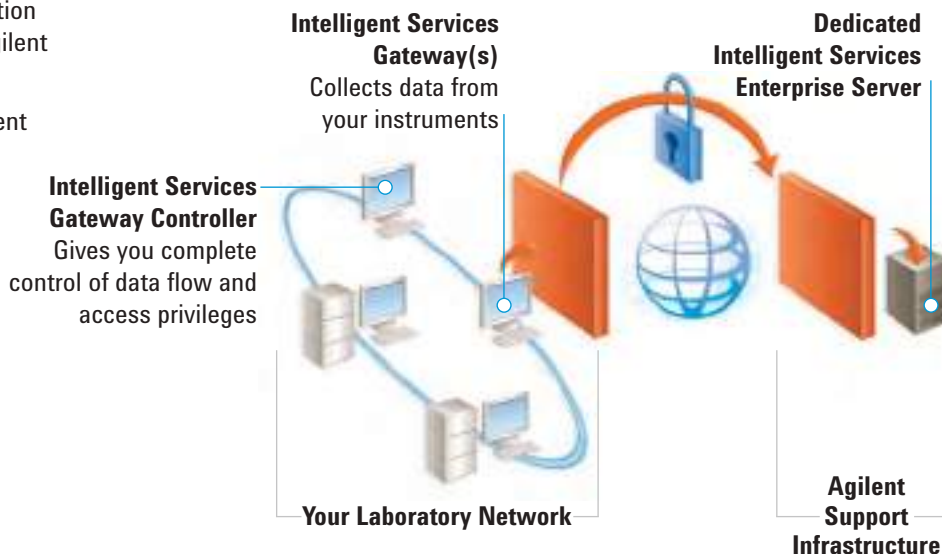
Agilent intelligent services

Using the remote capabilities of your instrument, the latest generation of Agilent services offers real-time insight into instrument utilization and performance. Backed by highly skilled Agilent service engineers and application scientists, these intelligent services provide a whole new level of performance.

- Agilent LC diagnostics instrument status report includes all important information, such as system configuration, error log book, EMF and guidance report
- Maximized lab productivity – secure and streamlined communication between your lab and the Agilent support organization
- Optimized return on instrument capital – proactively monitor instrument performance and utilization



At the push of a button, Agilent LC diagnostics generates complete instrument status reports in pdf format.



For more information visit: www.agilent.com/chem/1200reliability

Open and Organized

Scalable and open software architecture with Agilent OL operating system

In parallel to the development of enhanced analytical hardware, Agilent develops software solutions designed to meet your specific needs. The Agilent range extends from single workstations through to client-server solutions and an innovative informatics framework to unite your enterprise, ensuring that you can expand your operations easily and effectively.

Workstation software systems to improve your daily output

Agilent workstations give you high level instrument control, data acquisition and data management capabilities, designed to help you increase productivity. All software systems are available with Installation Qualification (IQ) and Operational Qualification (OQ).

- Reduce training costs
- Comply with regulatory guidelines
- Extend the system as lab needs grow
- Employ sophisticated level 4 and 5 instrument control

ChemStation for research and method development tasks

Agilent ChemStation enables you to acquire, review and organize large amounts of data, giving you instant access to online instrument modifications and results. The built-in macro language makes it easy to customize and the software supports numerous add-ons.

- Level 5 instrument control for your Agilent instruments
- Built-in diagnostics, maintenance and Early Maintenance Feedback (EMF) functions for maximum uptime
- Control of LC/MS, GC/MS, CE, CE/MS and generic A/D converters
- Add-on modules for specific solutions, such as high throughput purification software, GPC/SEC Data Analysis, Analyst, LC/MS Easy Access, ChemStation Data Browser

EZChrom Elite for maximum flexibility and compliance

Agilent EZChrom Elite workstation is an easy to use software solution for labs with instruments from multiple vendors. It also provides high automation capability with advanced "smart" sequencing and reporting capabilities with automated spreadsheet calculations.

- Full compliance features
- Integrated multi-vendor instrument control
- Powerful and flexible reporting
- SMART sequencing for flexible automation tasks
- Easy scale-up from workstation to client-server system

Agilent 1200 Series instant pilot

- Cost-effective, standalone solution for single instrument control
- Full instrument control and display of online signal(s), maintenance, diagnostic and Early Maintenance Feedback (EMF) functions
- Comfortable operation in the palm of your hand or securely mounted on one of the 1200 Series modules
- Large, high-brightness colored screen
- USB memory stick for method and sequence storage, and transfer to another 1200 system
- Intuitive software with online tip-tool and context-sensitive help for ease of use

Parameters can be changed immediately

Online tip-tool shows limits instantly for ease of use



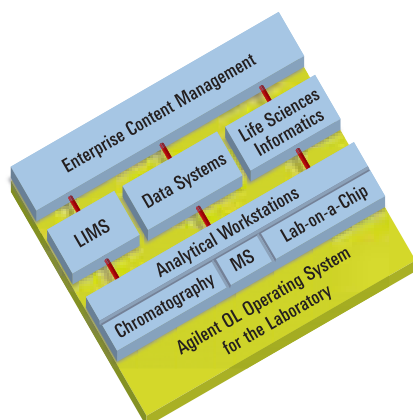
Color-coded information on status of 1200 Series system

Signal plot(s) can be enlarged to full screen

Agilent OL ECM reaches beyond the single laboratory

The Agilent OL philosophy lets you communicate beyond the boundaries of a single lab. By implementing Agilent OL's core component – the Enterprise Content Management system (ECM) – you can acquire and organize your data across laboratories and departments.

- Saves all documentation and data in a single repository
- Organize and retrieve data using advanced search engines
- Enables several people to rapidly and easily review a complete result set for a sample, including graphical results



Easy scale-up from single workstation to enterprise-wide solutions within the Agilent OL operating system for the laboratory.

Client-server systems expand your operations

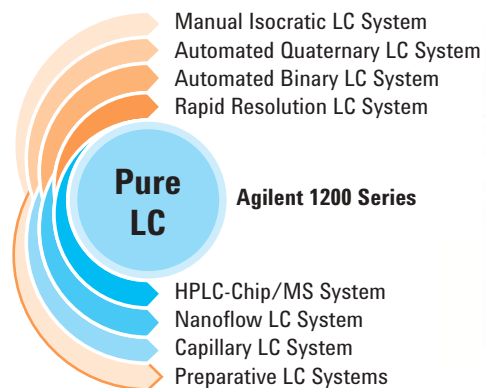
As your facility grows, EZChrom Elite workstations can be easily scaled up to client-server systems, enabling you to access and control your instruments from any PC within the network. If you are working in a highly regulated environment, Agilent Certify for Pharmaceutical QA/QC provides full workflow support of quality control operations.



Agilent OL enables total content management of instruments as well as general laboratory information.

Scalable Solutions

For future expandability and adaptability





Module Selection Guide

Agilent 1200 Series pumping systems * settable flow range with degasser



Isocratic Pump

Flow range: 0.001–10 mL/min*,
for isocratic analysis
(column ID: 2.1–9.4 mm)



Quaternary Pump

Flow range: 0.001–10 mL/min*,
for gradient analysis
(column ID: 3–9.4 mm)



Binary Pump

Flow range: 0.001–5 mL/min,
for fast gradient analysis
(column ID: 2.1–4.6 mm)



Binary Pump SL

Flow range: 0.001–5 mL/min*,
for ultra-fast and high resolution
gradient and analysis
(column ID: 1–4.6 mm)



Preparative Pump

Flow range: 0.001–100 mL/min
(extendable to binary gradient)
for isolation and purification
(column ID: 4.6–50 mm)



Capillary Pump

Flow range: 0.01–100 µL/min
(extendable up to 2.5 mL/min)*,
for gradient analysis
(column ID: 0.18–1 mm)



Nanoflow Pump

Flow range: 0.01–1 µL/min
(extendable up to 2.5 mL/min)*,
for gradient analysis
(column ID: 0.075–0.1 mm)

www.agilent.com/chem/1200pumps

Agilent 1200 Series column/valve organization



Thermostatted Column Compartment

Temperature range: 10 °C below
ambient to 80 °C



Thermostatted Column Compartment SL

Temperature range: 10 °C below
ambient to 100 °C



Column/Valves Organizer

Agilent interfaces



35900 A/D Converter for non-Agilent equipment



For more information you can download
Data Sheets from the Agilent website:
www.agilent.com/chem/1200datasheets

Agilent 1200 Series injection systems

Manual Injectors

Injection range:
loops for 5 μ L–20 mL



Standard Autosampler

Injection range: 0.1 μ L–100 μ L
(extendable up to 5000 μ L)
Sample container: vials



Micro Well-plate Autosampler

Injection range: 0.01–8 μ L
(extendable up to 40 μ L)
Sample container:
vials and well-plates



High Performance Autosampler

Injection range: 0.1 μ L–100 μ L
(extendable up to 1500 μ L)
Sample container: vials and
well-plates



High Performance Autosampler SL

Injection range: 0.1 μ L–100 μ L
(extendable up to 1500 μ L)
Sample container: vials and
well-plates



Dual Loop Autosampler PS

Injection range: up to 10 mL
Sample container: vials and
well-plates



Preparative Autosampler

Injection range: 0.1–5000 μ L
Sample container: vials



Thermostat for Autosampler

Temperature range: 4–40 °C



Plate Handler with automation

interface (scalable)
Shallow well-plates: up to 16 (80)
Deep well-plates: up to 4 (16)
Vial plates: up to 6 (24)

www.agilent.com/chem/1200autosamplers

Agilent 1200 Series degassers



Vacuum Degasser

Flow rate: up to 10 mL/min
Internal volume: 12 mL



Micro Degasser

Flow rate: up to 5 mL/min
Internal volume: 1 mL

Agilent 1200 Series fraction collectors



Micro Collector/Spotter

Flow rate: up to 100 μ L/min



Fraction Collector (AS)

Flow rate: up to 10 mL/min



Fraction Collector (PS)

Flow rate: up to 100 mL/min



Thermostat for Fraction Collector

Temperature range: 4–40 °C

All the performance.

Agilent 1200 Series detectors



Variable Wavelength Detector
for programmable single λ analysis,
1 signal, 13 Hz data rate



Variable Wavelength Detector SL
for ultra-fast, programmable single λ
analysis, 1 signal, 55 Hz data rate



Multiple Wavelength Detector
for multi- λ analysis
5 signals, 20 Hz data rate



Multiple Wavelength Detector SL
for ultra-fast multi- λ analysis
8 signals, 80 Hz data rate



Diode Array Detector
for multi- λ and spectral analysis
5 signals, 20 Hz data rate



Diode Array Detector SL
for ultra-fast multi- λ and spectral
analysis, 8 signals, 80 Hz data rate



Fluorescence Detector
for multi-signal detection and
online fluorescence spectra



Refractive Index Detector
for refractive index range:
1.00–1.75 calibrated

www.agilent.com/chem/1200detectors

Agilent 1200 Series external valves



2-position/10-port valve



2-position/10-port micro valve



2-position/6-port valve



2-position/6-port micro valve



6-position selection valve



12-position/13-port valve

Controllers



Agilent 1200 Series Instant Pilot



**Agilent Workstations and
Chromatographic Data Systems**

Agilent ChemStation

Agilent EZChrom Elite

**Agilent Cerity for
Pharmaceutical QA/QC**

All the time.

Agilent 6000 Series LC/MS systems



Agilent 6100 Series Single Quadrupole LC/MS Systems
Nominal mass detection



Agilent 6410 Triple Quadrupole LC/MS
Accurate MS/MS quantification



Flow range: 0.1–1 $\mu\text{L}/\text{min}$

Agilent 1200 Series HPLC-Chip/MS with nanospray source



Agilent 6210 Time-of-Flight LC/MS
Ultra-fast accurate mass



Agilent 6300 Series Ion Trap LC/MS Systems
Sensitive MSⁿ



Agilent 6510 Quadrupole Time-of-Flight LC/MS
MS/MS structural information with accurate mass

Ionization sources



Electrospray (ESI) Source



Atmospheric Pressure Chemical Ionization (APCI) Source



Multimode Source (ESI/APCI)



Atmospheric Pressure Photoionization (APPI) Source



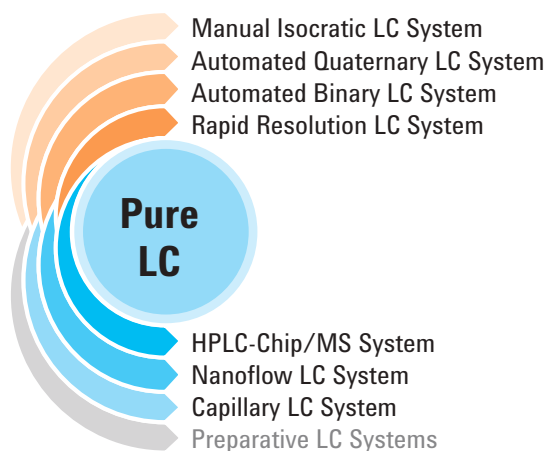
Nanospray Source



Pulsed Dynamic Focusing MALDI (PDF-MALDI) Source

Scalable Solutions

For multiple performance levels and future expandability



Speed and resolution

The performance of a liquid chromatographic system with regards to speed and resolution is influenced by various aspects of the overall system. The automation capabilities and cycle times have a big impact on speed, whereas column technology, temperature, gradient and detector performance will affect both speed and resolution.

Manual Isocratic LC System

Workhorse for demanding QA/QC applications

- Entry-level system for world-class LC technology
- Easy and fast maintenance
- Flow rates up to 10 mL/min for a wide range of column dimensions and applications
- Upgrade options from isocratic up to automated quaternary LC system

Speed and resolution

Sensitivity

Highest sensitivity detection, especially in combination with limited sample amounts, is a challenge in applications, such as proteomics and drug metabolism studies. At constant injection volumes, decreasing the column inner diameter creates smaller elution volumes. This results in higher concentrations, as well as higher signals in concentration sensitive detectors, such as UV absorbance or electrospray LC/MS.

- Electronic Flow Control (EFC) measures and actively controls the flow in real time for highest retention time stability
- Dedicated, thermostatted micro autosamplers designed for reproducible injection of small sample amounts, as low as 10 nL
- Theoretical sensitivity increase $= \frac{r_1^2}{r_2^2}$
r = column radius

Sensitivity

Automated Quaternary LC System

For routine method development and high throughput gradient applications

- Greatest flexibility for multi-solvent gradients by accessing up to 4 solvents
- Flow rates up to 10 mL/min support both standard bore and semi-preparative applications
- Wide selection of autosamplers for full flexibility in injection volumes and sample containers

Automated Binary LC System

For research, high-throughput and fast applications

- High pressure gradient mixing for superior gradient performance even at lower flow rates
- Optimized delay volumes for fast chromatography
- Flow rates from 0.05 to 5 mL/min provides ideal support for narrow and standard bore applications

Rapid Resolution LC System

Highest speed and resolution with uncompromised data quality

- Up to 60 % more resolution and up to 20 times faster compared to conventional LC
- Flow rates up to 5 mL/min provide universal applicability
- Full, uncompromised compatibility with existing methods
- Ideally suited for use with ZORBAX Rapid Resolution HT 1.8 μ m columns
- Throughput of 2000 samples per day

Capillary LC System

Enter the world of low flow applications

- Up to 500 times more sensitive compared to conventional LC
- Typical flow rates 1 – 100 μ L/min, extendable up to 2.5 mL/min
- Advanced diode array detection from 190 – 950 nm

Nanoflow LC System

Unsurpassed nanoflow performance and stability

- Up to 3500 times more sensitive compared to conventional LC
- Typical flow rates 0.1 – 1 μ L/min, extendable up to 2.5 mL/min
- Compatibility with third-party MS platforms

HPLC-Chip/MS System

For reliable high sensitivity nanospray LC/MS

- Up to 3500 times more sensitive compared to conventional LC
- No peak dispersion for uncompromised chromatographic performance
- Sample preparation and separation columns, connection capillaries, fittings and nanospray emitter directly integrated on the polymer chip



Preparative LC Solutions

For isolation and purification with highest recovery and purity

Preparative LC is the technique of choice for isolation and purification. For lowest peak dispersion, Agilent has developed dedicated preparative solutions for a range of sample quantities and flow rates, optimized for highest recovery and purity, throughput and productivity.

**Micro Collection/
Spotting System**
flow rates up to
100 $\mu\text{L}/\text{min}$

**Purification System
Analytical Scale**
flow rates up to
10 mL/min

**Purification System
Preparative Scale**
flow rates up to
100 mL/min

Flow rate →

Purification System

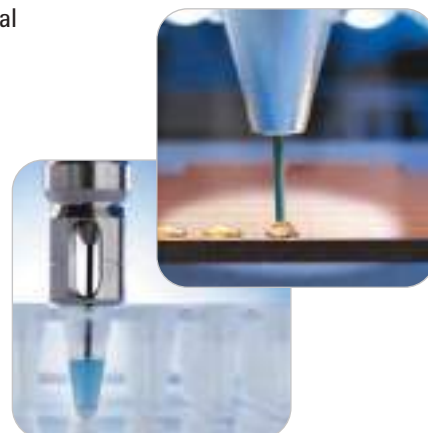
- Automated delay volume calibration
- Integrated safety features
- Software solutions for different user needs
- Smart fraction collection based on time, peak and mass, or both



Micro Collection/Spotting System

Allows the collection of micro fractions in different well-plate formats and also provides users the advantage of combining chromatography with the power of MALDI MS by direct spotting on MALDI targets.

- Active flow control for exceptional flow stability
- Flexibility of collection in well-plates, Eppendorf tubes and MALDI targets
- Liquid control for highest reproducible collection of small volumes
- Fraction cooling prevents evaporation and thermal decomposition



Extensive LC Column Portfolio

A superior level of chromatography performance to match your separation needs

Maximize system performance and reliability for all your separation needs by combining the new Agilent 1200 Series system with Agilent ZORBAX LC columns and LC supplies. Designed with the same attention to detail, quality and superior performance you have come to expect from Agilent instruments and backed by over 30 years of chromatography experience, you can count on Agilent's columns and supplies to deliver the high quality results you need and expect, time after time.



Unparalleled quality and flexible choices within the ZORBAX LC column family

- Wide selection of chemistries – Eclipse XDB, StableBond, Extend, Bonus-RP, Rx and more
- Column sizes from nano to preparative scale
- Security of reproducible performance with unparalleled column life over thousands of injections
- Individual column performance reports to document column-to-column and lot-to-lot reproducibility
- Superior particle strength for even the most demanding high pressure applications

ZORBAX Eclipse LC column family – an excellent first choice for your method development needs

- Unsurpassed peak shape performance and superior, reproducible separations of basic compounds with Eclipse Plus
- Flexible choices for a broad range of conditions and a wide variety of sample types
- Broad selectivity choices for enhanced resolution with **six** different bonded phases (two Eclipse Plus, four Eclipse XDB) for the column that is best for your separation needs
- Quick and seamless method transfer from analytical to prep and to fast and ultra-fast LC with particle sizes from 1.8 to 7 μm



Fast, high-throughput separations maximize your resources and improve productivity

- Achieve higher speed without compromising the quality of your separation with Rapid Resolution and Rapid Resolution High-Throughput LC Columns
- Separations up to 20 times faster with 1.8 μm RRHT LC columns
- Lengths from 20 – 150 mm for high speed and high resolution analyses
- 60% resolution improvement over conventional LC
- ZORBAX RRHT columns are available in 8 different bonded phases

Compliance

Complete qualification portfolio for highest level of operation

Agilent Qualification Portfolio is the cost-effective way to maximize system operability while minimizing regulatory exposure. With a complete qualification portfolio designed to maintain the highest level of lab operation, Agilent's services account for all phases of a system's life cycle and create customized compliance programs based on your needs.



An independent 2004 LCGC magazine survey ranked Agilent No. 1 in general compliance services, hardware and method validation, and system suitability.

Classic Edition

Installation Qualification (IQ)

Ensures that new Agilent hardware and software is installed correctly from the moment it is unpacked to the point it is ready for operation.

Operational Qualification (OQ)

A comprehensive test of the complete system to ensure basic accuracy and precision of instruments, as well as uncovering potential problems before they occur.

Instrument Re-Qualification (RQ)

Ensures that the qualified status of a complete system is restored after a given component has been repaired.

Enterprise Edition

Organizations which utilize many different types and brands of analytical instruments can rely on Agilent as their single source for instrument qualification.

Harmonized qualification protocols with comparable results provide a consistent approach to complete instrument qualification needs, now and in the future.

Partner Edition

Enterprise Edition managed by you. Licensed self-delivery of qualification protocols using the Agilent Compliance Engine allows you to complement Agilent's Enterprise Edition service by delivering the protocols when, where and how you want.

Software Edition

Fast, accurate and comprehensive qualification for Agilent software provides evidence that it is properly installed and configured.

Network Edition

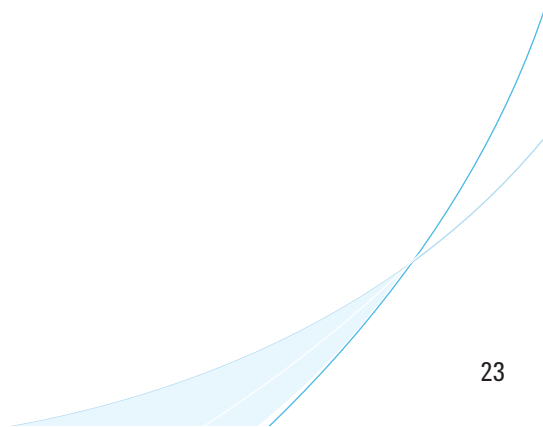
Patent-pending, metrology-based IQ/OQ and troubleshooting service for your network helps to maximize network uptime while minimizing regulatory exposure. It is the perfect complement to data system implementation and infrastructure validation.

"I believe Agilent provides the most complete range of compliance validation services in the world"

Ludwig Huber, Compliance Fellow at Agilent Technologies



All the performance.
All the time.



www.agilent.com/chem/1200

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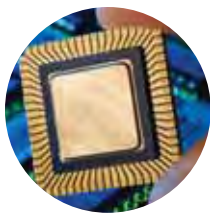


Spécifications

ICP-MS Agilent Série 7500

Plus simple. Plus rapide. Plus précis.
«Passez à un niveau supérieur d'ICP-MS»



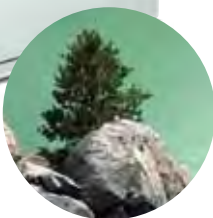


La gamme - Créée pour répondre à vos besoins

La nouvelle série 7500 comprend deux modèles distincts – le 7500cx et le 7500cs – pour répondre précisément à tous vos besoins. Ces modèles peuvent évoluer sur site d'un système à un autre.

Caractéristiques communes aux deux systèmes.

- Appareil de paillasse compact qui peut être intégré facilement dans un laboratoire existant
- Châssis en acier inoxydable pour une résistance accrue contre la corrosion
- Système d'introduction d'échantillon facilement accessible pour simplifier l'interfaçage avec des systèmes d'introduction alternatifs
- Chambre de nébulisation refroidie par effet Peltier pour une stabilité optimale et des taux d'oxydes minimum
- Position de la torche complètement automatisée, contrôlée informatiquement dans les 3 directions (x, y et z)
- Système ShieldTorch (STS) pour une sensibilité inégalée et un meilleur contrôle énergétique des ions
- Débitmètres massiques (AMFC) pour un contrôle précis et indépendant de tous les débits de gaz du plasma, de nébulisation et des gaz de collision/réaction
- Générateur radiofréquences à 27 MHz à état solide contrôlé numériquement. Il est de haute efficacité et ne requiert aucune maintenance
- Barreaux du quadripôle de profil réellement hyperbolique pour une excellente transmission des ions et une sensibilité en abondance optimale
- Quadripôle RF de fréquence 3 MHz, synthétisée numériquement pour une performance du spectromètre de masse accrue
- Détecteur fonctionnant simultanément en deux modes avec un amplificateur de signal à haute vitesse et permettant d'obtenir une gamme linéaire de 9 ordres de grandeur



Améliorations et mises à jour sur site possibles. Votre investissement est garanti lorsque vos applications changent.

Spécifications

Système d'introduction

Nébuliseurs

7500cx – Nébuliseur microconcentrique en verre MicroMist
 7500cs – Nébuliseur en PFA à microdébit (100 µl/min)
 D'autres nébuliseurs tels que les nébuliseurs à flux croisés, nébuliseur Babington, ...sont disponibles.

Chambre de nébulisation

7500cx et 7500cs – Chambre de Scott en quartz. Un kit inerte pour l'analyse d'acides agressifs (HF par exemple) en PFA est disponible en option pour les 2 instruments.

Pompe(s) Péristaltique(s)

Pompe de haute précision, à 3 voies et 10 rouleaux, totalement contrôlée informatiquement qui permet d'obtenir un pompage précis et contrôlé de l'échantillon, du standard interne et du drain de la chambre de nébulisation. Une seconde pompe péristaltique, optionnelle, est disponible pour des applications nécessitant l'utilisation de canaux supplémentaires ou de plusieurs vitesses de pompe simultanément. Les deux pompes sont placées à côté de la chambre de nébulisation pour des rinçages plus rapides et des volumes de tube minimum.

Plasma

Débitmètres massiques

Les débitmètres massiques actifs contrôlent les débits de gaz plasmagène, auxiliaire, d'appoint et de nébulisation sur le 7500cx. Un 5^{ème} débitmètre est disponible sur le 7500cs pour l'ajout d'oxygène ou de tout autre gaz dans le plasma (en option sur le 7500cx).

Torche

Torche en quartz monobloc avec un injecteur de large diamètre (2.5 mm) pour une décomposition optimale et une ionisation efficace de l'échantillon. Des torches avec des diamètres d'injecteurs plus faibles sont disponibles pour l'analyse d'échantillons organiques. Des torches démontables avec un injecteur en platine ou en saphir dans le kit PFA (optionnel sur le 7500cx et le 7500cs) sont utilisées pour l'analyse d'acides agressifs.

Positionnement de la torche en xyz

La position de la torche est complètement contrôlée par l'ordinateur et peut être optimisée automatiquement dans les trois directions (xyz), le mouvement sur un axe étant indépendant des deux autres. La position de la torche peut être réglée avec une précision de 0.1 mm sur chacun des trois axes.

Générateur RF

Tous les ICP-MS Agilent Série 7500 utilisent un générateur à état solide radiofréquence de fréquence 27 MHz contrôlé numériquement. La fréquence de 27 MHz permet d'obtenir des efficacités d'ionisation meilleures que les générateurs de fréquence 40 MHz. De plus le générateur Agilent, à l'état solide, ne requiert pas de remplacer régulièrement les tubes de décharge.

Système ShieldTorch

Tous les ICP-MS Agilent 7500 utilisent le dispositif ShieldTorch System. Il diminue efficacement la dispersion énergétique des ions, ce qui augmente la sensibilité et permet une discrimination d'énergie cinétique des ions polyatomiques sur les ICP-MS 7500 lorsque la cellule de collision/réaction est en fonctionnement. Ce système minimise le potentiel du plasma permettant un fonctionnement optimal en plasma froid.

Interface

Cônes

Une conception optimale du cône échantillonneur et du cône écréteur permet d'assurer à la fois une très bonne transmission du faisceau d'ions et une tolérance aux matrices chargées exceptionnelle.
 7500cx – Nickel (platine optionnel)
 7500cs – Platine (nickel optionnel)

Optique Ionique

Lentilles d'extraction

Les lentilles d'extraction sont positionnées dans l'axe du plasma et placées hors de la région de vide poussé pour faciliter la maintenance (démontage des lentilles sans couper le vide). Elles peuvent fonctionner avec des tensions permettant une extraction conventionnelle ou une extraction douce. La configuration des lentilles d'extraction permet d'obtenir une courbe de réponse « plate » offrant une sensibilité inégalée pour les éléments légers tout en minimisant les bruits de fond de l'interface.

Lentilles omega

Tous les ICP-MS Agilent de la série 7500 utilisent des lentilles « omega », de propriété Agilent, pour éliminer l'effet des photons et des neutrons sur le bruit de fond. Au contraire d'anciennes conceptions utilisant un système de « photon stop » ou de « shadow stop » qui nécessitent de défocaliser puis de refocaliser le faisceau d'ions, les lentilles omega assurent une excellente transmission des analytes sur toute la gamme de masse grâce à une meilleure focalisation des ions. Ces lentilles sont aussi placées hors de la région de vide poussé de l'instrument.

Système de vide

Zone d'expansion

Une seule pompe primaire, externe, reposant sur le sol est nécessaire. Elle peut être déplacée pour minimiser le bruit, les vibrations et le dégagement de chaleur.

Zones intermédiaires et du spectromètre de masse

Une seule pompe turbomoléculaire à 2 étages est utilisée.

Cellule de Collision/Réaction Octopolaire

Cellule de collision/réaction

Les systèmes Agilent 7500cx et 7500cs utilisent un dispositif de collision/réaction utilisant un octopole (Agilent Octopole Reaction

Agilent 7500 Series ICP-MS

System, ORS) pour éliminer les interférences polyatomiques. L'octopole focalise mieux les ions qu'un hexapole ou un quadripôle, ce qui permet de supprimer les interférences par collision à l'aide d'hélium pur. L'hélium supprime toutes les interférences provenant de la matrice, sans créer de nouvelles interférences, ce qui élimine le recours à des conditions spécifiques pour chaque élément ou chaque matrice. L'hydrogène (standard sur le 7500cs, optionnel sur le 7500cx) est utilisé pour l'analyse d'ultratraces de sélénium et les applications type semi-conducteurs. Une troisième voie (optionnelle sur les deux appareils) permettant d'ajouter un autre gaz (Xe, O₂, mélange NH₃/He) est disponible afin de résoudre des problématiques spécifiques.

Débitmètres de la cellule de collision/réaction

Pour l'Agilent 7500cx et 7500cs, 2 débitmètres massiques actifs contrôlent le débit de chacun des gaz ajoutés dans l'ORS. Un 3^{ème} voie (optionnelle) peut être incluse sur tous les ORS.

Analyseur de masse quadripolaire

Quadripôle

Tous les ICP-MS Agilent Série 7500 utilisent un quadripôle fabriqué par Agilent, conçu avec des barreaux de section réellement hyperbolique. L'allure des pics et la sensibilité en abondance est meilleure qu'avec un quadripôle utilisant des barreaux ronds. Seuls les ICP-MS Agilent disposent de barreaux à section hyperbolique.

Générateur RF du quadripôle

Le quadripôle est contrôlé par un générateur RF Agilent digital assurant plus efficacement le transfert de puissance que les générateurs analogiques conventionnels. Le générateur fonctionne à la fréquence de 3 MHz, la plus haute fréquence de tous les ICP-MS, et permet d'obtenir les meilleures spécifications en abondance du marché.

Gamme de masse:	2 – 260 AMU
Fréquence RF:	3 MHz
Temps minimum d'acquisition:	100 µs
Sensibilité en abondance:	
	Basses masses < 5 X 10 ⁻⁷
	Hautes masses < 1 X 10 ⁻⁷

Détecteur à mode dual

Détecteur

Tous les ICP-MS Agilent de la série 7500 utilisent un multiplicateur d'électrons, pouvant fonctionner simultanément en deux modes (modes pulsé et analogique) et offrant une gamme linéaire dynamique de 9 ordres de grandeur.

Electronique du détecteur

Le circuit amplificateur est un système unique. Il offre une vitesse d'acquisition rapide en mode analogique pour les signaux transitoires et une gamme linéaire de 9 ordres de grandeur.

Temps d'intégration minimum: 100 µs (dans les deux modes: analogique et pulsé) Gamme de linéarité: de la limite de détection jusqu'à 500ppm

La concentration maximale mesurable peut être étendue jusqu'à plus de 1000 ppm (1 g/L) en mode He (7500cx, 7500cs) – sans avoir à ajuster la résolution du quadripôle.

Logiciel facilitant le contrôle de l'ICP-MS et l'analyse de données

Le logiciel Chemstation de l'ICP-MS est conçu aussi bien pour les laboratoires de routine, analysant un grand nombre d'échantillons, que pour des laboratoires de recherche et développement. Chaque fonction de l'instrument est contrôlée par le logiciel. L'optimisation de l'instrument est totalement automatisée à partir de l'auto-optimisation, alignement de la torche après une opération de maintenance, tests de diagnostics, création de méthode avec l'assistant création de méthodes. Le logiciel permet de réaliser l'analyse complète de spectres de masse, d'analyser seulement certains éléments (saut de pic) ou d'acquérir des signaux transitoires, l'analyse quantitative de données à l'aide de rapports isotopiques, dilution isotopique, calibration externe et ajouts dosés. L'utilisation de standard interne distincts pour chacun des éléments est disponible pour chacun des modes. La fonction Standard interne virtuel "Virtual Internal Standards (VIS)" permet à l'utilisateur de définir un "standard interne" à n'importe quelle masse par interpolation des standards internes existants. L'analyse semi quantitative est possible pour une analyse rapide d'échantillons inconnus. Elle est compatible avec le mode hélium (avec le 7500cx ou le 7500cs) qui permet de supprimer l'ensemble des interférences. L'archivage de données ou des fonctions de recherche sont incluses ainsi que outils pour une connectivité bidirectionnelle avec le LIMS. Les résultats d'une séquence d'analyse incluant méthode, calibration et tous les résultats QA/QC sont automatiquement sauves par date dans un dossier pour exporter facilement les données. Les listes d'échantillons à analyser peuvent être importées du LIMS directement vers la séquence à analyser. Un langage de programmation macro est disponible et permet de personnaliser la Chemstation pour plus de flexibilité.

Système d'exploitation:	Microsoft Windows XP
Auto optimisation:	Inclus
Rapport personnalisé:	Inclus
Programmation Macro possible:	Inclus
Pack "séquençage intelligent":	Option
Pack "contrôle d'accès":	Option

Accessoires et périphériques

Une large gamme d'options et d'accessoires est disponible pour tous les instruments 7500. Ces options, incluant les accessoires et les logiciels, sont conçus pour répondre aux besoins d'applications spécialisées incluant le couplage de l'ICP-MS avec une HPLC, GC ou une ablation laser. Il permet aussi de répondre aux besoins de laboratoire travaillant avec des contrôles qualités précis. Le logiciel peut utiliser le séquençage intelligent (Intelligent Sequencing) et un contrôle d'accès (User Access Control Pack) qui répond aux normes exigées dans de nombreux laboratoires commerciaux et gouvernementaux. Des accessoires comme le Système d'Introduction d'Echantillon Intégré (Integrated Sample Introduction System, ISIS), les kits d'introduction inerte ou d'échantillons organiques, les kits de connexion GC et HPLC étendent les capacités de l'instrument, facilitent leur mise en œuvre et offrent une flexibilité complète sur la série ICP-MS 7500.

Logiciel

Séquençage intelligent (Intelligent Sequencing) – Système de QA/QC et d'automatisation des séquences configurable par l'utilisateur. Répond aux demandes des différentes normes. Permet à la ChemStation de prendre des décisions de type QA/QC et exécute les actions appropriées lors d'actions non prévues. Contrôle des systèmes comme la dilution automatique (lorsque l'ISIS est configuré), la vérification des calibrations et interférences, la recalibration, la ré-analyse d'échantillons et les rapports de QC personnalisés.

Logiciel de chromatographie (Plasma Chromatographic Software) – Pack permettant l'analyse chromatographique en temps réel basé sur la technologie des logiciels utilisés en GC/MS. Il inclue des outils sophistiqués pour l'analyse chromatographique des données obtenues lors de couplage HPLC, GC ou LA-ICP-MS. Puisqu'il opère en temps réel, il est possible lors de l'acquisition de données, d'automatiser les séquences de calibration, les temps de rétention et la génération de rapport.

Pack pour le contrôle d'accès (User Access Control Pack) – Conçu pour répondre aux besoins de laboratoires ayant besoin d'un haut niveau de sécurité et de traçabilité de données. Ce pack restreint, contrôle et enregistre l'accès des utilisateurs au système et aux données.

Accessoires

Passeur d'échantillon intégré Agilent (Agilent Integrated Autosampler (I-AS)) – C'est un passeur d'échantillons de faible volume (2 à 20 mL selon le plateau utilisé), couvert avec des postes de rinçages pour l'analyse d'ultra traces, placé au plus près du nébuliseur afin de limiter la consommation d'échantillons, le temps d'analyse et les éventuelles contaminations.

Système d'Introduction d'Echantillon Intégré (Integrated Sample Introduction System, ISIS) – L'ISIS peut être ajouté à tous les ICP-MS Agilent 7500. Il consiste en deux pompes péristaltiques additionnelles de haute précision et 2 vannes optionnelles à 6 voies, toutes sous contrôle informatique et proche du système d'introduction de l'échantillon. Le système ISIS peut être configuré pour auto-diluer en ligne et en temps réel les échantillons, pour améliorer les cadences d'analyse pour permettre l'injection par analyse de flux (flow injection), pour la chromatographie liquide basse pression, pour mettre en œuvre la génération d'hydrures, ou l'élimination en ligne de la matrice.

Seconde Pompe Péristaltique – Une seconde pompe péristaltique optionnelle peut être ajoutée à tous les ICP-MS 7500 pour augmenter la cadence d'analyse tout en conservant une introduction de l'échantillon à débit constant.

Interface GC-ICP-MS – L'interface Agilent GC-ICP-MS a été la première interface commerciale disponible et reste l'interface de choix pour les applications difficiles en GC-ICP-MS. Seule l'interface GC Agilent est chauffée du GC jusqu'à l'extrémité de l'injecteur de la torche ce qui élimine les points de recondensation des composés à haut point d'ébullition. En plus, l'interface Agilent utilise un liner inerte en SilcoSteel™ pour minimiser les dégradations de composés labiles. L'interface GC est complètement contrôlée avec les GC Agilent 6890, à travers la méthode GC et ne requiert aucun contrôleur ou source électrique externe.

Kit de connexion LC – Kit de spéciation de l'Arsenic – Le kit de connexion Agilent LC permet à tous les ICP-MS de la série 7500 d'être interfacés avec tous les systèmes HPLC (Agilent ou autres marques). Il inclue tous les tubes nécessaires, les connecteurs et les câbles pour faciliter le couplage LC-ICP-MS.

Kit de spéciation Arsenic – Le kit pour la spéciation de l'arsenic inclue les colonnes, précolonnes, connecteurs et instructions pour l'analyse d'espèces arsénisées dans les urines.

Kit de spéciation Chrome – Le kit de spéciation du chrome utilise une colonne propriétaire Agilent pour la spéciation du Cr dans les eaux naturelles.

Kit d'introduction pour les solvants organiques – Le kit pour l'introduction de solvant organique permet l'analyse directe de solvants organiques qui ne serait normalement pas possible en ICP-MS ou endommagerait les systèmes d'introduction standards.

Ablation Laser – La série 7500 peut être utilisée avec n'importe quel système d'ablation laser pour les applications réalisables en routine ou en recherche.



Integrated Autosampler

Agilent 7500 Series ICP-MS

Environnement

Température

15-30°C, <2°C / h (écart max: 5°C)

Humidité

20-80 % (pas de condensation)

Besoins externes

Puissance électrique

Monophasé 200-240 V, 30 A, 50/60 Hz

Eau de refroidissement

Température d'entrée: 15-40°C
Débit minimum: 5 L/min
Pression d'entrée: 230-350 kPa (33-51 psi)

Alimentation en argon

Pureté minimale: 99.99%
Débit maximum: 20 L/min
Pression: 700 kPa (100 psi) ±3.5%

Extraction

Débit d'extraction: 4-6 m³/min
(7-8 m³/min pour 7500cs)

Dimensions

Dimensions Produits (7500cx, 7500cs)

Chassis *

Hauteur: 830 mm (32.7 in)
Largeur: 1100 mm (43.3 in)
Profondeur: 720 mm (28.3 in)
Poids: 175 kg (386 lbs)

Pompe primaire

Hauteur: 550 mm (21.7 in)
Largeur: 570 mm (22.4 in)
Profondeur: 170 mm (6.7 in)
Poids: 36 kg (79 lbs)

Dimensions des colis pour l'expédition

Chassis *

Hauteur: 1020 mm (40.2 in)
Largeur: 1220 mm (48.0 in)
Profondeur: 850 mm (33.5 in)
Poids: 230 kg (508 lbs)

Pompe primaire

Hauteur: 900 mm (35.4 in)
Largeur: 1030 mm (40.6 in)
Profondeur: 680 mm (26.8 in)
Poids: 108 kg (238 lbs)

*PC, imprimantes, options et périphériques ne sont pas inclus

Sécurité

Sécurité

Tous les ICP-MS Agilent 7500 satisfont:
IEC61010-1:2001/EN61010-1:2001
CSA C22.2 No.1010
UL61010A-1

EMC

IEC61326-1: 1997+A1:1998+A2:2000
EN61326-1: 1997+A1:1998+A2:2001
ICES-001: 1998
AS/NZS 2064.1

ISO

Tous les ICP-MS Agilent 7500 sont fabriqués sur un site certifié ISO 9001 et ISO 14001.

*PC, imprimantes, options et périphériques ne sont pas inclus



Spécifications

Sensibilité	7500cx			7500cs		
	Mode Sans Gaz	Mode He	Mode H ₂ (si inclus)	Mode Sans Gaz	Mode H ₂	Mode He
Li(7) ¹ MHz/ppm	≥ 30			≥ 50	≥ 20	
Y(89) ¹ MHz/ppm	≥ 80	≥ 15	≥ 30	≥ 160	≥ 100	
Tl(205) ¹ MHz/ppm	≥ 40			≥ 80	≥ 90	
Co(59) MHz/ppm						≥ 40
Bruit de fond ¹	≤ 5 CPS ² (9 AMU)			≤ 5 CPS ² (9 AMU)		
Oxide % (CeO ⁺ /Ce ⁺) ¹	≤ 1.5	≤ 0.8		≤ 6		
Doubles charges % (Ce ²⁺ /Ce ⁺) ¹	≤ 3.0			≤ 6		
Limites de détection ppt (3s)	≤ 1.5			≤ 0.5		
Be(9)	≤ 0.5			≤ 0.1		
In(115)	≤ 0.5			≤ 0.1		
Bi(209)			≤ 4 ppt			
Se(78)					≤ 3 ppt	
Fe(56) (mode H ₂)				≤ 3 ppt		
Fe(56) (plasma froid)						
Stabilité court terme (%RSD)	< 3% (20 min)			< 3% (20 min)		
Stabilité long terme (%RSD)	< 4% (2 hrs)			< 4% (2 hrs)		

¹ Mesurés et vérifiés sur site lors de l'installation à l'aide d'un seul jeu de conditions.² Le bruit de fond mesuré correspond à la moyenne du signal (donné en coups) et non pas à l'écart-type sur le signal



www.agilent.com/chem

Restez à jour

Restez à jour sur les ICP-MS Agilent Série 7500 et sur les autres produits Agilent. Enregistrez vous sur www.agilent.com/chem/registration pour recevoir des bénéfices exclusifs tels que:

- Notifications emails en fonction de vos centres d'intérêts
- Accès aux vidéos "comment faire", bibliothèques de chromatogrammes, notes d'applications et bien plus encore
- Mise à jour de logiciels
- Enregistrement plus rapide pour les e-séminaires gratuits et pour les autres formations

L'engagement d'Agilent – 10 ans d'utilisation garantie

Cet engagement vous garantit au minimum 10 ans d'utilisation de votre ICP-MS Agilent Série 7500, à partir de la date d'achat ou Agilent vous créditera la valeur résiduelle de votre appareil si vous le remplacez avant cette durée.

Pour plus d'informations

Pour en savoir plus sur les ICP-MS Agilent Série 7500 – incluant comment il répond aux besoins des secteurs de l'environnement, de la toxicologie, des semi-conducteurs, de la recherche – visitez www.agilent.com/chem/icpms

ou appelez le numéro Azur 0810 446 446 (pour la France uniquement) ou le numéro +33 (0)1 6453 5750 pour une démonstration gratuite et sans obligations

The 7500cx can not be used with hydrogen cell gas or hydrogen cell gas mixtures unless the optional hydrogen cell gas line is installed.

The information and pricing in this guide are subject to change without notice.

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5989-6493FR



Agilent Technologies



Simpler. Faster. More accurate.
Step up to a new level in ICP-MS



Agilent 7500 Series ICP-MS

versatility and flexibility



Make the Change to ICP-MS with Agilent

ICP-MS is widely acknowledged as the premier technique for trace metals analysis. Today's routine lab requires much greater sensitivity than is provided by ICP-OES, and far higher sample throughput than GFAA. ICP-MS meets both these requirements, over a wider analytical working range, and is capable of simultaneously measuring the hydride elements and trace Hg, while adding semiquantitative and isotopic analysis capabilities. ICP-MS is also an extremely powerful and versatile detector for chromatography and laser applications.

But not all ICP-MS instruments are the same. Agilent's new 7500 Series delivers the highest levels of performance, while retaining ease of use, flexibility and reliability through automation and excellence in design. With second generation Octopole Reaction System (ORS) technology and the widest range of sampling accessories, backed by the finest applications and service support, the new 7500 Series is leading the way as labs make the change to ICP-MS.

The updated 7500 Series comprises of two different models, to suit different application requirements and different budgets. Guaranteed expandability and on-site upgradeability means that your investment is protected no matter how your application needs change.

Agilent 7500cx Collision Cell ICP-MS for All Routine Applications

Agilent's unique ORS technology uses helium (He) collision mode to make the new 7500cx the simplest, most flexible, most powerful ICP-MS available. The 7500cx is the clear choice for easy, ppt-level quantification in the most challenging sample matrices.

Universal He collision mode for reliable, predictable removal of all matrix interferences

- Easy setup – no “cookbooks”, no complex optimizations
- Enhanced productivity – no gas mode switching within run
- Improved data confidence in unknown matrices – unlike reactive gases, no new interferences are formed, no analytes or internal standards are lost
- No mathematical correction equations are needed

Designed for high matrix analysis

- 9 orders true linear dynamic range – the largest of any ICP-MS
- Matrix tolerant sample introduction system and interface handles tough samples like wastewaters, soils, foods, biomedical, petrochemical and geological samples with ease

Interference-free semiquantitative analysis – fast!

- He collision mode allows full-scan semiquantitative analysis (Semiquant) of unknowns - with no interferences and all in a single acquisition mode

Optional cell gas lines – reactive gas mode – for special applications

- Optional H₂ reaction mode – enables single digit ppt detection limits for selenium
- Optional Xe reaction mode – enables sub-ppb detection limits for sulfur



Agilent 7500cx



Many companies have already increased productivity and efficiency in their metals lab by replacing multiple techniques with a single Agilent 7500 ICP-MS. This trend has increased with the development of our ORS systems. With the widest dynamic range, coupled with freedom from matrix interferences, Agilent's ORS ICP-MS is replacing ICP-OES, GFAA and other elemental analysis techniques worldwide.



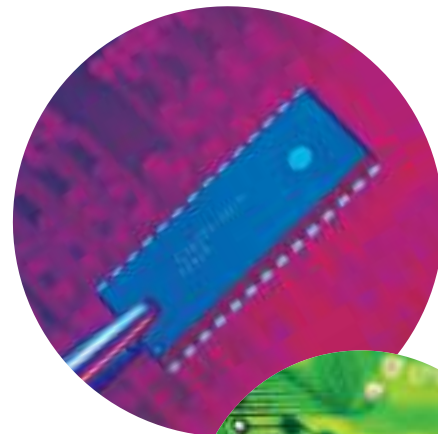
The 7500 Series comprises two models - 7500cx and 7500cs - to meet the dynamic application requirements of today's busy trace metal labs.

Agilent 7500cs

The Ultimate Semiconductor Analyzer

ORS technology extends the scope of ICP-MS for semiconductor applications

- Ultra high sensitivity for the ultimate in detection power, featuring the ORS for removal of matrix interferences in the toughest semiconductor sample types
- The interference removal power of the ORS removes even S-based polyatomics in sulfuric acid, uniquely allowing the direct, on-mass measurement of Ti and Zn
- Removal of Ar-based interfering species such as ArO or Ar₂ using H₂ reaction mode
- Unmatched cool plasma performance with Agilent's ShieldTorch interface gives ultimate BECs and complete flexibility for every application
- Optional 3rd cell gas line for NH₃ reaction mode — for ultratrace vanadium measurement in high purity HCl
- Sample introduction system and interface designed for semiconductor use. Special shipping prep and full exhaust ducting for cleanroom use
- New option: Agilent designed PFA inert sample introduction kit



Agilent 7500cs shown with optional I-AS autosampler

analysis without interferences



Collision/Reaction Cell Technology Made Routine

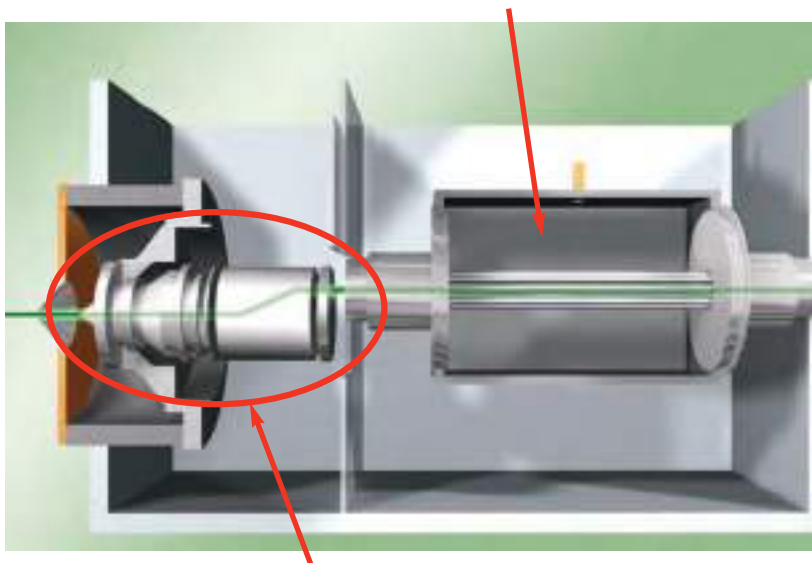
Agilent's ORS has revolutionized collision/reaction cell ICP-MS by bringing effective interference removal capability into the routine analytical lab. The ORS is easy to set up and use for routine trace analysis of complex, variable, and unknown sample matrices, without compromising the multi-element capability of ICP-MS. Analysts familiar with conventional (non-cell) ICP-MS will find the ORS is much simpler to operate.

Uniquely, the ORS removes interferences independently of the analyte (the same cell conditions remove interferences on multiple elements) and independently of the sample matrix (the same cell conditions remove multiple interferences on each element). This means that unknown samples can be analyzed, without requiring matrix-specific or

element-specific optimization, and without requiring any interference correction equations. And unlike other reaction cells, there are no cell scanning voltages to set up or optimize.

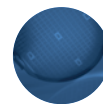
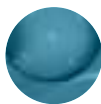
The ORS is standard on the 7500cx and 7500cs and available as an on-site upgrade for older non-cell models e.g. 7500a, 7500i. The 7500cx and 7500cs share the same ORS technology, but with different sample introduction systems, interfaces, and ion lenses. These differences address the different requirements of ultratrace analyte measurements in high-purity sample matrices, such as those analyzed in semiconductor labs (7500cs), and of trace and major analyte measurements in complex and variable sample matrices (7500cx).

High transmission octopole



Sample introduction, interface, and ion lens configuration are optimized for appropriate application

Schematic showing ORS featured in 7500cx and 7500cs models. Sample introduction system, interface, and ion lenses are different but are interchangeable between models. Off-axis ion lens can be removed for cleaning without breaking vacuum.



Any Analyte, Any Matrix

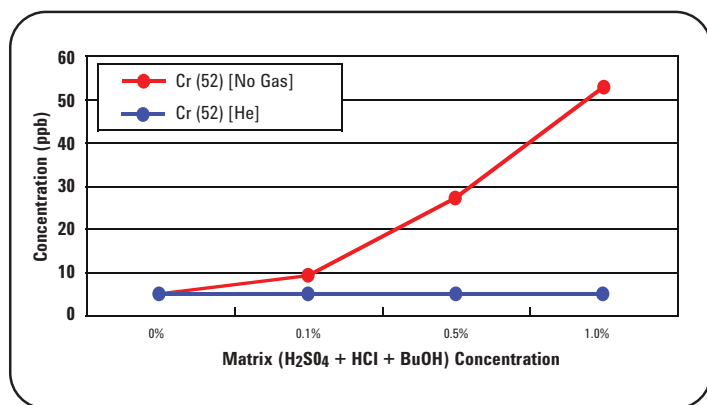
In complex and variable sample matrices, the ORS is typically operated in He (collision) mode, using pure He cell gas. This is a major advantage over the use of reactive or mixed cell gases: since He is inert, no new interferences are formed in the cell and no analytes are lost by reaction. The complete absence of new, cell-formed reaction product ions avoids the need for a dynamic, or scanning cell, which means that method setup is simplified and consistent operating conditions can be applied to multiple analytes and multiple sample types. If variable, high-matrix samples are analyzed on a cell system that uses highly reactive molecular gases, the sequential chemistry that is characteristic of these gases will generate many new interferences, the levels of which will vary depending on the levels of other analyte and matrix components present. This inevitably leads to errors in the results.

Screen Uncharacterized Samples with He Collision Mode

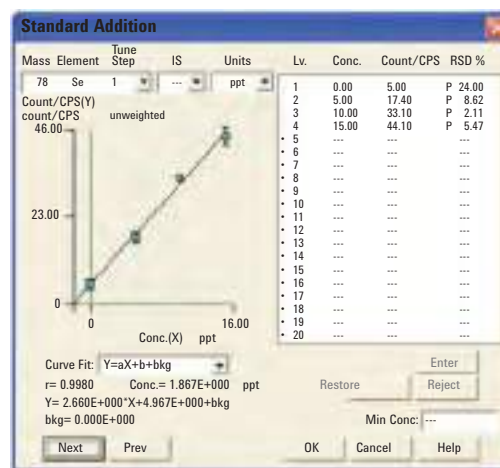
In He collision mode, interference removal is not matrix or interference-specific, which also makes He mode a very powerful screening tool, enabling interference-free semiquantitative analysis of unknown, high matrix samples. Freedom from matrix interferences means that semiquantitative data is much more accurate, even in unknown matrices. Interference correction equations are not needed, which in turn means that method setup is simpler and faster and that no analysis time is wasted performing daily checks and adjustments of correction equations.

High Efficiency Reaction Mode

In addition to the wide applicability of the He mode for complex sample matrices and multi-elemental analysis, a few elements have predictable, high intensity plasma-based interferences, which are more efficiently removed using reaction mode. These elements include Ca at its major isotope (m/z 40, which is overlapped by ^{40}Ar) and Se at m/z 78 and 80 (overlapped by Ar_2 polyatomic species). In these cases, H_2 is an ideal reaction gas, since it reacts quickly and efficiently with the Ar-based interfering species, but reacts slowly or not at all with the analyte. Thus, interferences can be reduced to the level of baseline noise, permitting single or sub-ng/L (ppt) detection limits to be achieved for these difficult elements. However, Ca and Se can be also measured at the ppt level in He mode, giving the analyst the option to measure all elements in a single gas mode, reducing analysis time.



Consistent interference reduction in a variable, complex matrix using He mode. Comparison plots showing no gas mode (red) and He mode (blue) spike recovery data for 5 ppb Cr in a variable matrix (up to 1% each of HCl, H_2SO_4 and Butanol). Potential interferences on ^{52}Cr include ArC , ClOH and SO . All are removed, regardless of reactivity, under a single set of conditions, allowing accurate quantification of Cr at the main isotope, despite the variable matrix composition.



Standard addition calibration of Se using H_2 reaction mode showing good linearity even at 5 ppt. BEC is 1.9 ppt Se. While He collision mode can also be used for trace Se, H_2 mode offers unmatched performance.

technology & design



Continuous Innovation in ICP-MS

Since the introduction of the highly successful 4500 Series in 1994, Agilent has been responsible for most of the innovation in ICP-MS design, including bench top format, Peltier-cooled spray chamber, cool plasma analysis with ShieldTorch, motorized ICP torch position with autotune, off-axis ion lens, ORS and GC interface.

All of these features come together in the new 7500 Series to deliver the most powerful range of ICP-MS instrumentation ever produced. And we continue to invest and innovate in ICP-MS, to keep our ICP-MS users ahead of their competitors.

1 Open Sample Introduction Area

- Easy access for maintenance and for switching between alternative sample introduction devices.
- High precision, 10 roller peristaltic pump – mounted close to the nebulizer to minimize sample uptake and washout time.

2 Spray Chamber Temperature Control

- Peltier controlled spray chamber prevents drift due to lab temperature change and reduces oxide formation. Compatible with both quartz and inert spray chambers.
- Enables routine analysis of volatile organic sample types, without requiring an additional mini-chiller.

3 Robust Plasma

- Maintenance-free, solid state RF generator. Unique digital-drive for highest coupling efficiency.
- 27.12MHz RF produces a more robust plasma for complete decomposition of sample matrix, giving low oxide and other matrix interferences.
- High precision, motorized, auto-alignment of ICP torch position with full autotune.

4 Agilent ShieldTorch System

- ShieldTorch System (STS) controls ion energies for increased sensitivity and improved interference removal in ORS collision mode, using energy discrimination.
- STS enables cool plasma mode for semiconductor applications, including high purity organic solvents.

5 Interface and Ion Lens

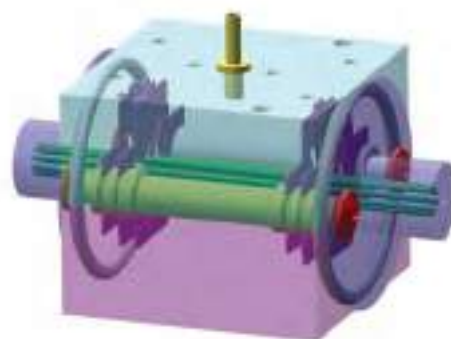
- Extraction lenses and off-axis ion lens system ensure high ion transmission across the entire mass range.
- Off-axis lens located before the gate valve in ORS systems: protects cell from contamination and can be cleaned without breaking vacuum.

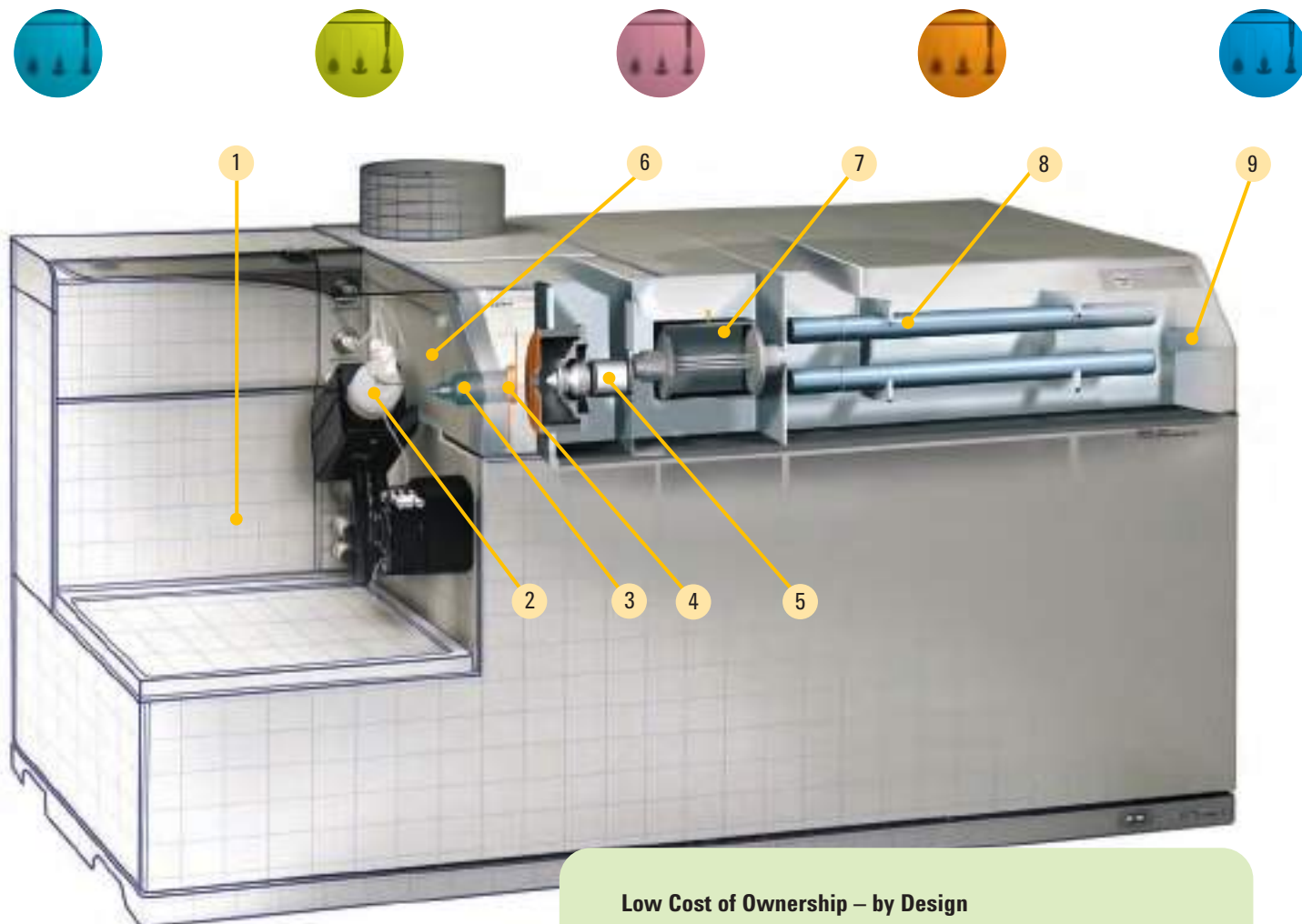
6 Active Mass Flow Control (AMFC)

- Agilent designed AMFC system precisely controls all standard gas flows (4 argon gas, and 2 cell gas flows in ORS systems) using sophisticated electronic pressure sensors.

7 Octopole Reaction System

- Collision/reaction cell for highly efficient removal of polyatomic interferences. Unique He collision mode for reliable analysis of unknown sample matrices. H₂ reaction mode for semiconductor applications and ultimate Se DLs.





8 Vacuum System and Analyzer

- High frequency 3MHz quadrupole with unique true hyperbolic cross section rods for superior abundance sensitivity and peak separation.
- Single split flow turbo pump backed by single rotary pump.

9 Advanced Detection System

- Simultaneous pulse/analog detector with fully automated calibration. High speed analog mode for transient signals.
- Unique log amplifier provides nine orders of dynamic range. Maximum measurable concentration >1000ppm.

Low Cost of Ownership – by Design

The 7500 Series has been designed for maximum reliability and uptime in routine use, even in the toughest lab environments. The extremely low failure rate allows us to price our support contracts equally low, and in combination with high uptime and high sample capacity, makes the 7500 Series the most profitable ICP-MS to own.

- Agilent ICP-MS are manufactured at ISO 9001 and ISO 14001 certified facilities.
- Extremely high build quality with all stainless steel chassis.
- Extensive shock, vibration, heat and humidity testing at production prototype stage - means optimum performance is guaranteed over a wide temperature/humidity range.
- Solid state RF generator is maintenance-free - no RF tubes to replace.
- Ion lens can be cleaned without breaking vacuum on ORS models.
- Predictive maintenance software ensures optimum performance.
- Advanced diagnostic tools enable easy fault finding, and modular design means fast fix times.

extending boundaries



Expanding Applications

Agilent has the widest range of sampling accessories to further enhance productivity and expand the applicability of the 7500 Series.

Agilent Integrated Autosampler (I-AS)

The I-AS is a fully integrated, covered autosampler for ultratrace analysis. Designed for semiconductor and other ultratrace applications and for when sample volume is limited. Maximum capacity 89 samples.

ASX-500 Series Autosampler

A high capacity autosampler suitable for high throughput labs. Maximum capacity 360 samples. Fully supported by Agilent.

Inert Sample Introduction Kit

The kit consists of an inert end cap, ultrapure polymer spray chamber and demountable HF resistant torch with sapphire or platinum injectors for minimum sample contamination.

Integrated Sample Introduction System (ISIS)

ISIS features two high precision pumps and up to two six-port switching valves, enabling constant flow nebulization, autodilution (with Intelligent Sequencing software), discrete sampling and matrix elimination. Hydride generation is also available.

GC-ICP-MS Interface

Programmable heated interface for GC-ICP-MS. Interface can be heated to 300 deg.C for high boiling point compounds. Unique torch design eliminates connections and avoids cold spots.

LC-ICP-MS Interface and Speciation Kit

All necessary tubing, connections and cables to enable fully automated LC-ICP-MS. Special ICP torch for organic mobile phases. Arsenic speciation kit – includes column and methodology to measure As species in urine.

Laser Ablation

Laser ablation ICP-MS is a widely used technique for the direct analysis of solid samples. The 7500 Series' excellent sensitivity, high speed simultaneous detector and 9 orders dynamic range makes it perfectly suited to laser ablation analysis.



Agilent Integrated Autosampler



Integrated Sample Introduction System



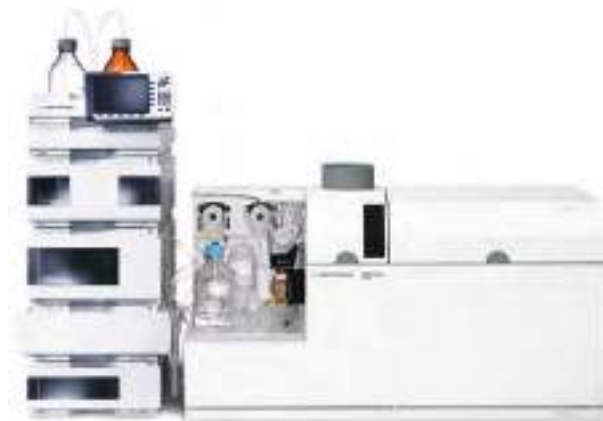
Laser ablation

Opening up the World of Elemental Speciation Measurement

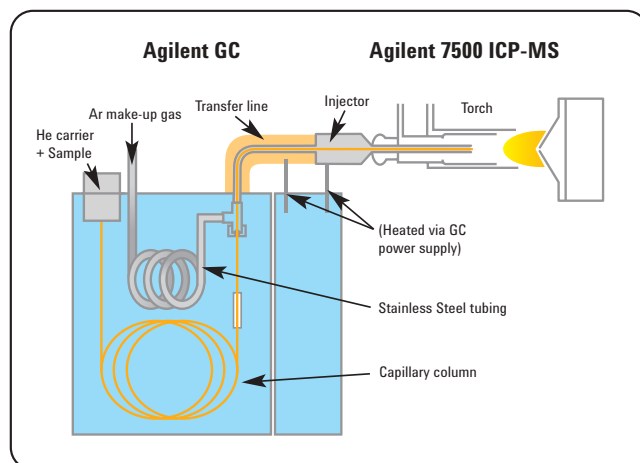
Combining Chromatography and ICP-MS for Elemental Speciation Analysis

In the environmental, biomedical, food, pharmaceutical, and petrochemical industries, it is becoming much more important to be able to determine not just the total amount of an element, but also its chemical form, since this can have a dramatic impact on the element's bioavailability, mobility, toxicity and other chemical properties. Combined with various chromatographic separation techniques, ICP-MS is now recognized as the most versatile and powerful tool for elemental speciation analysis.

As a leading supplier of GC, LC and CE as well as ICP-MS, Agilent is leading the way with routine hyphenated solutions and supporting the rapid growth in speciation measurement worldwide. Agilent developed the first commercial GC-ICP-MS interface in 2001, featuring a heated transfer line capable of handling high boiling point compounds. Also available is an LC-ICP-MS Connection Kit and complete analytical solutions such as the Arsenic in Urine Speciation Kit. Agilent's expertise in separation techniques ensures seamless installation and implementation of these hyphenated systems.



LC-ICP-MS combines the 1200 Series LC with the 7500 ICP-MS.



GC-ICP-MS system diagram



7500 ICP-MS with Agilent GC

productivity through automation



ICP-MS ChemStation Software – Intuitive. Flexible. Powerful.

The ChemStation software controls all instrument operations from setup and optimization to final reporting. The modern graphical user interface operating under Windows XP allows quick and intuitive operation. Context-sensitive help is always just a click away.



Top level layout is user configurable and includes all relevant programs from instrument control to data analysis



Flexible calibration plot and DL display and output

Simple Start-up

Prepare the 7500 for analysis simply by clicking the "ON" button – The sequence of plasma initiation events is fully automated and documented on screen.

Intelligent Automation

The Agilent 7500 Series provides full system control to ensure that optimum and consistent operating conditions are maintained. Sophisticated autotuning ensures consistent operation independent of operator expertise.

Easy Method Setup with Method Wizard

The Method Wizard guides inexperienced users through the process of creating a new method, providing regulatory compliant, preconfigured templates for common applications.

Flexible Data Acquisition

The 7500 Series can acquire data for a given sample in several gas modes. The software allows data from a single sample to be acquired automatically in multiple modes, with the results combined into a single report.

Data Processing and Reporting

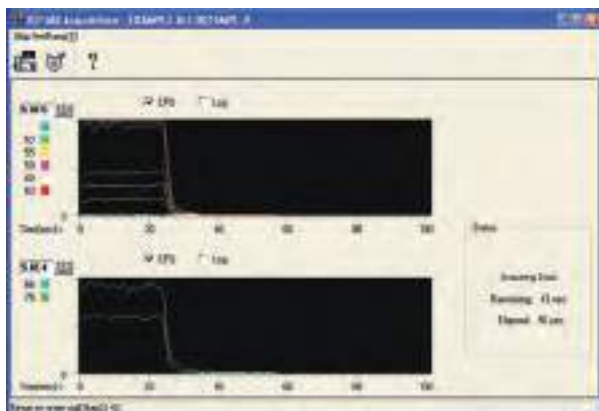
ChemStation allows complete flexibility for post-run data reprocessing, including the ability to change internal standards, curve fits, and even report formats. Virtual Internal Standardization allows the user to create a mass-interpolated internal standard. Flexible, open architecture and a powerful macro language allow connectivity to LIMS systems.

Intelligent Rinse Functions

Pre-emptive and Intelligent Rinse functions insure highest possible throughput and eliminate the risk of carryover from dirty samples. Pre-emptive rinse begins rinsing the autosampler probe and tubing prior to the end of acquisition using the sample remaining in the introduction system to complete data acquisition. Intelligent Rinse continuously monitors carryover and extends the rinse time only as needed.

Automatic Shutdown

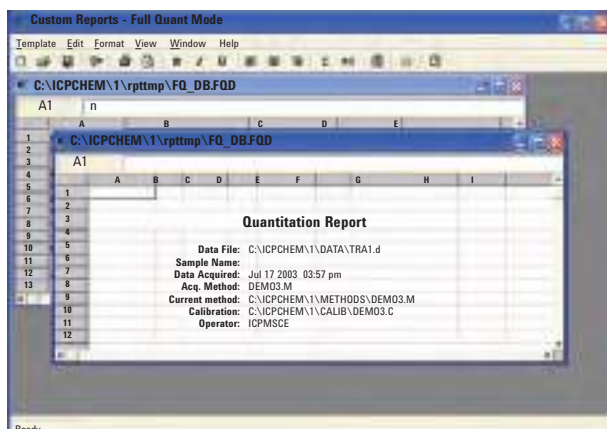
A series of built-in hardware and software interlocks continually monitor instrument parameters ensuring safe and intelligent unattended operation and fail-safe shutdown.



Intelligent Rinse and Pre-emptive rinse improve sample throughput



Method Wizard guides the user through setup of common applications with predefined templates



Custom reports templates are created by a simple drag-and-drop operation in a spreadsheet format

Optional Software

Optional software seamlessly integrates with the ChemStation to extend the capabilities of the Agilent 7500 ICP-MS to new applications and analytical requirements.

Intelligent Sequencing provides the ultimate in QA/QC software functionality. Intelligent Sequencing takes control of run-time quality assurance by evaluating data quality in real-time, comparing measured results against expected values and taking appropriate and flexible QC actions as a result. The software is delivered with a set of preconfigured templates that allow users to meet US EPA 200.8, 6020 and other internationally regulated requirements. It can be easily tailored to meet laboratory specific QA/QC requirements, allowing users to produce their own protocols by adding customized quality control samples and criteria.

Plasma Chromatographic Software seamlessly integrates chromatographic data analysis with ICP-MS sequencing detection creating a truly hyphenated system. It features powerful integration, calibration and quantification capabilities for handling chromatographic data. It enables the user to set up fully automated sample sequences for chromatography-ICP-MS runs with real-time data acquisition and analysis. Since it works in real time, Plasma Chromatographic Software can perform real time QC actions, such as recalibration of retention times, response factors and isotope ratios. Plasma Chromatographic software supports additional data file formats including Agilent GC/MS and industry standard AIA format and can export data in AIA and CSV formats allowing powerful integration of multiple techniques.

User Access Control Pack is optional security and log history software, designed primarily for laboratories needing to comply with strict regulatory standards. It provides configurable user access to various ChemStation functions and maintains a secure log of all user access.

Premier Service and Applications Support

The design, manufacturing and component-part standards of the 7500 Series are of the highest order, making our instruments extremely reliable and easy to use. But when you need support – with hardware, software or applications, a global network of factory-trained ICP-MS specialists is there to help you. Agilent provides the widest variety of support and training options to meet your requirements and to ensure you get the most from your ICP-MS.



Training

Familiarization training is provided at installation, along with comprehensive manuals and a **maintenance video DVD**. Agilent also offers training classes worldwide and onsite applications consulting for fast implementation. Our regular e-seminars on instrument operation are an efficient way to keep up to date.

Agilent ICP-MS Journal User Newsletter

The Agilent ICP-MS Journal is published 4 times per year and is a great source of information on ICP-MS. The Journal features technical articles, user contributed articles and information on instrument operation, support and upgrades.

Agilent ICP-MS Web site

Go to www.agilent.com/chem/icpms to find an array of ICP-MS services and the most comprehensive collection of literature and information – all freely downloadable, including:

- ICP-MS and other Agilent product information
- Agilent e-Seminars, user meetings and other events
- Application notes, posters, technical notes, back issues of the Agilent ICP-MS Journal, and other useful literature
- Extensive technical support tools

Register at:

www.agilent.com/chem/registration and select ICP-MS as your area of interest to receive e-mail notification of new additions to the ICP-MS website and upcoming events.

Agilent ICP-MS User Forum

Users of Agilent ICP-MS are encouraged to join the ICP-MS Forum – an on-line discussion group exclusively for Agilent users wishing to ask questions and share their experience and expertise in ICP-MS. Sign up at www.agilent.com/chem/icpms

For more information

For more information about the Agilent 7500 Series ICP-MS or other Agilent products and services, visit us online or call toll free:

www.agilent.com/chem/icpms

1-800-227-9770 (in the U.S. and Canada)

In other countries, please contact your local Agilent Representative or Agilent Authorized Distributor.

The 7500cx can not be used with hydrogen cell gas or hydrogen cell gas mixtures unless the optional hydrogen cell gas line is installed.

Agilent 7500 Series ICP-MS are manufactured at an ISO 9001 and ISO 14001 certified facility.

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Agilent Technologies

AAAnalyst 600/800 atomic absorption spectrometers



maximum **performance** from
the **leader** in inorganic analysis

maximum AA performance



Q U I C K G L A N C E

- High-efficiency optical system and solid-state detector provide outstanding signal-to-noise ratios
- THGA tube design eliminates most interferences
- Longitudinal Zeeman-effect correction for improved accuracy and detection levels
- Automated flame and furnace atomizer and alignment for optimized performance and day-to-day reproducibility

The high-performance line of AAnalyst™ atomic absorption (AA) spectrometers maximizes AA performance for even the most difficult samples. These systems generate superior results and provide faster, more accurate analyses. For over 40 years, PerkinElmer® has been the leader in inorganic analysis. With tens of thousands of AA spectrometers in operation worldwide, the PerkinElmer name is synonymous with performance, ease-of-use and reliability.

The AAnalyst 600 and 800 systems offer top-of-the-line technology and exceptional performance. The AAnalyst 600, a dedicated transversely-heated graphite atomizer (THGA) system, offers the best in graphite furnace. With Zeeman background correction, the AAnalyst 600 exceeds the requirements of today's laboratories, whether analyzing difficult samples or for achieving the lowest detection levels.

For laboratories that need the best in both flame and THGA furnace, the AAnalyst 800 provides a fully-integrated benchtop system with superior performance to meet all inorganic analysis needs. Switching between flame and furnace is as simple as a click of the mouse and includes automatic alignment for optimum performance. Other dual-system approaches not only require the purchase of two separate spectrometers, doubling the demand for bench space and the investment in lab facilities, but also require manual alignment.

The high-light-throughput optical system of the AAnalyst 600 and 800, combined with a solid-state detector, provides the highest quality efficiency and signal-to-noise performance of any AA system on the market. With the acclaimed WinLab32™ control software, the AAnalyst systems bring a new level of performance and ease-of-use to analysis and data reporting.

unprecedented **performance** for the **most demanding** applications

High-efficiency optical system for lowest detection limits

At the heart of these advanced AAnalyst systems is an exceptionally efficient optical system featuring a unique solid-state detector with a photoactive surface optimized to provide the highest quantum efficiency in the UV region. Combine our state-of-the-art detector with proven monochromator efficiency and spectrometer throughput, and even elements such as As and Ba can be measured with outstanding signal-to-noise ratios.

THGA furnace provides uniform temperature distribution

The patented THGA tube used in the AAnalyst systems provides a uniform temperature distribution along its entire length (Figure 1). This eliminates cooler temperatures at the tube ends and removes most interferences. With the THGA tube design, accuracy and sample throughput are improved by reducing the need for the time-consuming standard additions technique.

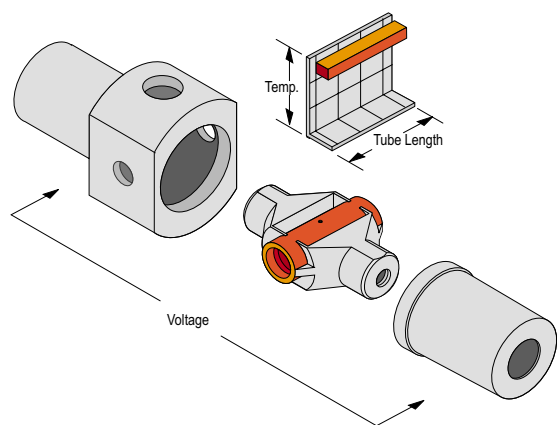


Figure 1. The THGA tube provides a uniform temperature profile.

Longitudinal Zeeman-effect background correction provides lowest detection limits

With longitudinal Zeeman-effect background correction, the amount of light throughput is doubled by eliminating the need for a polarizer in the optical system. All other commercial Zeeman designs incorporate inefficient polarizers that reduce light throughput and diminish performance. With this unique design, the AAnalyst systems provide the lowest detection levels available. To further improve detection levels and accuracy, the AAnalyst systems also include optimized sampling frequency and interpolated background correction.

Consistent temperature control enhances performance

In conventional furnace systems, the heating rate during atomization depends on the input-line voltage. As voltage varies from day to day, season to season or among laboratory locations, so does the heating rate. The AAnalyst high-performance systems use enhanced power control circuitry to maintain a uniform heating rate, so no matter where a system is located, you can be sure that it provides outstanding, consistent performance.

Safety first

Safety features are of foremost importance in any flame AA spectrometer. The AAnalyst flame systems include sensors and interlocks to ensure the utmost in safety. Operation is permitted only if all conditions are satisfied for totally safe operation. Flame ignition and switchover from air/acetylene to nitrous-oxide/acetylene are computer controlled and automatic. In the event of a power failure, the flame is extinguished safely and automatically.

Real-time continuous measurement for unmatched flame stability

The revolutionary double-beam design of the AAnalyst 800 provides continuous, simultaneous measurement of both sample and reference beams for flame measurement (Figure 2). Utilizing a high-efficiency fiber-optic cable, the sample and reference beams are simultaneously focused on the solid-state detector. This translates into increased signal-integration time (without increasing analysis time) for improved detection limits and reproducibility.

Burner system maximizes stability

The PerkinElmer premix burner chamber has been proven in thousands of laboratories worldwide. The corrosion-resistant, solid titanium burner head easily installs in the burner chamber, while a fail-safe mechanism ensures it is always properly restrained without the need for hold-down cables. An inert polymer spray chamber provides superior performance for corrosive and high-solids matrices. Manufactured from a high-strength composite, the spray chamber eliminates the need for pressure-relief devices. The high-precision nebulizer maximizes stability and sensitivity even for the toughest matrices. The nebulizer is adjustable so a wide variety of sample matrices – aqueous or organic, acids or bases, dilute or concentrated – can be analyzed under optimum conditions.

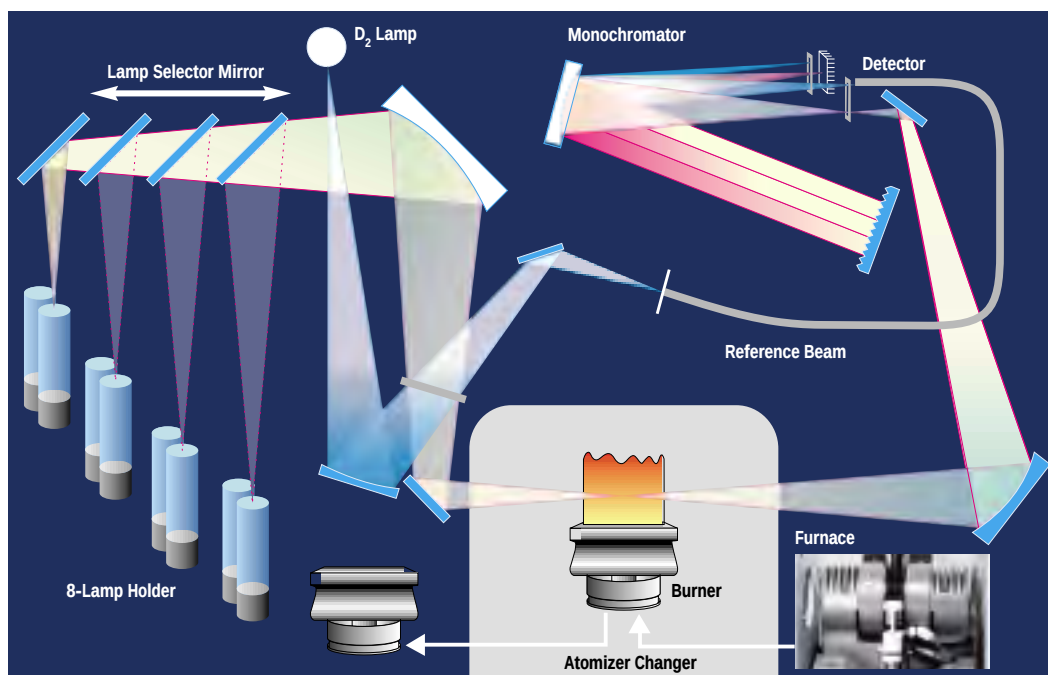


Figure 2. Revolutionary optical system for maximum performance.

easy to use for maximum productivity

The high-performance AAnalyst systems with automatic lamp selection and alignment make setup easier than was ever thought possible. High-capacity autosamplers along with WinLab32 software bring a new level of productivity to the laboratory.

Automatic lamp selection and alignment ensure proper installation

The systems include an eight-lamp mount with built-in power supplies for both hollow cathode lamps (HCLs) and electrodeless discharge lamps (EDLs) (Figure 3). EDLs provide much higher light output and longer lifetime when compared to conventional HCLs. The patented PerkinElmer cableless Lumina™ lamps ensure proper connection. Just slide them in – you cannot connect them incorrectly. The Lumina lamps are then recognized by the AAnalyst systems and the wavelength, slit and lamp parameters are automatically set and the lamps aligned.



Figure 3. Eight-lamp mount for maximum flexibility.

Switching between techniques has never been easier

A simple mouse click is all that is needed to change between flame and graphite furnace. Switching between flame and graphite furnace is computer controlled, ensuring each atomizer is returned to its previously determined optimum position. Only the high-performance AAnalyst systems offer fully automated alignment of both the flame and furnace for optimized performance and day-to-day reproducibility.

Automated optimization for maximum sensitivity

Sensitivity and accuracy in flame AA are directly correlated to the optimization of the burner position as well as the gas flows (Figure 4). Careful optimization of these parameters, which can be different for each element, maximizes sensitivity and can significantly reduce or eliminate interferences. The unique computer-controlled, motorized burner system and gas controls allow precise, automated adjustments. Since WinLab32 software allows optimized burner position and gas flows to be stored with an element method, each element in a sequential multielement run can be determined using its own optimized parameters.

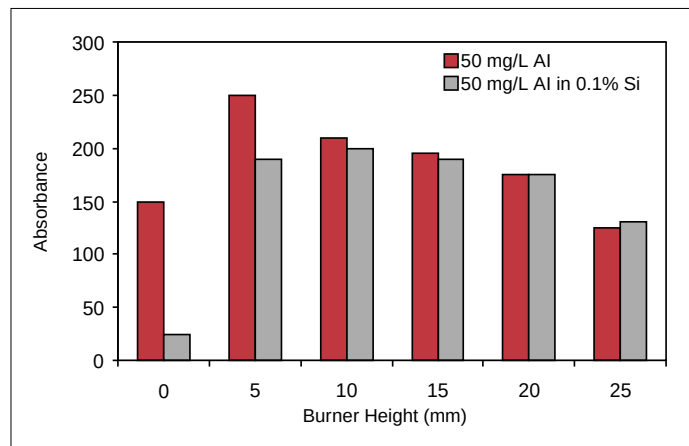


Figure 4. Optimizing burner height minimizes the interference of silicon on aluminum.

performance autosamplers exceed your flame and furnace needs

Furnace autosampler ensures high throughput

The AS-800 furnace autosampler can accommodate up to 148 samples with true random sampling (Figure 5). Digital micro-stepper, motor-driven pumps provide unmatched accuracy and reproducibility. The autosampler completely automates calibration, reducing operator time and eliminating dilution errors. The autosampler can be easily programmed to automatically add spikes and matrix modifiers, perform multiple injections and dilute over-range samples. Solutions can be automatically injected into preheated tubes to optimize drying conditions and increase analysis speeds. Additionally, the AS-800 autosampler offers variable pipetting speeds to maximize reproducibility for viscous solutions.



Figure 5. The AS-800 furnace autosampler easily swings into place.

Flame autosamplers offer exceptional sampling capacity

The AS-90*plus* or the AS-93*plus* flame autosamplers automate standard and sample introductions for instrument calibration and sample analysis, extending the capabilities of the AAnalyst 800 to those of a fully automated analytical workstation. Both PerkinElmer autosamplers come with a self-rinsing sampling probe and the flexibility to select from multiple tray configurations. An advanced drive system moves the sampling arm in the X and Y coordinates simultaneously, minimizing changeover time between samples (Figure 6).

Random access gives you exceptional flexibility in the placement of samples and reference solutions. Corrosion-resistant sampling components are made entirely of acid- and solvent-resistant materials, ensuring longer life. With the AS-93*plus* autosampler, a built-in peristaltic pump permits continuous rinsing of the sampling capillary between samples, significantly reducing the risk of carryover. In addition to the standard sample trays, the AS-93*plus* autosampler is compatible with trays from many 3rd-party suppliers, providing increased flexibility.



Figure 6. AS-93*plus* autosampler for fully automated analysis.

AutoPrep 50 automatic dilution system

The AutoPrep™ 50 system provides automatic, intelligent on-line dilution capabilities, eliminating the time-consuming manual tasks in flame AA analysis. The AutoPrep 50 also eliminates problems such as carryover and contamination. When used in conjunction with a PerkinElmer autosampler, the AutoPrep 50 provides fully-automated sample introduction.

STPF increases accuracy and productivity

More than 20 years ago, PerkinElmer pioneered the Stabilized Temperature Platform Furnace (STPF) technique to provide interference-free graphite furnace analyses. By eliminating the need for standard additions, STPF improves accuracy, precision and detection limits, while dramatically improving sample throughput. While some other instrumentation offers partial STPF implementation, the AAnalyst systems have fully implemented the technique, providing the best furnace performance.

enhance productivity

with WinLab32 software

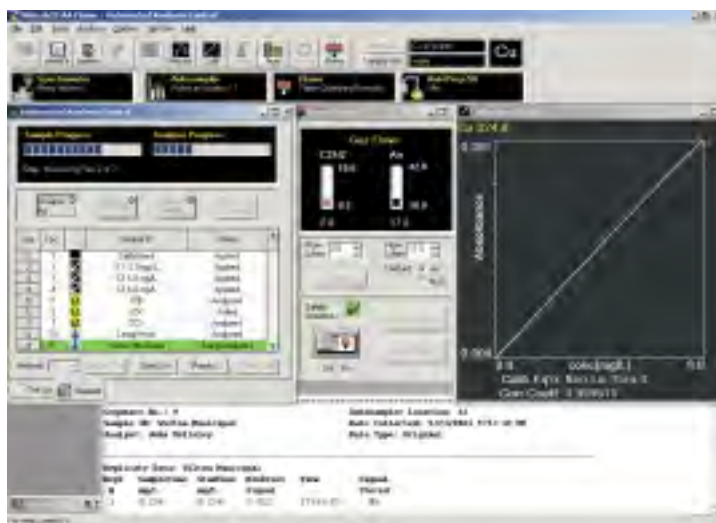


Figure 7. A suite of task-oriented windows can be displayed.

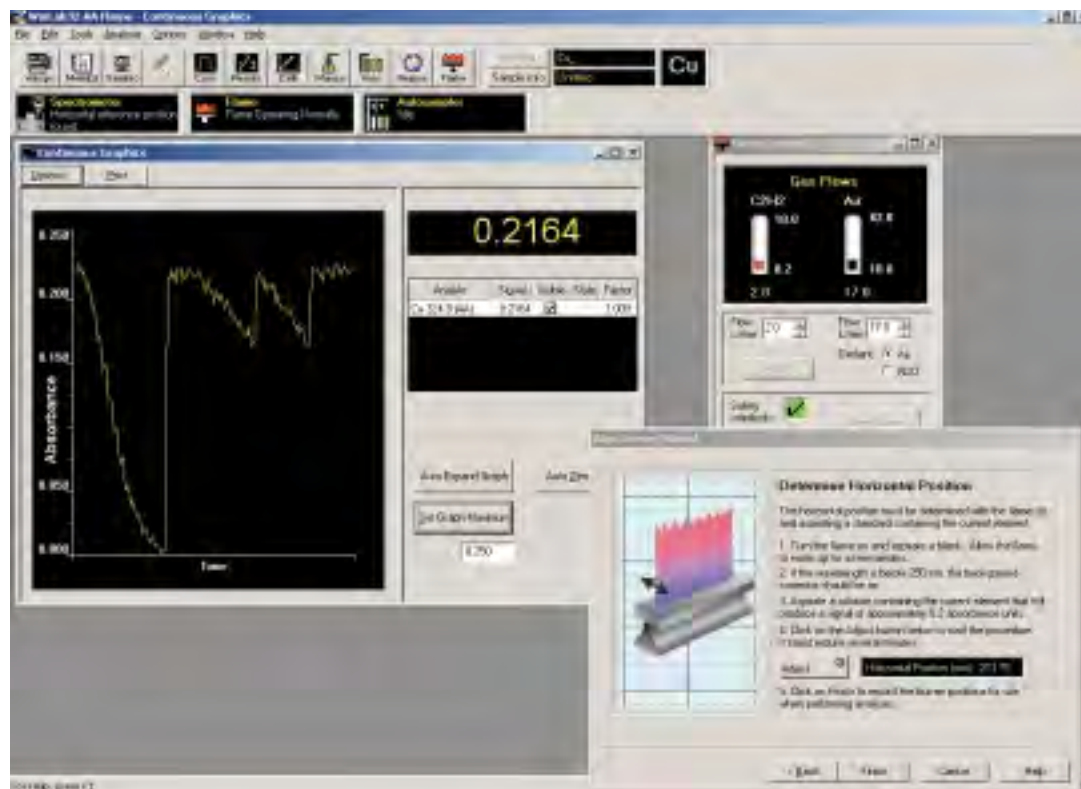


Figure 8. Wizards make complex tasks easy.

WinLab32 software combines ease-of-use and flexibility to bring a new level of productivity to your laboratory (Figure 7). Designed with extensive input from laboratory managers and AA users around the world, WinLab32 software provides all the tools and features needed to start running samples quickly and meet the requirements of today's laboratory.

Easy to learn and easy to use

The extensive Wizard features of WinLab32 make complex tasks easy with step-by-step instructions (Figure 8). Tool Tips, available in eight languages, provide additional information about screen text and entry fields. Status panels display the status of each instrument component for easy monitoring. The Analysis List combines standard, sample and method information into one list, showing the exact order in which the analysis will be run. This list also displays the analysis status at all times and can be printed as a summary at the end of the run.

Improved productivity

WinLab32 software improves laboratory productivity by reducing the time required for method development, sample analysis and report generation. Furnace method development is completely automated, helping to optimize the pyrolysis and atomization temperatures as well as sample and modifier volumes (Figure 9). You can create methods, review or reprocess data offline, even add samples anytime during an analysis, without interrupting the active analysis. Recall Calibration eliminates the need for initial calibration, while Edit Calibration gives you complete control over the quality of your calibration curve before you proceed with QC and sample analysis.

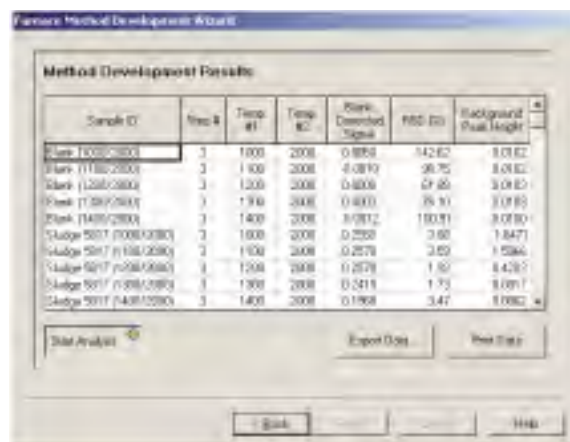
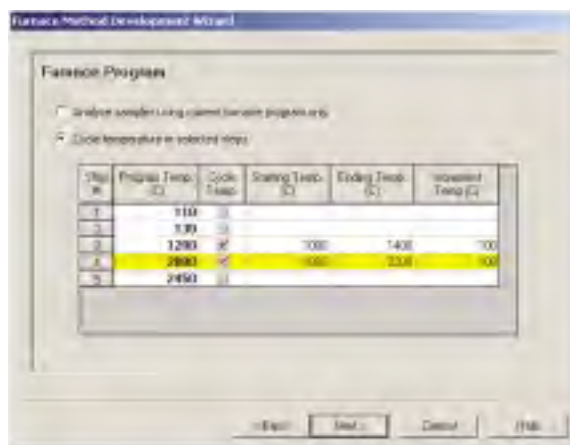
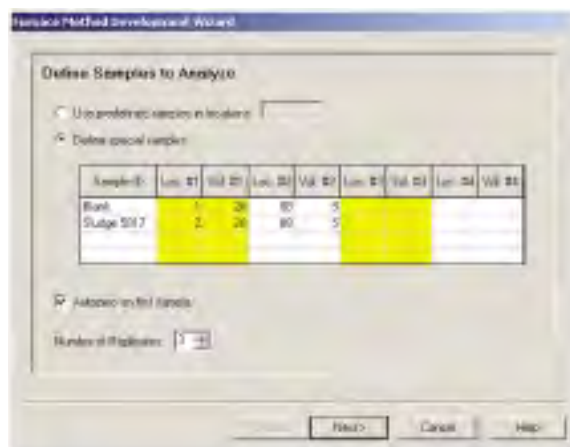


Figure 9. Method development is simplified using the Furnace Method Development wizard.

Easily work with data

Once you have performed an analysis, WinLab32 software makes it easy to work with your data in any way you wish. The Reporting Wizard in Data Manager allows you to report and save data in a variety of formats compatible with commercial word processing and spreadsheet formats, even HTML (Figure 10). The Export Wizard in Data Manager allows comma- or other character-delimited files to be created. You can also select and export data items describing the sample, mean values or replicate values from the Results Library. Peak profiles can be exported and read by most spreadsheet programs. Use a PerkinElmer LABWORKS™ LIMS system to create sample-information files from backlog lists or QA batches and to store results.

Meeting regulated laboratory requirements

Many laboratories must comply with a variety of regulations imposed by government agencies or quality protocols and WinLab32 software helps your laboratory meet these regulations.

Leveraging the powerful security features of the Microsoft® Windows® operating system, WinLab32 software provides the protection your laboratory needs. With WinLab32 software, the administrator can define groups and assign permission levels by establishing password-controlled access. Once an analysis is completed, a copy of the method is stored with the results and the software even “signs” its data during storage. The Data Manager’s Verify Signature feature ensures that any alteration is readily detected. Reprocessing doesn’t change the stored data, but rather new data is written to the database with an appropriate notation.

The optional Enhanced Security™ (ES) software adds additional capabilities needed for regulatory requirements such as 21 CFR Part 11. Some of the regulatory features include the following:

- A Master Event Log records all actions performed by the user
- Version numbers are added to all files and data sets
- Options are provided to prevent analysis without data storage



Figure 10. A suite of task-oriented windows can be displayed.

integrated solutions for a variety of applications

Based on over 40 years of experience in atomic spectroscopy, we understand your applications and also know the accessories required to meet your analytical needs. You can trust PerkinElmer, the leader in inorganic analysis, to provide you with the right tools for the job.

Mercury/hydride analysis systems for improved detection limits

The MHS-15 Mercury/Hydride System can adapt your AAnalyst system for high-sensitivity determinations of Hg and hydride-forming elements such as As and Se. The MHS-15 offers detection limits down to the ng range, while minimizing capital investment and operating costs.

An optional, automated flow-injection based mercury/hydride system can also be added to the AAnalyst systems. These Flow Injection Atomic Spectroscopy (FIAS) systems combine the advantages of mercury/hydride AA with those of flow injection, providing true automation and exceptional detection limits even for sequential multielement determinations (Figure 11).



Figure 11. FIAS-100 flow injection system with AS-91 autosampler for improved detection limits.

FIAS-furnace coupling combines the large sample-handling capability of a flow-injection system with the sensitivity of the graphite furnace. This provides detection limits that are two to three orders of magnitude lower than those obtainable with conventional graphite furnace for hydride-forming elements such as As and Se and for Hg. With flow injection or continuous-flow sampling, you can analyze milliliters of sample instead of the normal microliter volumes typical for graphite furnace AA. Since the matrix is completely removed, the analysis is simplified.

Microwave digestion system simplifies sample preparation

The Multiwave™ 3000 system is a versatile and powerful microwave sample preparation system that is easy to operate (Figure 12). Ideally suited for atomic spectroscopy techniques, the Multiwave simplifies sample preparation for all sample types, including foods, oils, plastics and environmental samples.



Figure 12. Multiwave 3000 for fast, easy sample preparation.

PerkinElmer, Inc.

Expect more from the leader in inorganic analysis

With over 40 years experience and a product line that includes flame AA systems, high-performance graphite furnace AA systems, flexible ICP-OES systems, and the most powerful ICP-MS systems, PerkinElmer is the undisputed leader in inorganic analysis. We have placed over 40,000 systems throughout the world, performing inorganic analyses every hour of every day. With the largest technical service and support staff in the industry and a solid reputation for quality products and service, the AAnalyst 600/800 high-performance atomic absorption spectrometers deliver the maximum in performance.

Whatever you're looking for, we've got it

PerkinElmer is a world leader in chemical analysis. Our analytical instrument technologies serve the fast-evolving pharmaceutical, chemical, environmental, forensics and semiconductor industries, providing integrated solutions – from sample handling and analysis to communication of test results.

As one of the best-known brands in research, analysis and testing, ours was probably the first analytical instrument you ever used. In addition to our AA systems, we offer a broad range of solutions in Luminescence, UV-Vis, NIR, GC, GC/MS, MALDI-TOF MS, HPLC, ICP-OES, ICP-MS, Thermal Analysis, Elemental Analysis, FTIR and LIMS. There are over 60 years of experience built into every product we make. So, for leading edge R&D and demanding QA/QC, you get the speed, accuracy and reliability you seek—for the productivity you need.

Our service and support people are located in 125 countries throughout the world and are factory trained. Compliance doesn't get any easier than with our software, including 21 CFR Part 11 technical compliance on many products. And convenient consumables and accessories ordering lets you get your hands on what you need fast.

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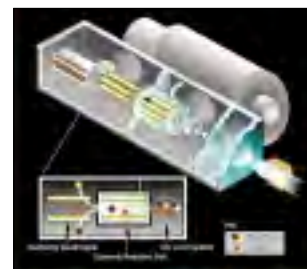
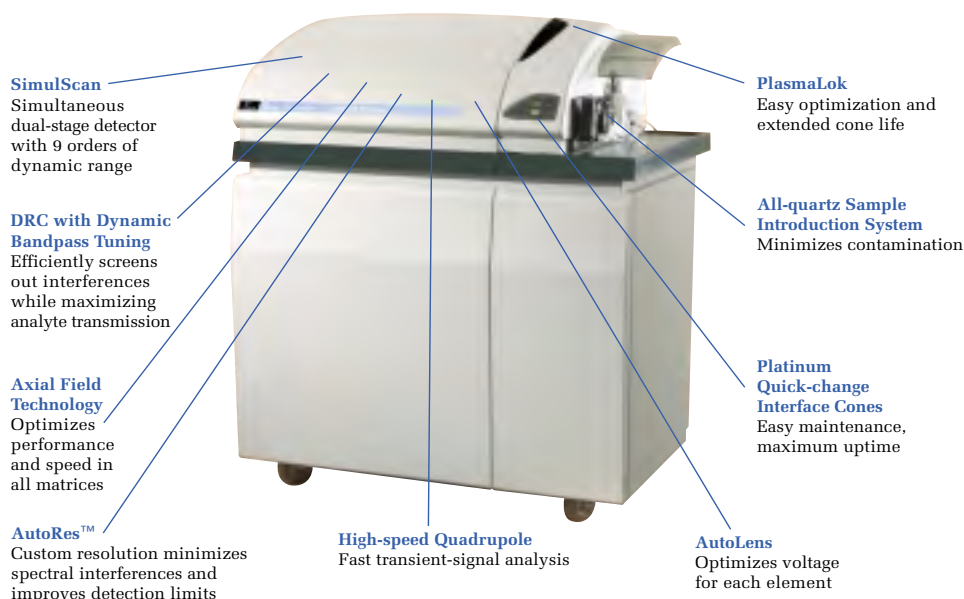
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ELAN DRC II



the **ultimate** in
ICP-MS **performance**

the **ultimate** tool for the world's most difficult **applications**



Dynamic Reaction Cell (DRC) with Axial Field Technology provides superior interference removal and performance for all applications.

When your applications extend beyond the capabilities of conventional ICP-MS or the ELAN® DRC-e systems, you need the power of the ELAN DRC II. The ELAN DRC II combines the power of patented Dynamic Reaction Cell™ (DRC) technology, performance-enhancing Axial Field™ Technology (AFT) and a high-performance sample introduction system with the ability to run any reaction gas. The result is the ultimate analytical tool, providing uncompromised sensitivity and performance in all matrices for the world's most difficult applications. Unlike collision-cell, high-resolution or cool-plasma systems, the ELAN DRC II completely eliminates polyatomic interferences, minimizing background equivalent concentrations, while maintaining analyte sensitivity, providing ultratrace-level detection limits in virtually any sample.

The ELAN DRC II uses chemical resolution to eliminate plasma-based polyatomic species **before** they reach the quadrupole mass spectrometer. This ion-molecule chemistry uses a gas to “chemically scrub” polyatomic or isobaric species from the ion beam before they enter the analyzer, resulting in improved detection limits for difficult elements such as Fe, Ca, K, Mg, As, Se, Cr, V and others.

Unlike other cell-based systems, patented DRC technology not only reduces the primary interference – it eliminates sequential side reactions before they can occur to create new interferences. Unless kept in check by DRC technology, these uncontrolled reactions increase spectral complexity and create unexpected interferences.

The lowest detection limits

The superior interference reduction and maximum analyte transmission provided by the ELAN DRC II produces excellent signal-to-background ratios. Background levels measured on-peak are typically less than 1 count per second – 50 to 150 times better than those reported by users of collision-cell based systems.

The ELAN DRC II does not use high-voltage ion-extraction lenses that can become contaminated. This results in lower on-peak background levels and more importantly, a lower background equivalent concentration (BEC) – the real measure of detectability. If the signal falls below the BEC, it is masked by the background. In situations where ultratrace measurements are made, the BEC actually limits the analysis, not the detection limit. Lower BECs mean that ultratrace levels can be accurately quantitated, not just detected.

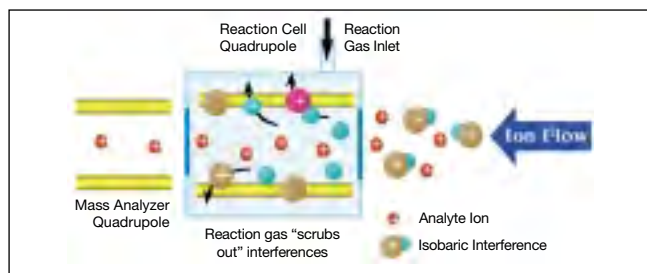
eliminates interferences for superior performance

How does the DRC work?

The DRC is located between the ion optics and the mass-analyzer quadrupole. It consists of a quadrupole placed inside an enclosed reaction chamber. This quadrupole eliminates polyatomic interferences caused by the combination of plasma gases and sample-matrix constituents before they can enter the analyzing quadrupole.

Gas inlets pressurize the reaction chamber with a low flow of reaction gas, such as ammonia, methane, oxygen or other gases and gas mixtures. The reaction gas is selected based on its predictable ability to undergo a gas-phase chemical reaction with the interfering species and remove the interference. Interference removal can occur through various processes, including collisional dissociation, electron transfer, proton transfer and oxidation. Analyte and interfering ions from the ICP enter the DRC. The reaction gas combines with the interfering ions, creating a non-interfering reaction product at a different mass. For extremely demanding applications, the DRC also provides the unique ability to carry out controlled reactions that can be used to predictably and reliably convert the analyte of interest to a different species, moving it away from the interference. No other system offers this level of predictable, controllable, reproducible or transferable chemistries, facilitating maximum interference removal in virtually any matrix.

Unlike collision-cell instruments, which pass all the reaction products into the analyzer quadrupole where they may cause interferences for other analytes, the DRC eliminates reaction by-products using the Dynamic



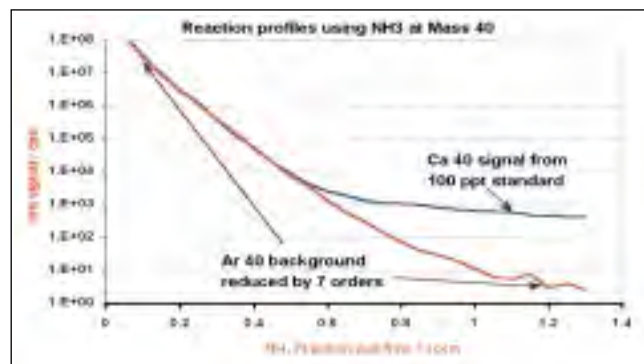
The Dynamic Reaction Cell chemically scrubs interfering species from the ion beam, using a reaction gas.

Bandpass Tuning (DBT) mechanism. The DBT function ejects the precursor ions **before** they can react to form new interferences – a real concern with complex sample matrices. The ELAN DRC II is able to eliminate interferences by up to 9 orders of magnitude, while retaining analyte sensitivity. This provides exceptional detection limits and the ability to use ICP-MS to determine more elements than previously thought possible.

Leaves cool plasma out in the cold

DRC technology always uses a high-temperature or “hot” plasma for analysis, eliminating the recognized drawbacks of cool- or warm-plasma approaches. Cooler-temperature plasmas have limited ability to ionize all but the most easily ionizable elements. As a result, cool plasmas also suffer from severe suppression of the analyte signal by matrix constituents and often require the use of standard additions calibration. This decreases sensitivity, degrades detection limits and restricts the number of interferences that can be removed.

Using the cool-plasma approach, elements which benefit from cool-plasma conditions must be run in a separate analysis from normal plasma elements, requiring each sample to be run twice. The ELAN DRC II can run all these elements in the same run, increasing productivity. And, the ELAN DRC II provides interference-free determination of elements that cold plasma cannot, such as Cr, V, As and Se.



The DRC can eliminate $^{40}\text{Ar}^+$ interference on $^{40}\text{Ca}^+$, as is shown by the reaction-gas optimization plot. The red line shows the reduction of the $^{40}\text{Ar}^+$ signal by over 7 orders of magnitude.

no limits performance for demanding applications

In addition to eliminating interferences in traditionally difficult-to-determine elements, the ELAN DRC II system has been specifically designed for the world's most difficult applications, including semiconductor analyses, providing unsurpassed levels of performance for ICP-MS.

The ELAN DRC II utilizes a low-background quartz sample introduction system that has been field-proven in hundreds of laboratories around the world, including semiconductor, clinical and research facilities. The quartz concentric nebulizer and cyclonic spray chamber maximize analyte transmission, while minimizing the possibility of background contamination, providing the lowest possible background signal levels. The open architecture design makes switching to different sample introduction devices quick and simple. The ELAN DRC II can utilize a variety of alternate sampling devices, including laser ablation, ultrasonic or low-flow nebulization systems or even liquid- or ion-chromatography systems for speciation analysis.

The unique single-ion lens simplifies operation with automatic optimization and specific on-the-fly mass settings for each element, minimizing undesirable space-charge effects that can lead to signal and performance loss. The ELAN DRC II has unsurpassed detection limits, specificity and sensitivity – all requirements for the laboratory pushing the limits of detection.

Axial Field Technology maximizes performance for all matrices

Innovative Axial Field Technology, developed specifically for ICP-MS, applies a linearly accelerating axial field to the ions inside the Dynamic Reaction Cell. This technology decreases matrix effects, improves stability and increases the speed of the DRC. This makes the ELAN DRC II the ultimate analytical tool for all applications including semiconductor, environmental, clinical and geochemical, where unsurpassed performance in challenging matrices is required.

Collisional focusing provides improved sensitivity and precision

The ELAN DRC II offers exceptional sensitivity and stability. Using collisional focusing (Figure 1), sensitivity can be enhanced by up to 5 times, when compared to a standard ICP-MS.

Collisions with the reaction gas allow ions to spend more time in the DRC, reducing short-term signal fluctuations. This lowers plasma noise, leading to improvements in short-term precision.

This excellent short-term precision dramatically improves isotope-ratio measurements performed on the ELAN DRC II. Relative standard deviations for isotope ratios of less than 0.03% are routinely achievable.

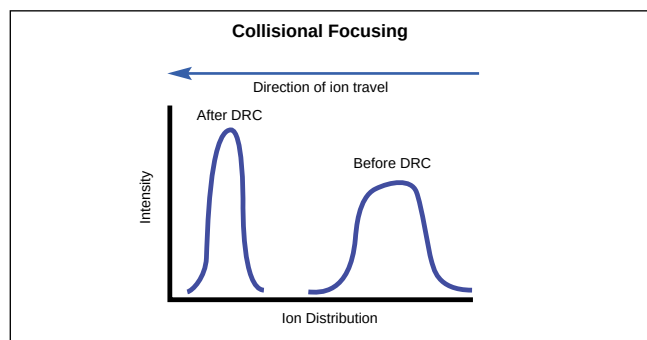


Figure 1. In the DRC, the ions collide with the reaction gas, causing them to lose energy and focus their motion on axis. This allows the ions to spend more time in the DRC, reducing short-term signal fluctuations. This collisional energy damping reduces the energy spread, while collisional focusing (migration of ions towards the quadrupole axis) results in improved ion transmission and sensitivity.

DRC gets the right answer, faster

Unlike “cool plasma” and high-resolution analyses where optimization of analytical conditions is done for each analyte and multiple runs are required to determine several analytes, the DRC II removes multiple interferences during the same analytical run. The ELAN DRC II significantly improves productivity by reducing the number of runs required. You can combine different sets of DRC conditions for different elements in the same analytical method along with conditions for elements run in standard mode, providing faster, more accurate results.

controlled, predictable chemistry maximizes interference removal

Dynamic Bandpass Tuning

Unlike other systems that use rf-only hexapoles and octapoles as simple ion guides, the quadrupole used in the patented DRC technology provides both high- and low-mass cutoffs – defining a precise mass bandpass window. The mass bandpass window ejects all ions with masses outside the window **before** they can react inside the DRC, **preventing** the formation of new interferences. The bandpass window is selected via the automated setup procedures based on the specific chemistry that needs suppression or promotion. And, since a specific bandpass range can be selected for each analyte, the bandpass filter can be dynamically tuned to best suit the analyte of interest. As a result, species falling outside of the analytical bandpass are completely eliminated, preventing the formation of new species and possible interferences (Figure 2).

In contrast, competitive systems use energy filtering, which only allows new interferences to be reduced **after** they are formed. This restricts interference removal, since the number of collisions in other systems must be limited in order to maintain a sufficient kinetic-energy spread between the analyte and interfering species for the filter to be effective. And, since energy filtering is non-selective, both interferent and analyte intensities are reduced.

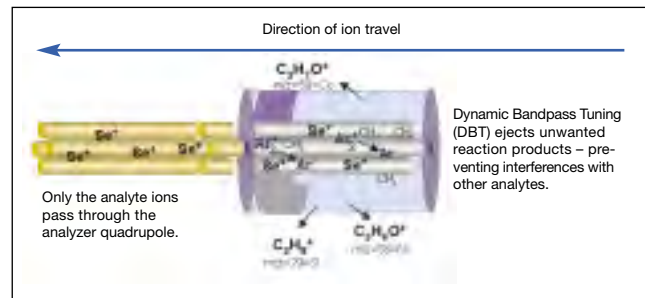
DBT optimizes chemical specificity

Differentiation between the analyte and an interfering species is critical to success in ICP-MS. The ELAN DRC II provides greater accuracy by eliminating false positives due to interferences. The presence of an isobaric or molecular interference can lead to an elevated signal at the analyte mass. For example, ArCl^+ and CaCl^+ are two molecular species that interfere with arsenic determinations at mass 75. In some cases, these interferences are extremely difficult to resolve, either because the analyte is monoisotopic (such as in the case of arsenic) or the interference is too large.

While other cell systems can partially remove some plasma-based interferences such as the ArCl^+ interference on $^{75}\text{As}^+$, they are limited in their ability to remove

many matrix-based interferences, such as the CaO^+ interference on $^{75}\text{As}^+$. In contrast, the ELAN DRC II allows the interference to be removed, whether plasma- or matrix-based, giving you confidence that the correct results for the analyte – and not a matrix interference – are reported. Using the ELAN DRC II, molecular interferences that have plagued trace-level determination of many elements by ICP-MS can be completely eliminated. Also, the superior specificity achieved with the ELAN DRC II through the use of Dynamic Bandpass Tuning (DBT) means reaction by-products are eliminated, **preventing** new interferences from forming. Left unchecked in all other systems, these by-products produce new interferences, which must be reduced by increasing the kinetic-energy filter – leading to additional analyte signal loss.

Method development on the ELAN DRC II using the powerful ELAN software is now easier than ever. Use one of our predeveloped methods and you will be up and running quickly. For more unique applications, automated procedures determine the best reaction-gas flow conditions and DBT settings, making the system easy to use. Unlike other cell instruments, where reaction-gas selection must be restricted in order to reduce formation of reaction by-products, the ELAN DRC II allows you to use virtually any reaction gas for interference removal. The ability to use more reactive gases including NH_3 , CH_3F , CH_4 , CO_2 , O_2 and others provides superior interference reduction and improved detection limits in a wide variety of sample types.



proven technology and innovative design

Not only does the ELAN DRC II include the industry's most effective method of eliminating interferences – it features a wealth of proven capabilities that make it superior to other ICP-MS systems.

- **Quick-change cones** – The platinum interface cones have large diameter orifices (1.1 mm sampler and 0.9 mm skimmer) to resist clogging and signal drift. The easy-in, easy-out design makes routine maintenance simple and easy.
- **Patented PlasmaLok technology** – Secondary discharges between the ICP torch and the interface cones can lead to signal drift and high background levels. PlasmaLok® technology essentially eliminates the possibility of secondary discharges, extending cone life, reducing background signal levels and stabilizing ion-energy distributions. As a result, switching between plasma conditions and sample matrices, including aqueous, organic and dry aerosols, is virtually transparent, with no special optimization required or consumable parts to replace.
- **Simple, effective Shadow Stop technology** – The ion optics in the ELAN were designed specifically for ICP-MS. Instead of bending the ion beam numerous times using complex multi-component lens systems to prevent uncharged species from entering the quadrupole, the ELAN DRC II uses a simple, grounded Shadow Stop. The result is minimal maintenance and the elimination of tedious ion-tuning adjustments required by other systems as lens components and cells become contaminated, causing resistivity changes and requiring subsequent tuning changes. Since it is grounded, the Shadow Stop never needs to be optimized or cleaned to maintain its performance.
- **The industry's only single ion lens** – Designed specifically for ICP-MS, the unique SwiftMount™ single ion lens used on the ELAN systems provides worry-free operation. Protected by the Shadow Stop, cleaning requirements for the SwiftMount lens are also minimized. In contrast, complex competitive

systems may have as many as 30 to 40 pieces in the ion-optic system – making them time-consuming to clean and reassemble. Unlike these competitive systems, changing the exclusive SwiftMount ion lens on the ELAN ICP-MS is as easy as changing a light bulb. In fact, the process takes just a few minutes. And, since the SwiftMount lens is so economical, when it does need to be cleaned you can simply swap the dirty lens for a spare and clean the dirty lens while your samples are being processed. This maximizes system productivity – an important requirement in high-throughput labs.

- **The industry's only scanning, single ion lens with AutoLens™ one-touch adjustment** – Not only does it optimize itself at the click of a button, the unique SwiftMount single ion lens optimizes automatically for each specific mass – providing the best possible sensitivity for each analyte, at all times. In contrast, competitive systems must be tuned on a single mid-mass element, compromising analyte sensitivity and require frequent tuning as ion-lens settings change over time.

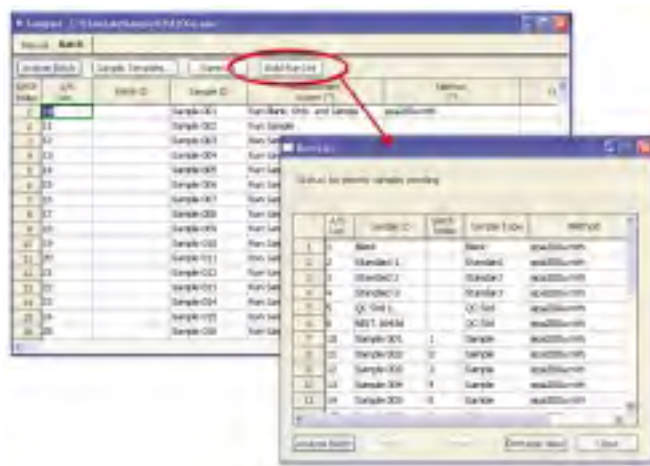


Figure 3. The new Build Run List feature will automatically build an exact listing of all your standards, quality-control checks and samples before you start your automated analysis – eliminating unexpected sample-run orders and errors.

superior productivity and reliability

- **Integrated peristaltic pump with tubing saver** – The sample introduction system uses an integrated peristaltic pump to dramatically reduce sample-uptake time. The tubing-saver feature ensures optimum measurement precision and prolongs peristaltic tube lifetimes.
- **Simultaneous dual detector** – The SimulScan™ dual-stage detector measures both high- and low-level analytes simultaneously. This conserves valuable or limited samples, eliminates the need to perform time-consuming sample dilutions and allows you to quickly analyze uncharacterized samples.



Figure 4. PathFinder HTML-based Help will guide you step-by-step through instrument setup, optimization, method development and sample analysis.

- **Powerful ELAN software** – Whether your lab performs qualitative, semi-quantitative, quantitative or specialized analyses such as isotope-ratio, isotope-dilution or even speciation analyses, the powerful ELAN software has all the features you need.

Priority samples, flexible quality-control checks, transient-signal handling, speciation analysis, run-list build and customizable reporting are just a few of the features that will make your life easier (Figure 3). Plus, integrated maintenance videos and our new PathFinder™ HTML-based Help will make routine tasks even easier (Figure 4). And, if you're in a highly regulated environment, our Enhanced Security™ software provides all the features you need to comply, even with 21 CFR Part 11 requirements.

- **The SmartTune™ software wizard** automatically sets up all your tuning procedures, runs them in the sequence you select and prints out a final tuning report based on user-selected pass/fail criteria (Figure 5). The result is effortless operation, all day, every day.

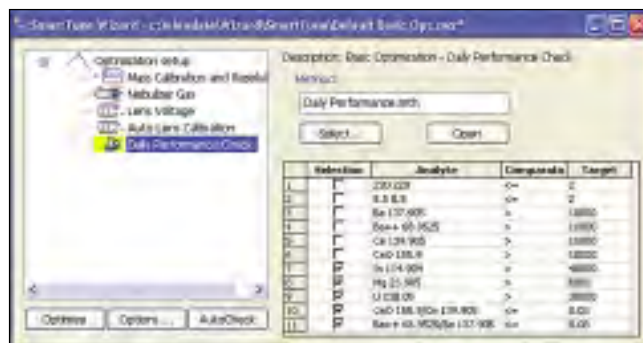


Figure 5. The SmartTune optimization wizard sets up user-defined optimization and performance-check procedures, automatically running them while you perform other tasks – maximizing your productivity.

the **power** you need for the most **challenging** applications

Unrivalled DRC technology has provided hundreds of the world's best laboratories with significant improvements in their ability to perform a wide variety of challenging applications by ICP-MS. Whether using a single gas for maximum productivity or using specific, selected gases for unsurpassed interference removal, the ELAN DRC II provides the performance and flexibility for your needs today – and tomorrow.

Interference removal provides superior detection capabilities

Many elements suffer from common matrix-based interferences that can degrade BECs and detection capabilities. The ELAN DRC II can dramatically reduce or eliminate these interferences, providing enhanced analytical capabilities.

The ground-breaking DRC technology has already provided hundreds of users with significant improvements in their ability to perform a wide variety of applications.

Breaking the ppq barrier

Fe, Ca and K are three of the most critical elements in the manufacture of semiconductor devices. Unfortunately, detection limits for these elements are degraded by interferences from ArO^+ , Ar^+ and ArH^+ species. The ELAN DRC II completely eliminates these interfering species and others, allowing accurate determinations at ppq levels (Table 1).

Unlocking selenium

Prior to the development of DRC technology, interferences from the Ar_2^+ dimer severely diminished the detection power of ICP-MS for selenium. Due to this large interference, selenium had to be determined at the less abundant ^{77}Se and ^{82}Se isotopes. The ELAN DRC II unlocks selenium, allowing ppt detection with an accurate isotopic signature, using the most abundant selenium isotope ^{80}Se (Figure 6).

Table 1. Typical detection limits (DLs) and background equivalent concentrations (BECs) on ELAN DRC II.

Element	DL	BEC	Element	DL	BEC
Li (7)	0.26	0.22	Ge (74)	0.58	0.57
Be (9)	1.00	0.87	As (75)	0.48	1.60
B (11)	1.93	1.50	Sr (88)	0.03	0.02
Na (23)	0.14	0.22	Zr (90)	0.05	0.04
Mg (24)	0.08	0.18	Mo (98)	0.11	0.12
Al (27)	0.05	0.09	Ag (107)	0.09	0.10
K (39)	0.27	2.60	Cd (114)	0.08	0.11
Ca (40)	0.10	0.10	In (115)	0.03	0.02
Ti (48)	0.92	1.70	Sn (120)	0.12	0.08
V (51)	0.12	0.04	Sb (121)	0.08	0.08
Cr (52)	0.12	0.12	Ba (138)	0.06	0.04
Mn (55)	0.17	0.54	Ta (181)	0.06	0.05
Fe (56)	0.12	0.40	W (184)	0.07	0.07
Ni (60)	0.10	0.20	Au (197)	0.15	0.05
Co (59)	0.04	0.04	Tl (205)	0.02	0.01
Cu (63)	0.05	0.10	Pb (208)	0.07	0.09
Zn (64)	0.45	1.20	Bi (209)	0.02	0.01
Ga (69)	0.06	0.05	U (238)	0.02	0.01

* Unit: ppt Integration time: 1 sec. ■ DRC mode

Note: Data obtained on the ELAN DRC II for a 1% nitric-acid matrix. All units are in ng/L (ppt). Elements in blue were obtained in DRC-mode using NH_3 reaction gas. Elements in black were obtained in standard mode. All data obtained in Class-100 clean room using 1-second integration times.

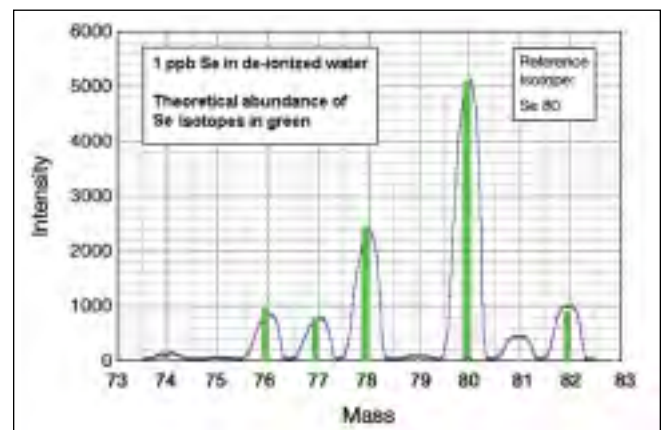


Figure 6. DRC allows determination of Se at mass 80. The green bars show the theoretical isotopic abundance fingerprint for selenium.

Simultaneous speciation of As, Se and Cr in natural waters

Speciation is an important environmental application, particularly the determination of arsenic and chromium species. Unfortunately, a spectral peak from ArCl^+ interferes with arsenic while a ArC^+ peak interferes with the determination of chromium. Selenium is also affected by the large Ar_2^+ background. While conventional interelement correction equations can be used, detection limits are compromised. In the ELAN DRC II, oxygen reaction gas can be used to move arsenic away from the interference (as $^{75}\text{As}^{16}\text{O}$) under robust hot-plasma conditions, allowing simultaneous detection of low ppt levels of As, Se and Cr species being separated in the same chromatographic run (Figure 7).

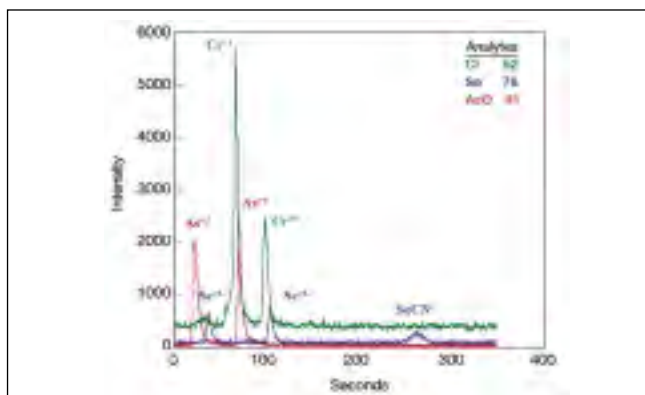


Figure 7. Utilizing the ELAN DRC II, an oxygen reaction gas can be used to move As away from the interference under robust hot-plasma conditions, allowing simultaneous detection of low ppt levels of As, Se and Cr species being separated in the same chromatographic run via HPLC/ICP-MS.

Separation of ^{87}Sr and ^{87}Rb – fast geochronology

The use of the ELAN DRC II permits fast Rb/Sr geochronology. By using CH_3F as a reaction gas to convert Sr^+ ions into the corresponding SrF^+ ions, the problem of isobaric overlap of $^{87}\text{Sr}^+$ and $^{87}\text{Rb}^+$ can be circumvented, a feat unachievable by high-resolution ICP-MS. Hence, chemical separation of Sr from Rb prior to analysis is no longer necessary and the amount of sample pre-treatment required is substantially reduced – dissolution and appropriate dilution only. By mixing the

reaction gas CH_3F with Ne as a collision gas, the isotope-ratio accuracy and precision attainable are comparable to or even slightly better than the best values ever reported for single-collector ICP-MS instrumentation.

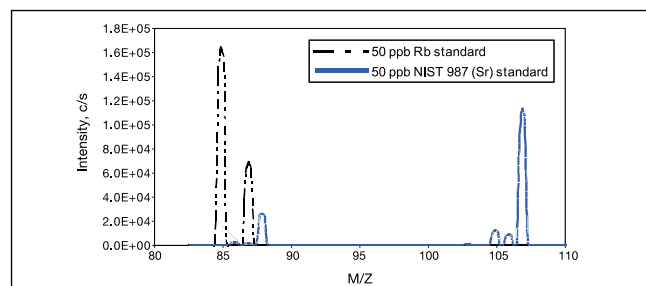


Figure 8. Mass spectrum observed for a standard solution containing equal amounts of Rb (signals indicated in black dashed-dotted line) and Sr (signals indicated in blue solid line) when using CH_3F as a reaction gas (0.6 mL/min) and Ne as a collision gas (1.5 mL/min). From “Chemical Resolution of $^{82}\text{Rb}^+ / ^{87}\text{Sr}^+$ Isobaric Overlap Fast Rb/Sr Geochronology by Means of DRC ICP-MS” – Application Note D-6538, PerkinElmer, Inc. 2001.

The ultimate challenge – seawater

The determination of trace metals in seawater is a difficult application. The high matrix concentrations present in seawater cause many interferences for elements such as As, Se, Ni and Cr. The ELAN DRC II takes the difficulty out of seawater analysis by removing these troublesome interferences, allowing parts-per-billion and parts-per-trillion level determinations.

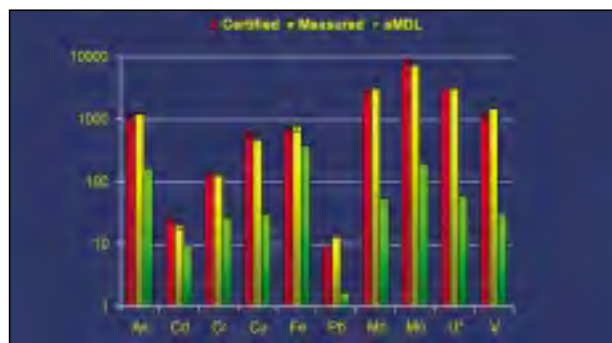


Figure 9. Results obtained for CASS-4 (Near-shore reference seawater sample from Canadian Research Council (CRC), Ottawa, Canada) using ELAN DRC II to reduce interferences. Estimated calculated detection limits in the matrix are given by e-MDL. Results obtained courtesy of Frontier Geosciences, Seattle, WA, USA.

DRC – a totally **unique** approach

Dynamic Reaction Cell technology coupled with Dynamic Bandpass Tuning and Axial Field Technology provides the latest innovation in ICP-MS.

The ELAN DRC II brings you:

- **Superior interference reduction** – The ELAN DRC II provides the highest level of interference reduction possible using any reaction gas, up to 9 orders of magnitude – one million times better than other cell-based systems. And, the ELAN DRC II maintains analyte-signal levels, unlike other systems.
- **Greater selectivity** – Dynamic Bandpass Tuning allows the ELAN DRC II to completely control the chemistry occurring inside the cell, resulting in greater selectivity and maximum interference rejection.
- **Increased sensitivity** – Collision cells use a simple energy filter to attempt to stop new interferences from reaching the detector **after** they are formed. This passive technique also reduces analyte transmission and allows many interferences to still be detected. The ELAN DRC II uses the active mass-filtering quadrupole inside the DRC to remove any precursor species that could form new interferences **before** reaction can occur. The result is superior interference rejection with full analyte transmission, resulting in higher analyte sensitivities.
- **Uncompromising performance** – Innovative Axial Field Technology ensures maximum transfer of the ions from the DRC to the detector, while reducing scan times in difficult matrices. As a result, the ELAN DRC II provides unmatched ruggedness, reliability and performance for all applications, including multi-element determinations in environmental, clinical, geological and semiconductor matrices.
- **No reaction by-products** – The ELAN DRC II not only reduces primary interferences – it eliminates sequential side reactions that create new interferences **before** they can occur. Only a system with an active mass bandpass filter inside the reaction cell can control the cell chemistry to this extent. Other systems attempt to limit side reactions by restricting the types of reaction gases used and by using a simple kinetic-energy filter to eliminate by-products. This results in compromised performance and uncontrolled reaction chemistries – requiring the use of tedious standards addition calibration procedures.
- **Proven quadrupole design** – Other systems use hexapoles and octapoles inside a low-pressure enclosed cell. Due to the complex nature of the mass-stability characteristics of these devices, these higher-order multipoles are only suitable for use as ion guides. In contrast, the quadrupole used in the ELAN DRC II provides a well-defined mass bandpass, resulting in superior selectivity through its unique mass-filtering DBT function.
- **Use of multiple gases** – Different matrices may require different gases to optimize interference removal. Some analyses even require multiple gases on the same run to achieve uncompromised detection limits. Since collision cells don't have Dynamic Bandpass Tuning, they must restrict operation to only one or two simple gases and may require specialized calibration techniques. The DBT function of the ELAN DRC II allows the use of a variety of reaction gases, providing a wide range of solutions for demanding applications. In addition, computer control allows automatic switching of reaction gases during analysis and provides complete control of any make-up gases used.
- **High-performance all-quartz sample introduction system** – The all-quartz sample introduction system used on the ELAN DRC II has been purposely designed to minimize background contamination levels, resulting in the lowest possible BECs. Combined with platinum interface cones, the system provides ultimate sensitivity and detection capabilities, in addition to being easy to use. The open architecture allows quick change-over if other sample introduction systems are used.

Why is the DRC better than high resolution?

For many years, high-resolution ICP-MS was the only option to resolving some interference problems.

The ELAN DRC II provides a superior alternative:

- DRC technology eliminates interferences, including $^{40}\text{Ar}^+$ from $^{40}\text{Ca}^+$, $^{87}\text{Rb}^+$ from $^{87}\text{Sr}^+$ and $^{40}\text{Ar}^{40}\text{Ar}^+$ from $^{80}\text{Se}^+$ that high-resolution ICP-MS cannot remove, because the required resolution is too great or the resulting analyte signal is too small.
- Unlike other cell-based and high-resolution systems, the DBT function used in the DRC system eliminates interferences without compromising sensitivity.
- The ELAN DRC II has 10 times better abundance sensitivity than high-resolution ICP-MS, providing the ability to measure small analyte signals next to large matrix peaks without peak overlap.
- The ELAN DRC II is less expensive and easier to operate than high-resolution systems that offer a fraction of the performance.
- Automated method development makes the ELAN DRC II easy to use, while its design provides a rugged, workhorse instrument for your lab.

The undisputed leader in ICP-MS

For over 20 years, PerkinElmer and SCIEX have partnered to develop and distribute the most innovative and powerful ICP-MS systems. There are over 2000 ELAN ICP-MS systems and over 600 ELAN DRC systems installed in industries ranging from environmental and clinical to semiconductor, geochemical and metallurgical, making PerkinElmer SCIEX™ the industry leader in ICP-MS.

PerkinElmer SCIEX also leads the industry in innovations and improvements. Technology has evolved from standard ICP-MS to cold plasma to collision cells and now to the Dynamic Reaction Cell technology used in the ELAN DRC II. At each step in the technology development cycle, interference removal has improved, allowing the use of ICP-MS for more elements than previously imaginable.

A history of innovation by PerkinElmer SCIEX

1983 – SCIEX introduces first commercial ICP-MS

1986 – PerkinElmer SCIEX joint venture established

1990 – PerkinElmer SCIEX shows first ICP-MS with turbomolecular pumps

1994 – PerkinElmer SCIEX introduces ELAN 6000

- First ICP-MS with simultaneous extended dynamic-range detector
- First ICP-MS with single, scanning lens optimized for ICP-MS
- Improved signal-to-noise ratios through single-point peak-hopping

1999 – PerkinElmer SCIEX introduces ELAN 6100

- 5th-generation ICP-MS with quick-change lens design
- Stable torch mount eliminates the need for XYZ adjustment

1999 – PerkinElmer SCIEX introduces DRC technology

- First system with automated DRC optimization and Dynamic Bandpass Tuning
- Pittcon Editors' Award – Gold medal

2001 – PerkinElmer SCIEX introduces the ELAN DRC^{Plus}

- 2nd-generation DRC instrument with Axial Field Technology for optimal performance in all matrices

2002 – PerkinElmer SCIEX introduces the ELAN DRC II

- Integrated peristaltic pump for superior unattended operation
- New design allows use of heat-exchanger-based cooling system

2003 – PerkinElmer SCIEX introduces the ELAN DRC-e

- First DRC system for routine analytical use in high-throughput labs
- Enhanced ELAN software speeds setup and optimization, provides new features to make ICP-MS even easier

PerkinElmer, Inc.

Expect more from the leader in inorganic analysis

With over 40 years experience and a product line that includes flame AA systems, high-performance graphite furnace AA systems, flexible ICP-OES systems and the most powerful ICP-MS systems, PerkinElmer is the undisputed leader in inorganic analysis. We have placed over 40,000 systems throughout the world, performing inorganic analyses every hour of every day. With the largest technical service and support staff in the industry and a solid reputation for quality products and service, the ELAN DRC II instruments deliver the performance required to maximize ICP-MS performance and productivity.

Whatever you're looking for, we've got it

PerkinElmer is a world leader in chemical analysis. Our analytical instrument technologies serve the fast-evolving pharmaceutical, chemical, forensics, environmental and semiconductor industries, providing integrated solutions – from sample handling and analysis to communication of test results.

As one of the best-known brands in research, analysis and testing, ours was probably the first analytical instrument you ever used. In addition to our ICP-MS systems, we offer a broad range of solutions in Luminescence, UV-Vis, NIR, GC, GC/MS, MALDI-TOF MS,

HPLC, AA, ICP-OES, Thermal Analysis, Elemental Analysis, FTIR and LIMS. There are over 60 years of experience built into every product we make. So, for leading edge R&D and demanding QA/QC, you get the speed, accuracy and reliability you seek – for the productivity you need.

Unbeatable service and support – worldwide

Maybe you are new to ICP-MS or maybe you are an expert who wants to discuss an application with a knowledgeable ICP-MS scientist. In either case, PerkinElmer SCIEX has more people focused on ICP-MS applications than any other company. Clearly, we understand sample preparation, interferences and method-development issues facing today's laboratory. With extensive applications experience and knowledgeable service specialists, you can be assured that our organization is here for you well after the system has been installed.

Our service and support teams are located in 125 countries throughout the world and are factory trained. Compliance doesn't get any easier than with our software, including 21 CFR Part 11 technical compliance on many products. And, convenient consumables and accessories ordering lets you get your hands on what you need fast.

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Series 275 HRes UV/Vis LC System

Flexibility to expand your separation capabilities



Isn't it time you consider HRes™ fast liquid chromatography to expand your separation capabilities while increasing your sample throughput? The flexible PerkinElmer® Series 275 HRes LC System leverages small particle-size column technology at ultra-high pressures, giving you greater flexibility to develop methods across a wider operating range.

Improve your efficiency, easily. The Series 275 HRes LC System enables today's LC laboratories to achieve higher levels of performance and throughput to meet escalating scientific and business challenges. Your lab is on the line to do it better, and do it faster. Whether you are evaluating candidate compounds, controlling product quality, assuring consumer safety or assessing environmental impact, the Series 275 HRes LC System has the power and the flexibility to accelerate your productivity.

Key Benefits

- Greater operating flexibility to optimize method development
- Improved resolution and throughput with higher-pressure operating range (500-10,000 psi)
- Outstanding linearity and repeatability even at small injection volumes and high operating pressures
- "Best-in-class" cycle time with exceptionally low carryover drives increased throughput
- Extremely low dispersion for maximum resolving power
- High-speed data capture assures excellent peak fidelity at high sample throughput
- 21 CFR Part 11 architecture allows operation in a regulated environment

Preconfigured integrated system

for both HRes and cor

HRes LC made practical

Precisely designed and configured to minimize system-delay volume, optimize operating pressure and flow, and maximize detector response, the Series 275 HRes LC System is compatible with sub-3 μm particle-size high-resolution columns for improved performance. Our Brownlee™ HRes LC columns, available in a wide variety of stationary phases and dimensions, can be operated over a wide range of flow rates and operating pressures. This allows you to select the throughput and resolution best suited for your specific application needs.

Even though your method development options are greatly increased with the Series 275 HRes LC System, you don't have to abandon your valuable tried-and-true methods developed over all these years. The flexibility of the System allows you to run all your HRes and your existing conventional methods on a single LC system! A wide variety of mixers and detector flow cells are available to address both HRes and conventional applications.

Expanding upon a proven platform

The Series 275 HRes UV/Vis LC System makes new technology and performance breakthroughs available in a flexible, affordable and easy-to-use package. Everything you need is preconfigured into a single, integrated system.

Series 275 Binary Micro Pump

A platform proven at tens of thousands of installations worldwide, PerkinElmer's micro-pump technology is widely recognized throughout the industry for its ruggedness and reliability. The Series 275 Binary Micro Pump builds upon this very platform, now embodying numerous advancements in chromatographic science. Operating up to 10,000 psi, the Series 275 Binary Micro Pump delivers optimum resolution and speed with sub-3 μm columns, while providing efficient high-pressure solvent gradient mixing.

Series 200 Vacuum Degasser

The Series 200 Vacuum Degasser, configured as a standard component of the system, provides convenient degassing to assure baseline-signal stability.

Series 275 Autosampler

The Series 275 Autosampler delivers best-in-class cycle time and low carryover with exceptional precision and linearity. With derivatization/serial dilution capability, and Peltier cooling and heating, this flexible autosampler manages your sample load reproducibly and efficiently. A wide range of injection modes, including μL -pickup mode, assures that even low-volume injections can be achieved with high repeatability.

Series 200 Column Oven

Convenient high-pressure finger-tight fittings – optimized to maintain the rigorous low dead-volume requirements of Fast-LC technology – efficiently connect the sample injector to the column, assuring convenient column exchange with minimum peak dispersion. The Series 200 Column Oven provides precise thermal stability and exceptional retention-time reproducibility.

Series 200 UV/Vis Detector

The Series 200 Programmable UV/Vis Absorbance Detector is one of the most popular detectors used in LC today. Combining a high-efficiency flow cell and high data-acquisition rate, this detector captures Fast-LC peaks with high resolution and sensitivity. The detector employs a dual-beam optical design for high sensitivity and supports Deuterium (D_2) and Tungsten source lamps – offering true visible wavelength performance.

Conventional LC applications

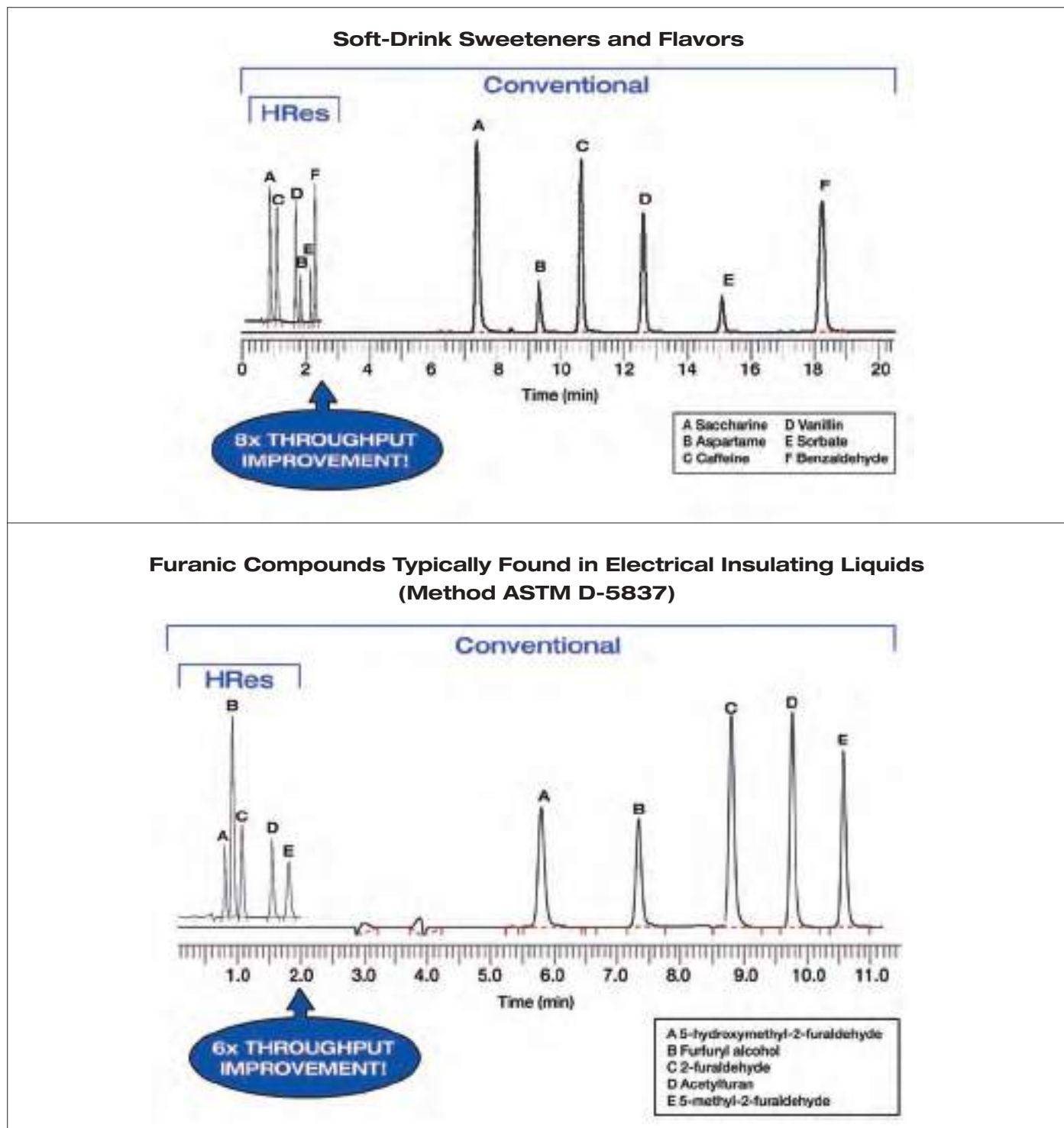


Figure 1. Increase your productivity – the Series 275 HRes UV/Vis LC System can reduce retention times and increase sample throughput dramatically.

PerkinElmer – a trusted partner for liquid chromatography

With over 30 years of experience developing liquid chromatography solutions, PerkinElmer is a leading provider of scientific instruments, consumables and services to environmental, biomedical, pharmaceutical, energy, food/agriculture, chemical, forensics and general industrial markets worldwide. We provide integrated solutions from sample handling and analysis to communication of test results. With more than 70 years experience and over 1000 factory-trained professionals serving more than 125 countries worldwide, PerkinElmer is your most trusted single source for instrument care and repair, validation services, software and hardware upgrades, training and more.

Our award-winning integrated chromatography data systems have set the standard for workstation and client-server compliant solutions for regulated or non-regulated laboratories. With software designed, developed and supported by PerkinElmer, you can be assured of an integrated solution to support your business needs – for the long term.

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Bruker **AXS**



S2 RANGER

● Spectrometry Solutions

think forward

EDXRF



S2 RANGER – Leading the performance class

Time is money!

And so as not to take up too much of your time, we have done something slightly unusual. We have placed a short description of users who will not purchase our system right at the beginning of this brochure. If you find yourself here, then we part ways now and thank you for spending a moment.

Here is the short check:

You can stop reading if you are not interested in reliable, stable results.

Also please lay this brochure aside if you are only interested in investigating a single element or a single sample type, both today and for the next ten years.

If you are merely looking for the cheapest system and you do not care about actual operating costs, stop reading right here.

If you like working your way through fat manuals or enjoy never ending training lessons, you can close the brochure at this point, please.

So, you're still reading!

Excellent, then we sincerely welcome you to the performance class. Our S2 RANGER is obviously just the right solution for you and your demanding elemental analysis applications.



S2 RANGER with sample changer and tray for 28 samples



S2 RANGER with sample changer and tray for 28 samples



S2 RANGER with single sample loading



TouchControl



Rugged design



Industry certified



Integrated printer



Magnetic gripper



Adjustable screen



All-in-one system



XFlash detector



Fully protected



Automatic loading



Manual loading



Small sample chamber

This is how easy multielement analysis can be.

What do you think of when you hear the term multielement analysis? Inserting a sample into a spectrometer, moving to the computer, programming it with a whole series of measurement conditions, and interpreting a confusing table of numbers? If so, you are quite right – with other systems, that is how X-ray fluorescence (XRF) usually works.

With TouchControl XRF works better and easier by far. Simply insert your sample, start your measurement on the integrated touchscreen and get color-coded results. TouchControl means no time-consuming training, no need for fat manuals, no tangled cables, and no complicated setups – just efficient work and excellent results right away.

TouchControl is as easy as 1-2-3. Here are the three steps to successful elemental analysis:

Say goodbye to extensive instruction and welcome to TouchControl™



Results

- Free language selection – English, German, French, Spanish, Portuguese, Russian, Chinese ...
- No training required
- Tailored results for process and quality control
- Maximum data integrity due to user access levels

1.



- First, insert your sample and select the desired application. It goes without saying that the list of applications can be configured freely. You determine the access rights of users to specific applications.

2.



- Next, type in relevant sample information. The name of the sample is sufficient, but the sample quantity or information on the sample preparation can be specified if you like.

3.



- Last, start the measurement simply by touching the screen and get your results. With a sample changer you can automate the analysis of up to 28 samples.

This is how clearly analysis results can be presented.

The measurement results that you receive on the touchscreen are tailored exactly to your needs. In addition to concentrations, ratios and totals can be automatically displayed for production control. And if quality control sets quantitative limits for a sample, the sample status is indicated by a traffic light symbol, showing red, yellow or green.

Now you know everything you need for your daily work with the S2 RANGER!

Tailoring your own system made easy

We have already shown you how fast and simple your daily work can be thanks to TouchControl. But what about calibration, the selection of measurement parameters, analyzing standards and setting up drift corrections?

Or, to put it in different terms, how can the S2 RANGER be adapted to special tasks? Two options: you can either rely on us and use one of our special, ready-made application packages, or you can create your own application.

The requirements of the cement industry, petrochemistry and geology are each entirely different. This is precisely why we have developed a tool of unparalleled flexibility for the creation of your own application, tailored according to your standards: SPECTRA EDX.

This is how easy it can be to create individual applications.

Step by step the SPECTRA EDX guides you to your goal: fast, easily and reliably, like a navigation system.

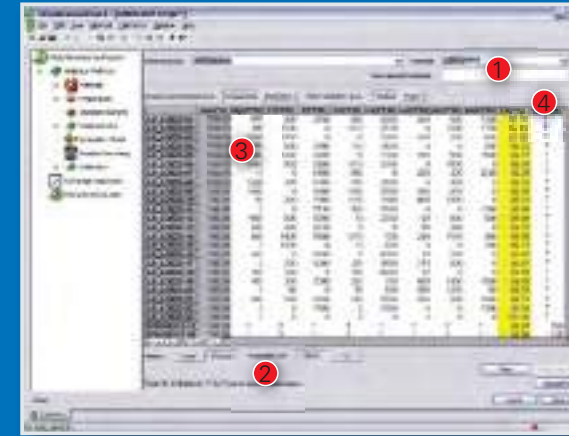
Let's start with the first step: defining the standards, which will serve as references for the measurement. Simply enter the names of the standards, the concentrations of the elements and the sample quantity and preparation parameters. The information is stored in a database and can be reused any time.

Next step: setting up the measurement. Based on your inputs, SPECTRA EDX automatically proposes a measurement method, which already takes into account all the information and covers the range of elements required. You can simply adopt this method, or adapt it to your special requirements. The process continues in the same simple way: insert standards and start measuring.

As you have probably guessed, now comes step three: calibrating the system. The calibration curve is calculated for each element. Numerous tools are available even for the most sophisticated calibrations. SPECTRA EDX can correct matrix effects via theoretical, empirical and variable alphas. You can modify your calibration settings whenever you like and check the effects on the calibration curve.

Lastly, to have your application appear as a button on the integrated touchscreen, simply give it a name. And that's it!

- 1 Name a new standard
- 2 Select units – ppm or %
- 3 Type concentrations of standards – T for trace and B for bulk matrix
- 4 Data import and export

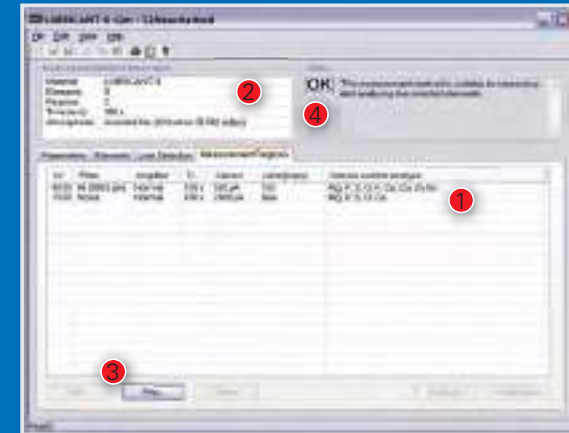


Standards

Convenient data input

- Tree-guided workflow
- Fast spreadsheet editing
- Import & export of composition data
- Definition of sample preparation

- 1 Automatically generated measurement ranges for different elements
- 2 Total measurement time and atmosphere (He, vacuum or air)
- 3 Edit predefined measurement ranges or create a new one
- 4 Consistency check of the measurement settings

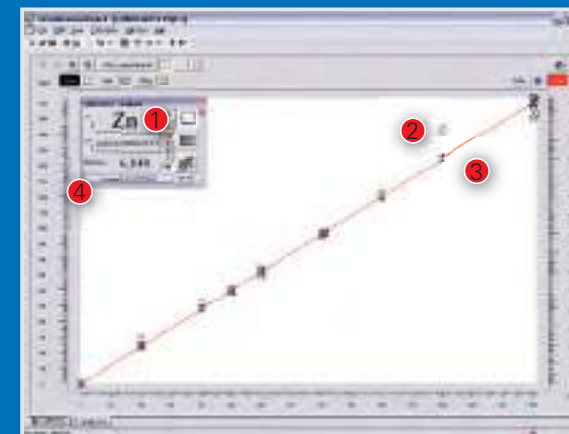


Measurement

Integrated analytical intelligence

- Best excitation voltage preselected
- Optimized filter settings
- 4 modes – air, vacuum, reduced and atmospheric He
- Fixed current or fixed count rate settings

- 1 Toggle between selected elements
- 2 X-ray intensity without corrections
- 3 Intensity with corrections applied
- 4 Standard deviation of the calibration in ppm

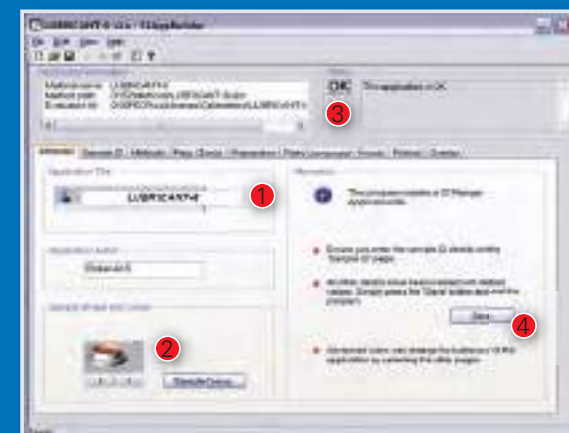


Calibration

State-of-the-art fundamental parameter evaluation

- Direct correlation of intensity vs. concentration
- Correction for line overlaps
- Internal standard
- Theoretical, fixed and variable alphas

- 1 Name the button for the application
- 2 Change sample shape and color for loader display
- 3 Consistency check of the application
- 4 Save and create the touchscreen button



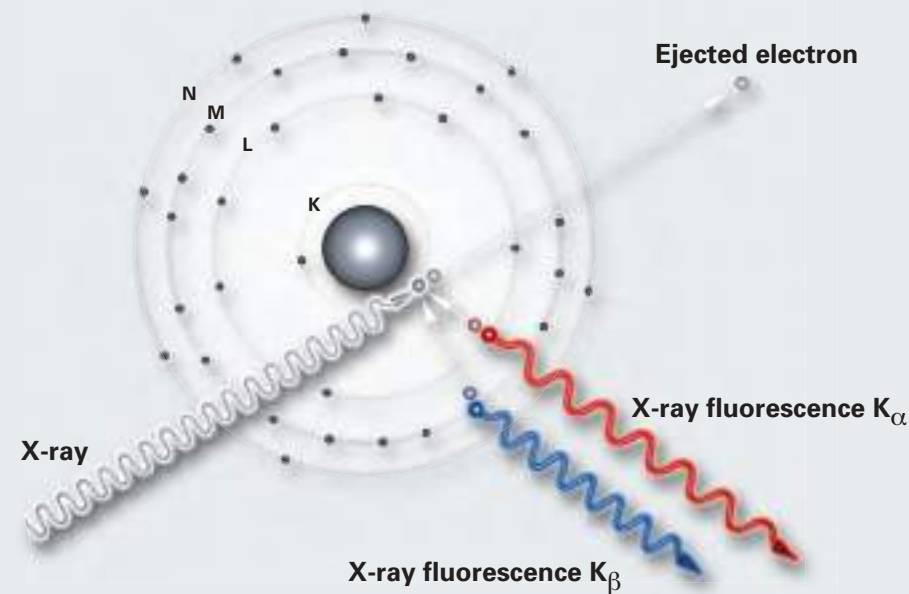
Application

Easy TouchControl integration

- One-button methods
- Variable sample preparations
- Color-coded quality limits
- Automatic module calculation

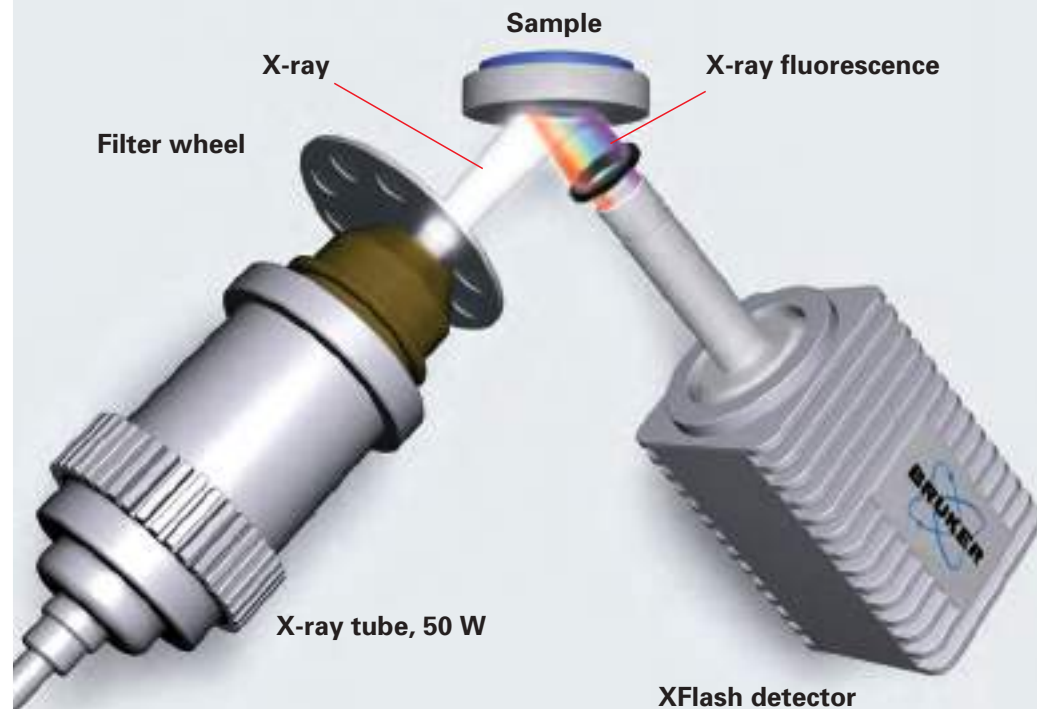
How does X-ray Fluorescence (XRF) work?

Bromine atom



■ The sample is bombarded with X-rays. This excites the sample to generate X-ray fluorescence. The X-rays “shoot” individual electrons out of the atoms of the elements, primarily out of the inner atomic shells K and L. The resulting vacancies are filled up again by electrons from higher energy shells. The excess energy of these electrons is then emitted in the form of X-ray fluorescence radiation. This radiation is characteristic for each element like a fingerprint and virtually independent of the atom’s chemical bond. The intensity of the radiation is proportional to the concentration of the element in the sample.

Energy-dispersive XRF with the S2 RANGER



■ The S2 RANGER uses a 50 W X-ray tube to directly excite the X-ray fluorescence in a sample. By specifying the high voltage and choosing a filter, an elemental or energy range is selected. In order to analyze lighter elements, the sample chamber is either evacuated by means of an integrated vacuum pump or it is flooded with helium. The XFlash detects the X-ray fluorescence radiation of the sample. The multi-channel analyzer divides up the different energies and accumulates counts to form an intensity vs. energy spectrum.

XFlash® detector – best resolution and count rate – can get the most out of 50 W power

Not to overwhelm you with technical details or confuse you with cryptic jargon, suffice to say that, if there were a world champion in the category “performance, functionality and quality of results”, it would be S2 RANGER!

50 watts of pure X-ray power.

Our S2 RANGER applies up to 50 watts of X-ray power directly to the sample. This has the following advantages:

- no need for moving parts such as primary optics or monochromators,
- elements at very low concentration levels are excited,
- and higher intensity sets the stage for maximum precision.

Award-winning XFlash technology.

Thanks to our outstanding XFlash detector we are in a position to fully exploit the entire output of the 50 W X-ray tube and can convert this into stability and sensitivity.

Owing to its Silicon Drift Detector (SDD) technology, the XFlash is empowered for maximum count rates and the best possible energy resolution:

- High count rates facilitate reliable results very fast.
- High count rates minimize statistical errors and lead to very accurate results.
- Optimal energy resolution permits different elements to be clearly separated and guarantees that even traces can be detected alongside the main components.
- Due to Peltier cooling, no liquid nitrogen is required for cooling; this minimizes hassle and significantly reduces operating costs.

Reduced to the max – S2 RANGER.

The small sample chamber of our S2 RANGER has three crucial advantages:

- short beam path means maximum intensity at the detector,
- fast evacuation with the integrated vacuum pump ensures high sample throughput,
- and in the case of liquid samples, only the sample chamber needs to be filled with helium, thereby cutting operating costs.

That’s it for the technological basis of our S2 RANGER and the secret of our success – but the best is yet to come.

- Highest excitation power in benchtop EDXRF class
- Unrivalled XFlash detector 145 eV with 100 000 cps at Mn K_{α}
- Peltier cooled SDD technology
- Smallest sample chamber for instant switch and lowest He consumption



50 W X-ray source



Award-winning XFlash technology

- Fully equipped benchtop analyzer with minimum space requirements
- Perfectly matching components for reliable operation
- GLP/GMP compliant user access level control
- IQ/OQ procedures for norm compliant analysis



All-in-one design

S2 RANGER – all in one – integrated PC, printer, vacuum pump and touchscreen monitor

Do you remember the good old days when you worked with a "really big" spectrometer? Back then you didn't just have a monitor, mouse and keyboard, you also had an external PC, a separate printer and a noisy vacuum pump. And as if that weren't enough, all of this had to be purchased, set up, installed and maintained.

If you are wondering why such peripherals are missing in our pictures of the S2 RANGER, you do not need to conjure them up, because they are already built in: A complete PC, touchscreen, printer and vacuum pump. Everything you need, truly an all-in-one machine!

What are the advantages of the all-in-one design?

Firstly, all you really need to operate the S2 RANGER is a standard power outlet and, if necessary, helium gas for liquid samples. This means no extra devices, no extra costs, no extra time and effort, and no extra risk!

Secondly, all the components of our S2 RANGER work together perfectly and are well protected inside the housing. After all, you must be able to rely 100% on your analytical results.

To ensure your trust that the system stays that way, we have designed the S2 RANGER as a robust standalone system. Regardless of whether it is in the laboratory, directly next to the furnace or in a remote mine, our S2 RANGER never lets you down.

Although it is self-sufficient, you always have complete control of your S2 RANGER, anywhere in the world. This is because your S2 RANGER is fully network capable. You can therefore access all results and system controls via the Internet or Intranet. If need be, our service staff can remotely check your S2 RANGER, identify problems at an early stage and take preventive action.



Status display



Language selection



Thermal printer



Sample changer



Vacuum chamber



Integrated PC	Integrated Touchscreen	Integrated Printer	Integrated Vacuum System
Windows® XP with user access rights	Easy operation – no training required	Direct printout of sample report	Integrated vacuum pump for light elements measurement
TCP/IP interface for network integration	Free language selection	Customizable layout	Lowest He consumption for liquid samples
Hard disk for secure data storage	Database for results		Small chamber for fast evacuation or gas exchange
DVD writer for backup	Spectrum for results check		Separate sample changer for continuous loading
	Status display		
	User management and access levels		

S2 RANGER – one for all –
all kinds of samples,
all elements and
all concentrations – from
ppm to 100 %

- General Requirement
- Advanced Requirement

S2 RANGER Performance	Cement	Minerals & Mining	Geology	Metals	Slags & Foundry	Chemistry	Pharmaceuticals	Petrochemistry
Long term stability								
Low detection limit								
All concentrations								
Multi-element analysis								
Universal standardless calibration								
Standard based calibration								
Ease-of-use								

We have already shown you the insides of an S2 RANGER. Now we will show you how to discover the insides of your sample with the S2 RANGER.

The X-ray fluorescence (XRF) analysis provides very precise answers to two crucial analytical questions: Which elements – and how much of them – does your sample contain?

If you have a sample of unknown composition, as a rule you will proceed as follows with your S2 RANGER: Insert sample, start multielement analysis and that's it! Was that too fast for you? Ok, here it is in a little more detail.

Using the S2 RANGER the entire XRF spectrum of the sample is measured at once. The excellent energy resolution of the XFlash detector permits all of the elements from sodium to uranium to be measured and clearly separated from one another. This means that with a single measurement you receive a reliable qualitative multielement analysis of your sample. We now know which elements are present in your sample, but still not the amounts.

EQUA ALL – the universal calibration with variable alphas – for quantitative results.

Thanks to EQUA ALL software you can pull off the feat of qualitative multielement analysis and, at the same time, get quantitative results from a completely unknown sample. EQUA ALL is the method for standardless analysis and is included with your S2 RANGER. It comprises a unique universal calibration created by us by means of innumerable certified standards. The interaction of the various elements – the so-called matrix effect – is corrected with the aid of the variable alphas – thus enabling the intensities to be correlated directly with the element concentrations. Voilà: the quantitative multielement analysis of an unknown sample has been achieved!

Top performance and long term stability with your own calibration.

If you know exactly which element and how much of it your sample must contain, then you require above all maximum accuracy and maximum stability. The high precision quantitative analysis of a sample requires first and foremost for the S2 RANGER to be calibrated with standards. This is the best way to get the most out of your system. As a result you obtain a measurement method of your own, ready to be used on your touchscreen.

Besides individual calibration, here two good friends guarantee success: our 50 W X-ray tube and our XFlash detector. Their excellent performance not only brings about unparalleled stability, it also permits reliable quantification of the concentrations of elements down to a few ppm.

- Flexible multielement analysis – full range of elements measured
- Qualitative identification of elements by line position
- EQUA ALL – the universal calibration for standardless analysis
- Best quantitative results with standard based calibrations



Element selection on the touchscreen

So many samples, so little time



Sample preparation

As you already know, one main advantage of the XRF is that almost all elements of the periodic table can be measured quickly and easily in all concentrations. However, one thing is clear:

Good quality samples are the basis of good measurement results!

This sounds reasonable but other analytical methods keep silent on this subject. Why is that so?

Quite simply, the way to good samples is significantly easier, more reliable and hence considerably cheaper using XRF analysis. The advantage of XRF over other methods is its ability to handle a wide variety of samples, including powders, liquids and solids. Unlike other methods, there is no need for elaborate dilution, digestion, or enrichment, nor must the instrument be recalibrated constantly.

Nevertheless, even for XRF samples must be selected and prepared correctly. This begins with representative sampling, goes through homogenization and ends with a smooth measuring surface.

So you can see that, unlike other methods, sample preparation for XRF is by no means sorcery. But if you still need a little help, we do not leave you out in the cold. We are glad to advise you on selecting the correct equipment and setting up sample preparation geared for your material. Ultimately, you obtain optimal procedures that your staff can follow and perfect results, measurement after measurement. After all this is what counts!

- Direct analysis of solids, powders and liquids
- Save method – no hazardous materials needed
- Lowest cost of operation
- Simple recipes for reliable results



Pressing
5 min

Prepared Samples



Pressed pellets



Melting
10 min



Glass beads



Dripping
15 sec



Sample cups



Polishing
1 min



Metal cuts

Analytical Results

Presentation variations



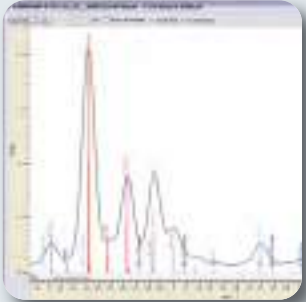
EDXRF Spectra



Printout



Results table



Lines in SPECTRA EDX

- Fast and easy with pressed pellets
- Most accurate results with glass beads
- Cup loading for loose powders and liquids
- Solids with clean and smooth surfaces

Sample preparation – simple recipes, not rocket science

We are by no means telling you a secret if we point out that the most frequent form of sample preparation for XRF is the creation of pressed pellets. The reason for this is clear, since the method is ingeniously simple and fast: Weigh out sample material, grind and press it, and put the pressed pellet into the S2 RANGER. To ensure that you obtain reliable and reproducible results, all you have to do is, find the right recipe and then stick to it every time!

To obtain the most accurate results for major and minor components you can melt the powder together with a fluxing agent. After it cools down you have a glass disk of homogeneous composition.

Preparation of liquid samples is the easiest of all. For this purpose you use a cup covered with a transparent plastic film. Fill the cup with the predefined quantity of liquid and then place the cup into the S2 RANGER. By the way, this method is also ideal for loose powder.

Lastly, here is the preparation method for all solid samples such as metals or ceramics: cut, mill, grind or polish – anything that creates a smooth and clean sample surface is fine. If the sample already has an appropriate surface, you can insert and measure it.

So you can see that sample preparation for XRF analysis is certainly not alchemy. Rather it involves following simple recipes. For your convenience and with a little “magic”, it can also be fully automated.



■ Use weighed amount of sample



■ Add grinding tablets



■ Mill in grinding vessel



■ Finished powder material



■ Pour powder into sample press



■ Get pressed pellet



Pressing
5 min

Prepared Samples



Pressed pellets

Analytical Results

Presentation variations



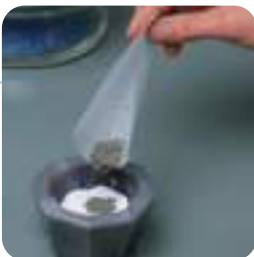
EDXRF Spectra



■ Pour flux melting agent into mortar



■ Weigh sample amount



■ Add sample to flux material



■ Mix sample and flux



■ Pour material into crucible



■ Heat crucible in melting furnace



■ Casting mold with finished glass bead



Melting
10 min



Glass beads



Printout



■ Cover bottom of liquid cup with transparent film



■ Check for holes



■ Pipette sample amount to defined weight



Dripping
15 sec



Sample cups



Results table



■ Clamp metal cut



■ Check sample height at molding cutter



■ Mill



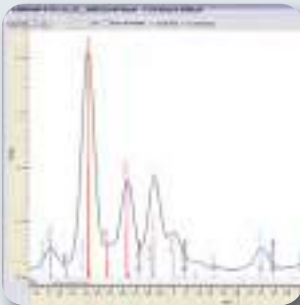
■ Check surface



Polishing
1 min



Metal cuts



Lines in SPECTRA EDX

Technical Data	
Elemental range	Sodium to uranium (Na-U)
Concentration range	From ppm to 100 %
Sample types	Powders, solids and liquids
Sample size	Liquids, loose powders: up to 50 ml Solids: 40 mm (1.56") Ø ring for sample changer Solids: 75 mm (3") for manual loading
Sample preparation	Direct, sample cups, pressed pellets, and fused beads
Sample changer (optional)	28-position tablet Constant loading during measurements Up to 40 mm (1.56") Ø and height, max. weight 200 g
TouchControl™	Integrated 12" TFT touchscreen
X-ray tube	Pd anode Max. power 50 W, max. voltage 50 kV, max. current 2 mA
Primary beam filters	9-position automatic filter changer
Detector	XFlash® Silicon Drift Detector Resolution <145 eV at Mn K _α and 100 000 cps Peltier cooled (no need for liquid nitrogen)
Vacuum pump	Integrated
Helium flushing	Integrated – extra helium supply required
Operation Modes	Vacuum for solids, helium flushing for liquids and loose powders, air (> Ti)
Printer	Integrated thermal printer
Network	Built-in modem and Ethernet port
Automation	Data exchange to LIMS possible
Power requirements	110/240 V, 50/60 Hz, max. consumption 1 kVA
External cooling water	No cooling water
Dimensions	65 cm (25.4") x 80 cm (31.3") x 60 cm (23.4"), 96 kg (211 lbs) (height x width x depth, weight)
Quality & safety	DIN EN ISO 9001:2000 CE certified Meets "Safety Category No. 3" as defined by the EN954-1 standard, and the requirements defined by the DIN 54113 standard.



The Counter Solution.

LS 6500

SCINTILLATION COUNTING SYSTEM





A Single-System Solution for Unprecedented Flexibility

Now you can create your own customized, integrated scintillation system. The LS 6500 Value Systems combine advanced technology, accuracy, and configurability to meet your exact requirements. With our unique upgradability design, you can even add features at a later date. Beckman Coulter offers unparalleled flexibility in a single system and a partnership that begins before system installation and continues throughout the lifetime of your instrument.

The LS 6500 System Provides:

Advanced Technology. A state-of-the-art basic system that eliminates early obsolescence.

Configurability. Enhancement packs and single options let you tailor the system to meet your needs.

Upgradability. Add features and enhancement packs throughout the lifetime of your instrument, if your applications change.



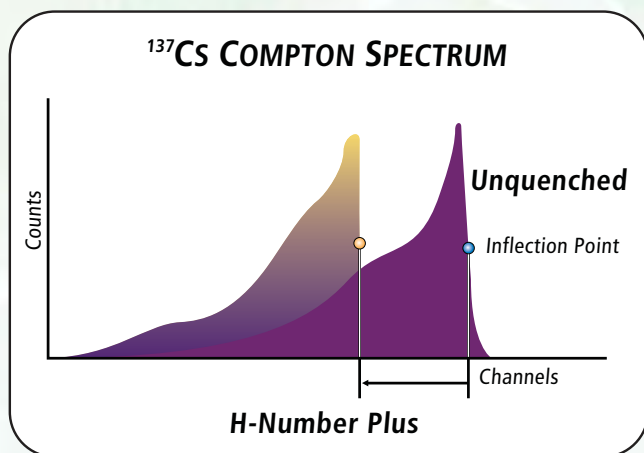
State-of-the-Art Design ...

Advanced electronic components — a Motorola microprocessor supported by a digital signal processor — maximize the technological lifetime and make the LS 6500 a fast and efficient liquid scintillation counter.

High Spectral Resolution ...

A 32,768-channel multichannel analyzer gives you an effective resolution of 0.06 keV per channel and an eight-fold improvement over conventional liquid scintillation counters with 0.5 keV per channel. This provides the basis for accurate results for a wider variety of samples:

- DPM without quench curves (Auto-DPM)
- A more precise quench monitor (H-Number Plus)
- Superior multi-label studies with Automatic Quench Compensation (AQC)
- Automatic color detection and correction



Accurate Results ...

At the heart of the liquid scintillation counter is our patented H-Number Plus. For samples with variable quench, the H-Number Plus significantly improves accuracy and reproducibility. The quench is determined very accurately to a tenth of a channel.

... And Simple Operation

The LS 6500 liquid scintillation counter guides you with easy-to-follow menus and context-sensitive help screens throughout the operation. Actually, after setting up your counting conditions for up to 50 user programs, the system becomes a one-button system—press “Start” and simply add your racks to the sample chamber.

Versa-Rack™, a standard feature on all Value Systems, lets you count samples in any combination. Up to 336 standard vials (20 mL), 648 mini-vials (7 mL), Bio-Vials™ (4 mL), and even Microfuge® tubes.





Customized Value

One system with advanced technology design, the LS 6500 liquid scintillation counter allows you to customize the system to meet your exacting applications requirements. Although the Basic and Value Systems include many features, Enhancement Packs and Single Options give you unprecedented flexibility to create your own liquid scintillation counter.

Standard Features

Hardware and Electronics

- 32,768-channel multichannel analyzer
- Advanced mini-size photomultipliers
- Effective interlocking lead shielding
- Fast/slow component pulse analyzer

User Interface and Output

- Color flat panel display
 - Spectrum display/print
 - Histogram display/print
- Proprietary windowing user interface
- Context-sensitive help screens
- User-selectable output formats

Basic Calculations

- Fixed background subtraction
- First-vial background subtraction
- Half-life correction
- Final result normalization
- Repeat and replicate averaging with %CV
- Single-label % of reference

General

- Automatic power-up diagnostics
- Automatic calibration and verification
- Diagnostic program
- Versa-Rack™ A, B
 - 336 standard vials
 - 648 mini- or bio-vials
- Automatic batch repeat
- Bi-directional sample changer
- Positive sample identification
- Electrostatic controller

Instrument Editing

- 20 user programs
- Program protection
- Isotope library
- Auto-Isotet™
- Interrupt mode

Sample Monitors

- H-Number Plus A, B
- IC-Number
- High count terminator
- Random coincidence monitor



Enhancement Packs

P/N 510706 Productivity Pack [1]

Enhance productivity by obtaining final DPM results for all types of samples and add computer communications capabilities. Requires Value System or H-Number Plus (P/N 500629).

P/N 510707 Confidence Pack [2]

Obtain accurate results under all circumstances by on-line sample monitoring. Requires Productivity Pack (P/N 510706) or H-Number Plus (P/N 500629) and Single-, Dual-, or Triple-Label DPM (P/N 500657, 500625 or 500626).

P/N 510659 System 96 Plus Pack [3]

Obtain accurate results under all circumstances by on-line sample monitoring and perform detailed analysis of non-radioactive luminescence assays. Requires Value System 96 or H-Number Plus (P/N 500629) and Single-, Dual-, or Triple-Label DPM (P/N 500657, 500625, or 500626).

P/N 510708 Data Management Pack [4]

Provides trouble-free data storage and transfer of data to external computers and eliminates the guesswork when tracking radioactive waste.

P/N 510660 Network Pack [5]

Provides software and hardware to put data on a computer or network.

P/N 510709 Environmental Pack [6]

Ensures highest sensitivity when counting low activity or low-level samples and provides efficient monitoring for samples containing overlapping alpha and beta emitters.

Individual Options

- [1] • Xtalscint CPM/DPM
- [1] • Single- and Dual-Label DPM^{B,1}
- [2] • Luminescence Correction (Lum-EX)^B
- [2] [3] • Color Detection and Correction¹¹
- [2] [3] • Two-Phase Monitor¹¹
- [3] • Single Photon Monitor
- [4] • Data Buffer and Transfer System
- [4] • Radioactive Waste Manager
- [5] [1] • RS-232 Interface
- [5] • LS WinConnection Suite (PC software)
- [6] • Low-Level Count Mode
- [6] • Alpha/Beta Discrimination
- Versa Rack^{A, B}
- H-Number Plus^{A, B}
- Auto DPM
- Single-Label DPM
- Single-, Dual-, and Triple-Label DPM¹¹
- Dual-Label % of Reference¹²
- 30 Additional Users

Standard Features

- [1] Part of Productivity Pack
- [2] Part of Confidence Pack
- [3] Part of System 96 Plus Pack
- [4] Part of Data Management Pack
- [5] Part of Network Pack
- [6] Part of Environmental Pack
- ^A Included in Value System
- ^B Included in Value System 96
- ¹¹ Requires H-Number Plus
- ¹² Requires Dual- or Triple-Label DPM

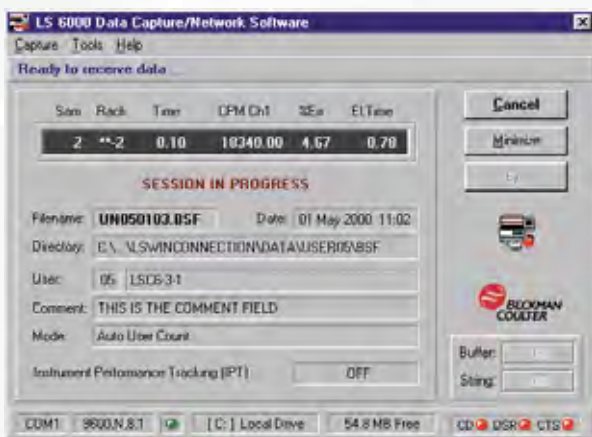


Efficient Data Management

In today's environment, data handling with networked PCs and automatic collection of data on a secure server have become commonplace. The LS 6500 liquid scintillation counter with LS WinConnection is ideally suited for this task. Automatic capturing of data in a variety of formats and further data manipulation with third-party packages are made easy.

LS WinConnection Suite

Efficient reporting and management of data is imperative to enhance overall productivity in today's environment. The LS WinConnection Suite includes Microsoft Windows* (Windows NT 4.0 and later) programs to simplify and automate the collection, storage, and communication of scintillation counter data via an existing network. The LS WinConnection Suite includes three independent but complementary programs:



Data Capture/Network Software

The Data Capture/Network Software can run unattended in the background to collect and save data in a variety of formats. Data are stored in a secure binary format - Beckman Standard File (BSF) - onto the local drive or a network drive.

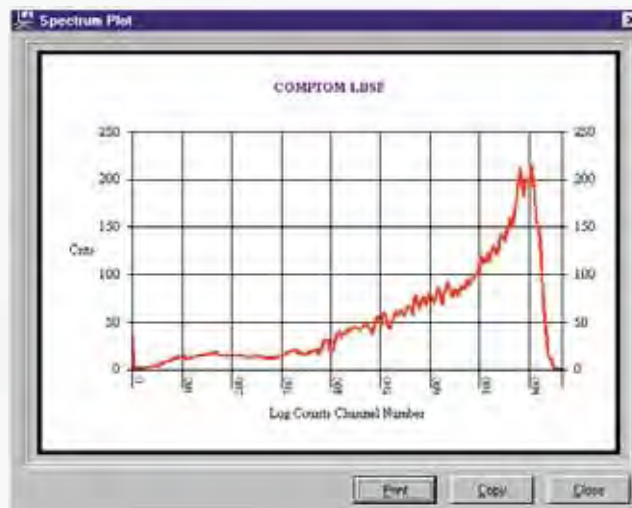
Other file formats, such as ASCII (print and delimiter format), native Excel* Worksheet, and native Lotus* 1-2-3 Spreadsheet formats can also be obtained automatically.

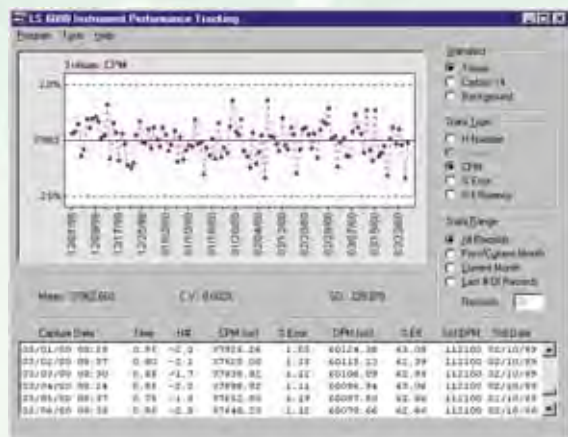
Also, the Data Capture/Network Software will collect quality control data from standards and appends them to a Microsoft Access database for use with Instrument Performance Tracking (IPT).

BSF File Utility

The BSF File Utility allows for the analysis, interpretation, and reporting of collected data and can convert data in BSF format to other formats - on demand. The utility provides the following key benefits:

- Direct review and printing of binary BSF file in an easy-to-read format
- Immediate graphic presentation of the data as histogram, spectrum, or kinetic for chemiluminescence assays.
- On-demand conversion of files into ASCII, Excel, Lotus, applications-specific BSF as well as Hex-Dump formats.
- Adding and/or editing of records in a BSF file for specific purposes.





Instrument Performance Tracking (IPT)

The Data Capture/Network Software automatically generates and expands a Microsoft® Access database that includes performance data of the scintillation counter. This information is then used with the Instrument Performance Tracking (IPT) program to tabulate and graphically display performance parameters, such as H-Number, counts, CPM, counting error, and % efficiency for multiple standards over time. Tolerance levels can be set by the user to clearly indicate outliers. Statistical analyses such as mean, standard deviation, and coefficient of variance (% C.V.) are performed automatically.

As specified by the user, "old" performance records are automatically moved to an archive database to keep the active database small enough and manageable.

Sample Preparation and Support

Beckman Coulter provides an outstanding biodegradable multipurpose cocktail that contains a solvent with rapid biodegradability characteristics and outstanding sample holding capacity. Other pseudocumene-based cocktails are available for specialized sample preparation needs.

Scintillation Cocktails and Solid Scintillators

With the Xtalscint CPM/DPM option, the LS 6500 liquid scintillation counter can efficiently count both liquid samples (e.g., mixture of sample and cocktail, filters in cocktail) and solid scintillators (e.g., proximity assays).

Our Commitment to Total Customer Satisfaction

Creating customer-sensitive solutions, developing state-of-the-art instrumentation, providing responsive, quality service and guiding you with full-scale support is our commitment to you. Beckman Coulter's worldwide team of dedicated professionals will support you for the lifetime of the system.



BASIC SYSTEM

Part No.	Description
510702	LS 6500 Miniature Vial System, 120 V
510703	LS 6500 Standard Vial System, 120 V
510719	LS 6500 Miniature Vial System, 240 V
510720	LS 6500 Standard Vial System, 240 V
510713	LS 6500 Miniature Vial System, 100 V
510714	LS 6500 Standard Vial System, 100 V

VALUE SYSTEM

- Complete set of miniature and standard vial racks
- Versa-Rack to count both miniature and standard vials
- H-Number Plus, External Quench Monitor (¹³⁷Cs) with Automatic Quench Compensation (AQC)

Part No.	Description
510705	LS 6500 Value System, 120 V
510722	LS 6500 Value System, 240 V
510716	LS 6500 Value System, 100 V

VALUE SYSTEM 96

- Complete set of miniature and standard vial racks
- Versa-Rack to count both miniature and standard vials
- H-Number Plus, External Quench Monitor (¹³⁷Cs) with Automatic Quench Compensation (AQC)
- Single- and Dual-Label DPM calculations, with factory stored quench curves for ³H and ¹⁴C, pipetting monitor, quench curve setup, correlation table and background quench correction
- Luminescence Correction (Lum-EX) automatically corrects for luminescence interferences

Part No.	Description
510654	LS 6500 Value System, 120 V
510656	LS 6500 Value System, 240 V
510658	LS 6500 Value System, 100 V

TECHNICAL SPECIFICATIONS**Dimensions and Weight†**

Width:	91.4 cm (36.2 in.)
Height:	67.3 cm (26.5 in.)
Depth:	80.0 cm (31.5 in.)
Weight:	210 kg (460 lbs.)

[†]without display, shelf and printer

Minimum Power Requirements

LS 6500	120V	3.0 A
	240 V	1.5 A
	BTU/Hr	1230

Space Requirements

A minimum bench or table space of 132 cm (52 in.) wide and 71 cm (28 in.) deep is required.

The surface must be level and flat and capable of supporting 275 kg (600 lbs.) without bowing or flexing.

To allow for optimal air circulation and ease of service, a recommended space of 152 cm (60 in.) wide and 81 cm (32 in.) deep should be dedicated to the system.

An additional 30.5 cm (12 in.) of width should be free of permanent structures to allow for installation and service.

The area above the bench or table, 91 cm (36 in.), should be clear of shelves or cabinets.

^{*}All trademarks are the property of their respective owners.



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ICP-MS

VARIAN, INC.

810-MS and 820-MS

ICP MASS SPECTROMETERS



VARIAN

Your partner in ICP-MS solutions

Innovation you can trust

Varian continues to find new and novel ways to meet your changing needs. As a world leader in elemental analysis you can be assured that when you buy a Varian ICP-MS, you're buying more than just an instrument. You're buying a relationship with one of the most respected and experienced instrument companies in the world.



Choosing an ICP-MS has never been easier

If you've ever wished that ICP-MS could be simpler, wish no more. The Varian 810-MS and 820-MS make ICP-MS effortless. No matter what your requirements, with a Varian ICP-MS, you can tackle any application with ease.

Ease-of-use features of the Varian 810-MS and 820-MS include:

- Fast switch-over. Varian's unique* collision/reaction interface (CRI) system makes setup of complex reaction cell conditions a thing of the past. Simply turn on the gas flow to remove interferences. It's that simple. (820-MS only)
- Auto-optimization. Take the guesswork out of ICP-MS. With auto-tuning of all instrument parameters, you can spend less time on instrument setup and more time on sample analysis.
- Great software. The ICP-MS Expert software provides one-step optimization and method development. And it makes standard preparation easy; it can instruct you on what solutions to make and how to make them.

* Patents pending

Atomic Spectroscopy Innovation Timeline:

1957	1962	1971	1993	1994	1995	1997
Built components for world's first AAS (as Techtron)	Developed the AA2, Techtron's first commercial AAS	Varian applied for patent on Zeeman background correction	Varian introduced the first fully automated ICP-MS	Varian applied for patent on SIPS, providing online calibration and fast online dilution for flame AAS	Varian applied for patent on the VistaChip, used in the world's fastest simultaneous ICP-OES – the Vista-PRO™	Varian applied for patent on Fast Sequential AAS, reducing analysis times by up to 50%



ICP-MS: It's never been easier

With two ICP-MS models, the choice is yours

Core to both the 820-MS and 810-MS, Varian's patented high-efficiency 90 degree ion optics and double off-axis quadrupoles deliver exceptionally low background noise and unmatched sensitivity – at more than 1 million counts per second for 1 µg/L.

The 820-MS features Varian's unique collision reaction interface (CRI) system, which provides simple, routine removal of troublesome spectroscopic interferences. The result is faster, more flexible interference-free analysis without the worry of complex multipole or scanning quadrupole ion guides, or cells. And, by coupling auto-tuning of all instrument parameters, including CRI gases, instrument productivity is greatly enhanced.

For samples that don't require CRI, the Varian 810-MS is an ideal instrument with industry leading sensitivity for trace and major elemental analysis.

1998	2001	2001	2002	2003	2005	2006
Varian applied for patent on ion mirror optics for ICP-MS, providing highly efficient transport of ions to the mass analyzer	Varian's Duo AAS introduced simultaneous flame and furnace analyses	Varian applied for patent on curved fringe rods for ICP-MS, providing very low background and unmatched sensitivity	Varian applied for patent on collision/reaction interface (CRI) for ICP-MS, providing a simple solution to interference management	Varian introduced the world's most sensitive ICP-MS, incorporating interlaced coils, ion mirror optics, and curved fringe rods	Varian introduced the 810/820-MS, incorporating the novel CRI interference management technology	Varian introduced the entry level 710-ES series and the high performance 720/730-ES series

The benchmark for analytical performance

When you require ease-of-use and the ultimate in analytical performance, the Varian 810-MS and 820-MS deliver.

- Unique* collisional interface/extraction optics minimize interferences, providing reliable, routine, trace level quantification.
- Optimized sample introduction system, including computer-controlled Peltier-cooled spraychamber, reduces interferences and improves stability.
- Robust, high-efficiency plasma system and patented Turner Interlaced Coils break down the toughest sample matrices, reduce matrix effects, and minimize ion energy spread for maximum sensitivity and stability.
- Patented 90 degree ion mirror and low noise double off-axis quadrupole provide industry leading sensitivity and background.
- All-digital extended range detector – more than nine decades of dynamic range in pulse counting (digital) mode. Ease-of-use, fewer dilutions, and a guaranteed one year detector lifetime mean greater productivity and lower running costs for your laboratory.
- Varian's ICP-MS series takes your laboratory to the leading edge of laser ablation performance (LA-ICP-MS), providing a solution for the direct analysis of challenging solid samples.
- A range of accessories to further expand the productivity and capabilities of the new ICP-MS series are available. Options like the Clean Room Pack, Productivity Pack and SPS3 autosampler, provide solutions for your most demanding applications.
- Fully integrated LC-ICP-MS using Varian Galaxie chromatography software and Varian ICP-MS Expert software, making elemental and molecular speciation easy.

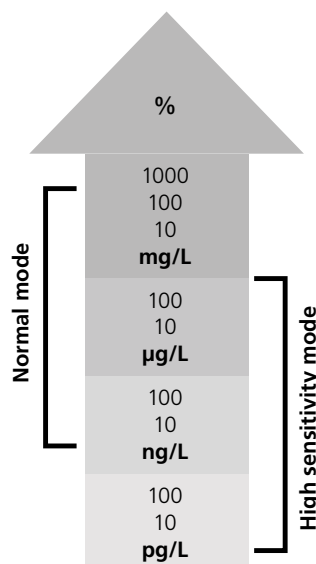
* Patents pending

Feature	810-MS	820-MS
Collisional interface	•	•
Optimized sample introduction	•	•
Interlaced coils	•	•
90 degree ion mirror	•	•
All-digital detector	•	•
LA-ICP-MS	•	•
LC-ICP-MS	•	•
Collision/reaction interface (CRI)	○	•
Clean Room Pack	○	○
Productivity Pack	○	○

• Standard feature
○ Optional feature

Isotope/Species	Typical Hot Plasma Performance
⁹ Be	> 50 million cps/mg/L
¹¹⁵ In	> 1000 million cps/mg/L
²³² Th	> 500 million cps/mg/L
CeO ⁺ /Ce ⁺	< 3%

Industry leading sensitivity, patented Turner Interlaced Coils, and 27 MHz plasma combine to deliver the remarkable performance of the Varian ICP-MS.



In high sensitivity mode, oxides such as CeO remain at <3% and can be further reduced under normal mode conditions to <1%.

"Our 90 degree reflecting ion optics revolutionizes ICP-MS performance"

Low noise quadrupole with curved fringe rods* for ultimate efficiency and low background.
* US Patent 6,762,407 B2

Turner Interlaced Coils*
* US Patent 5,194,731

Varian's ion mirror* reflects the ion beam through 90 degrees, focusing the analyte ions into the quadrupole with the highest possible efficiency.

By keeping photons and neutrals away from the mass analyzer, the ion mirror greatly reduces background signal.
* US Patent 6,614,021 B2

Varian's 820-MS collision/reaction interface* (CRI) provides fast, flexible, interference-free analysis.
* Patents pending

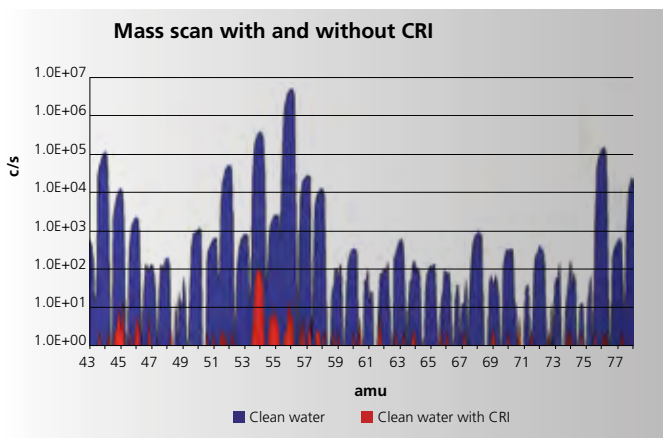
Varian 820-MS – fast, flexible, interference-free analysis

Determine the toughest analytes in any sample without interferences

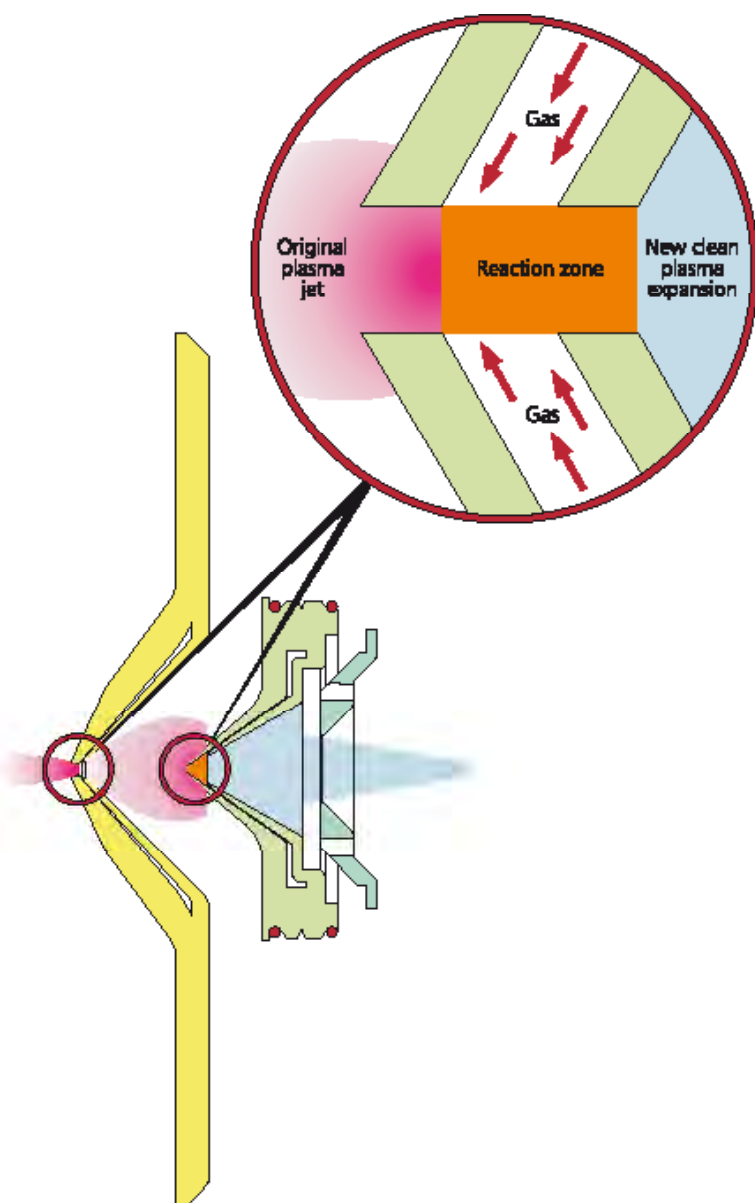
How does CRI work?

The collision/reaction interface (CRI) injects helium (He) and hydrogen (H₂) collision and reaction gases directly into the plasma as it passes through the orifice of the cones. This innovative approach suppresses interferences before the analytes are extracted into the ion optics. It's that simple!

- No need for corrosive or expensive gasses, such as ammonia and methane.
- Setup and analysis are fast and easy as there are no complex multipole ion guides.
- The CRI reaction is not confined to a cell, so you can quickly switch from CRI to non-CRI mode, or between different collision and reaction gases.



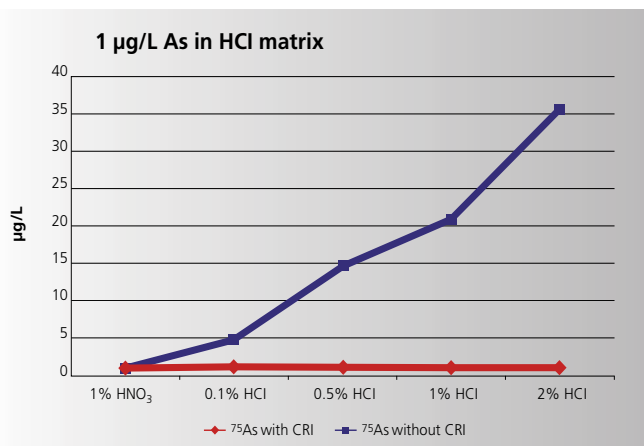
Dramatically reduce or eliminate troublesome plasma and sample matrix based interferences, using CRI.



Innovation you can trust

Determination of As in Cl containing samples

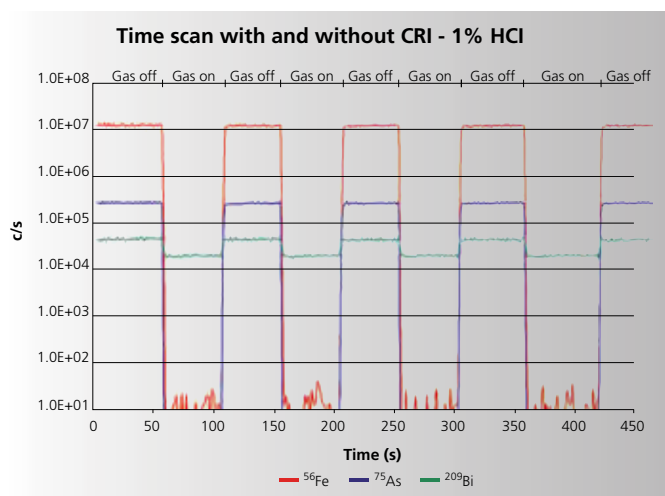
Use CRI in H₂ mode to remove the ArCl interference when determining As in samples ranging from drinking water to seafood to soil.



Comparison plots showing 1 µg/L spike recoveries for ⁷⁵As without correction equations. ArCl interferences are removed, allowing accurate trace level quantification of As.

Quickly and reproducibly reduce interferences

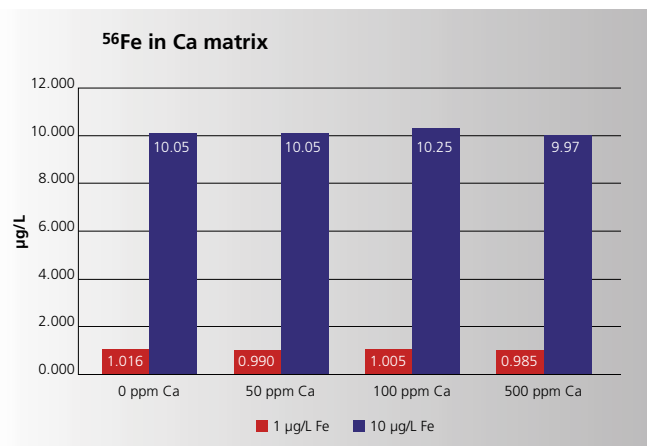
With CRI you can quickly switch from CRI to non-CRI, or between different collision and reaction gases.



With CRI, ⁴⁰Ar¹⁶O and ⁴⁰Ar³⁵Cl interferences on ⁵⁶Fe and ⁷⁵As respectively are reduced by over six orders of magnitude with minimal effect on the ²⁰⁹Bi spike sensitivity.

Removing Ca interferences from Fe

With CRI you can easily remove CaO interferences when detecting low levels of Fe in a wide range of samples. This makes it ideal for environmental applications.



Recovery of low level Fe in various calcium concentrations shows that CRI effectively removes both ⁴⁰Ca¹⁶O and ⁴⁰Ar¹⁶O interferences.

Unmatched performance for biological samples

Remove As, Se, V and Cr interferences in challenging biological samples such as blood, serum, and urine, with ease and confidence.

	Certified range µg/L	Measured value µg/L
²⁷ Al	13 - 21.2	20
⁵¹ V	0.27 - 0.37	0.29
⁵² Cr	0.42 - 0.78	0.42
⁵⁶ Fe	404 - 460 mg/L	420 mg/L
⁷⁵ As	1.4 - 2.2	1.8
⁷⁸ Se	74.4 - 85.2	77.2
²⁰⁶ Pb, ²⁰⁷ Pb, ²⁰⁸ Pb	26.2 - 29	27.6
²³⁸ U	0.16 - 0.18	0.17

Obtain accurate results in complex biological matrices. Above, certified and measured values for Reference Whole Blood Seronorm WB1 show that trace and major levels can be determined with accuracy and confidence using CRI.

The complete solution...

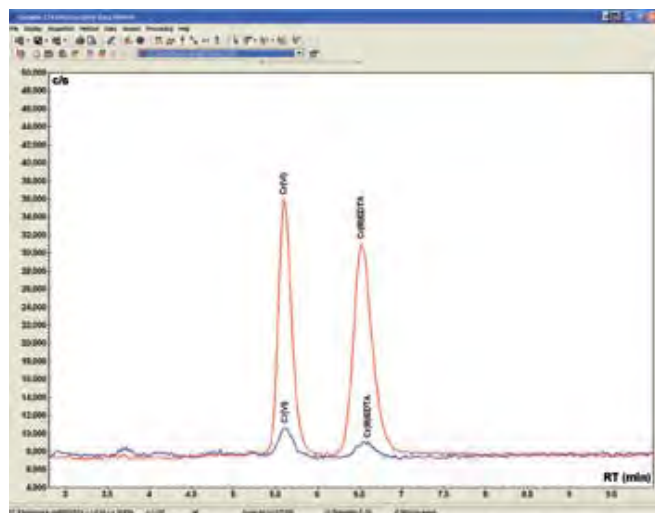
Seamless speciation

Obtain accurate, low level quantification of both Cr^{VI} and Cr^{III} species by using CRI to remove interferences such as $^{40}\text{Ar}^{12}\text{C}$.

The Varian 810/820-MS also feature fully integrated LC-ICP-MS compatibility using Varian Galaxie chromatographic software for simple, interference-free LC-ICP-MS.

Brand	Cr^{III} recovery %	Cr^{VI} recovery %
Mineral water A	105	99
Mineral water B	98	102
Mineral water C	106	108
Mineral water D	103	95
Mineral water E	102	106
Mineral water F	104	104

Spike recovery data for 0.1 $\mu\text{g/L}$ spikes of Cr^{III} and Cr^{VI} in commercial mineral waters.



Chromatogram showing mineral water (blue) and mineral water spiked with 1 ppb Cr^{VI} and Cr^{III} (red). Samples were stabilized with EDTA prior to analysis.

A family of atomic spectroscopy solutions

Varian, Inc. is a recognized world leader and innovator in AAS, ICP-OES and ICP-MS, with over 50 years of comprehensive experience in analytical instrumentation.

Varian's AAS range enables analysts to extend the performance and productivity boundaries of AAS determinations, and is equally at home in routine laboratories where reliability and simplicity are vital.



The Varian AA280 FS is the instrument of choice for high-throughput AAS analysis where sensitivity, reliability, and productivity are essential.

Varian's ICP-OES systems provide the ultimate in productivity, flexibility, and sensitivity, to meet every application requirement.

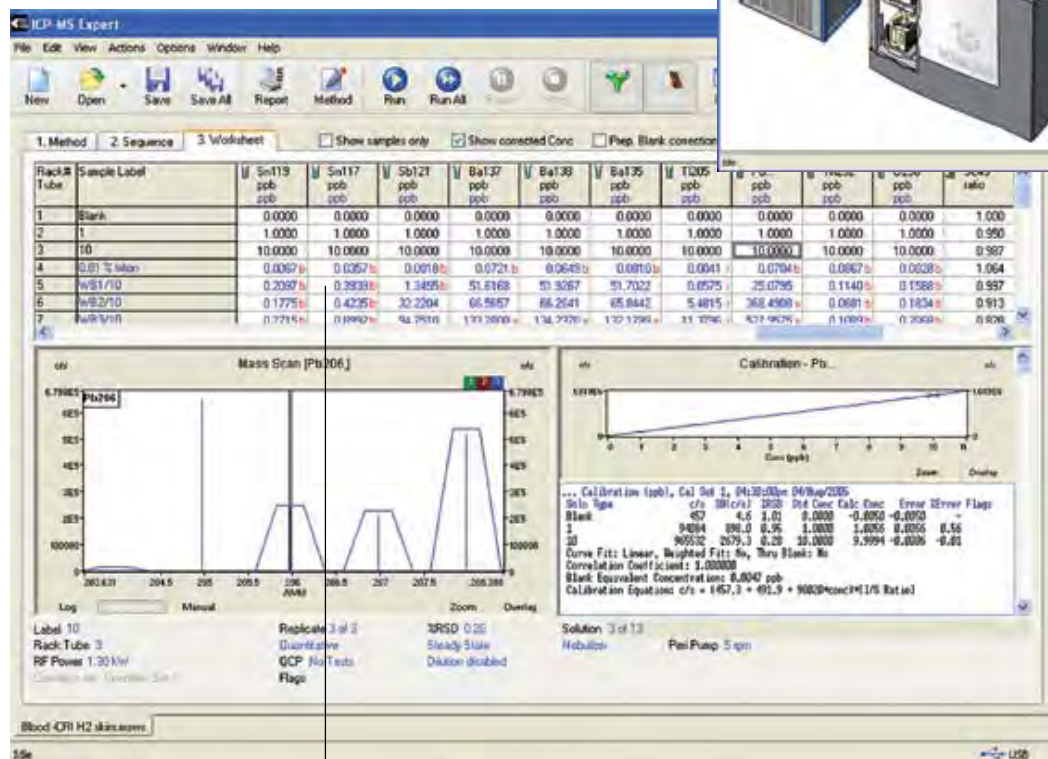


The Varian 720/730-ES is the world's fastest simultaneous ICP-OES series, offering the ultimate in performance and productivity.

Setting the benchmark for ease-of-use

ICP-MS Expert software

Varian redefines ease-of-use with our Web-integrated ICP-MS worksheet software. ICP-MS Expert features a range of automated options, including setup and initialization routines, such as plasma alignment, mass calibration, and resolution tests. Varian's AutoMax makes method development easy by automating all ion optics, nebulizer, and plasma settings for optimum results.



The dynamic Instrument Status window provides a quick visual check of the status of all system components. It is an excellent diagnostic tool that maximizes instrument up time.

ICP-MS Expert switches automatically between multiple method condition sets within a single sample, giving optimum performance for specific element suites, without having to re-run samples.

Each worksheet cell provides all the results you need – including concentrations, intensities, statistics, replicate readings and graphical mass scans.

VARIAN, INC.

810-MS and 820-MS

ICP MASS SPECTROMETERS

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Varian, Inc. – serving markets worldwide

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HPLC

VARIAN, INC.

920-LC

ANALYTICAL LIQUID CHROMATOGRAPHY SOLUTIONS



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Integrating Performance and Reliability

Fast HPLC

The Varian 920-LC analytical high performance liquid chromatograph is a fully integrated, pre-configured and pre-tested system. Designed to get you quickly up and running, the automated Varian 920-LC is easy to customize, install and use.

Whether you require excellent sensitivity, high sample throughput, sophisticated data handling, regulatory compliance, or special services, the Varian 920-LC offers a choice of configurations and options to meet all your analytical needs, today and into the future.

The Varian 920-LC delivers:

- Fast LC
- Superb analytical performance
- Industry-leading detection limits
- Enhanced productivity
- Maximized uptime

With Our Experience, Your HPLC Needs Are Covered

The Varian 920-LC stems from a history of liquid chromatography excellence. For four decades, Varian's range of reliable and easy-to-use HPLC instruments has served pharmaceutical, environmental, chemical, and other industrial R&D and QA/QC laboratories worldwide. So when you buy a HPLC from Varian, you can rest assured you are investing in a relationship with proven experts in HPLC.

Our customized HPLC systems, combined with the widest range of Varian-produced column chemistries, packing materials and dedicated software, provide versatile solutions for all your analytical to process-scale separations. Varian is your one-stop-shop for everything HPLC!



The Varian 920-LC liquid chromatograph is a fully-integrated HPLC, delivering performance, reliability and flexibility.

Dedicated to Your Application

Flexible Enough For All Your Applications

Whether you need a robust HPLC for routine analysis, productivity for high-throughput applications, or flexibility and sensitivity to develop analytical methods in a regulated environment, the Varian 920-LC has many options to create the system that works best for you.

- Analyze thermally unstable compounds using the temperature-controlled autosampler.
- Confirm the presence of specific analytes, such as pesticides and explosive residues, using automatic column switching.
- Ensure retention time reproducibility using the precise column heater.
- Gain extra detectability for trace analytes such as polyaromatic hydrocarbons using the sensitive fluorescence detector.
- Add the refractive index (RI) or evaporative light scattering (ELS) detector for universal detection of carbohydrates or polymers.

Flexible Systems

	Routine	Method Development	Research Grade
Isocratic pump	•	○	○
Quaternary gradient pump	○	•	•
Degasser™	○	•	•
Autosampler	•	•	○
Temperature-controlled autosampler	○	○	•
Column heater	○	○	•
Switching valve	○	○	○
UV-Vis detector	•	•	○
PDA detector	○	○	•
Fluorescence detector	○	○	○
RI detector	○	○	○
ELS detector (external)	○	○	○
Solvent organizer	•	•	•
Storage compartment	•	•	•

• Standard feature ○ Optional feature

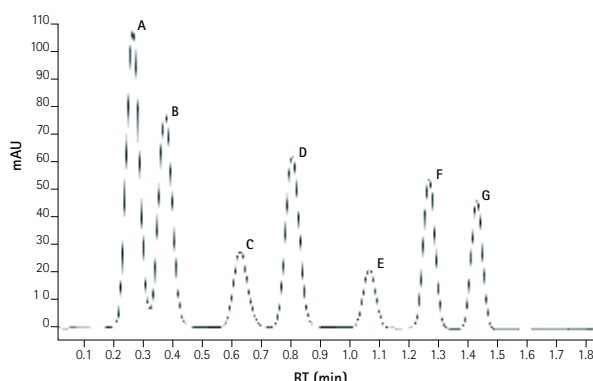
VARIAN, INC.

Designed For Performance

Take Advantage of Fast LC

We have extended the boundaries of HPLC performance with Fast LC, for faster method development, reduced solvent consumption, and increased sensitivity. The Varian 920-LC delivers:

- Rapid and reproducible gradient formations, a low carry-over autosampler and sensitive detectors — all essential requirements for Fast LC.
- A low delay volume kit with semi-micro mixer, narrow bore plumbing and micro flow cell.
- New, short, sub 3 μm Varian columns packed with small particles, for even faster LC.



Use 2.8 μm particle columns with rapid gradients for Fast LC, increasing productivity and sensitivity. Above, seven phenones were analyzed in less than 1.5 minutes. (A–G: acetophenone, propiophenone, benzophenone, valerophenone, hexanophenone, heptanophenone, octanophenone)

Column: Varian Ultra; Mobile phase: water/acetonitrile gradient, 45 to 100%; Detection: UV at 245 nm; Flow: 1.6 mL/min

Superb Solvent Delivery

The Varian 920-LC delivers virtually pulse-free solvent flow for outstanding performance.

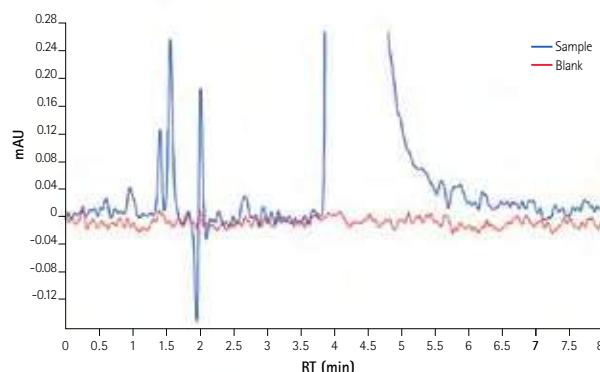
- State-of-the-art dual-piston, pulseless, low pressure, quaternary gradient solvent delivery system improves detection limits by reducing noise at the detector.
- Precision proportioning valves maximize productivity and reproducibility by delivering rapid, accurate and reproducible gradients.

- Dual-piston pump accurately blends the mobile phase for isocratic runs, improving retention time reproducibility and eliminating the need for manually pre-mixed solvent blends.
- Built-in vacuum Degasser™ eliminates bubble formation, maintains pump prime, and improves pump reliability.

Automated Sample Handling

Good chromatography begins with careful sample introduction. With the Varian 920-LC:

- Use the built-in autosampler to run your instrument unattended, and increase your laboratory's productivity, without sacrificing data quality for throughput.
- Sample injection is synchronized with piston position in the solvent delivery cycle to improve retention time reproducibility for gradient runs.
- Sample-to-sample contamination is eliminated by the external needle wash and needle-in-flow path design, which flushes the needle and injection path with solvent between samples.
- Temperature-controlled sample compartment maintains sample integrity for thermally unstable compounds.
- Use up to two hundred 2 mL HPLC vials or three 96 format wellplates, to further boost productivity.



Measure low concentration samples with ease — flushing of the needle and injection path with solvent drastically reduces carry-over. Above, a caffeine sample injection immediately followed by a blank injection produced no discernable carry-over.

Column: Varian Pursuit™ XRs C18; Mobile phase: 85% water, 15% acetonitrile; Detection: UV at 273 nm; Flow: 1 mL/min

Unrivalled Sensitivity and Precision

Outstanding Detection

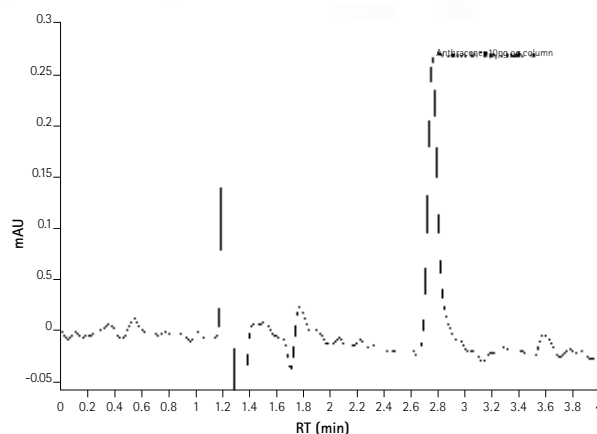
Whether you require UV-Vis detection for traditional analyses or information rich detection using photodiode array (PDA) technology, Varian has a solution for you. You can also add a fluorescence detector for more sensitive and selective detection, and for non-UV-Vis absorbing compounds you have the option of a refractive index or evaporative light scattering detector.

The UV-Vis detector for the Varian 920-LC features:

- Deuterium and quartz-halogen lamps with high light throughput optics, ensuring low noise and excellent linearity across the wavelength range.
- Outstanding detection limits and good response across a wide concentration range.
- Wavelength time programming, allowing you to optimize the detector performance.
- The ability to ratio two wavelengths for monitoring peak purity during a run, giving you greater confidence in your results.

The information-rich PDA detector for the Varian 920-LC features:

- Advanced double-beam optics design to minimize noise and drift, ensuring the best performance at the detection limits, and the highest analytical reproducibility.
- Automatic spectral searching against a library of known compounds, for fast identification of unknowns.
- Pre-aligned flow cells with focusing lenses to dramatically reduce refractive index effects, improving accuracy at low concentrations.
- Programmable slit widths from 1 μm to 16 μm for optimum light throughput, and unmatched performance and versatility.
- 1024 diode PDA detector with a wide wavelength range from 190 nm up to 900 nm.

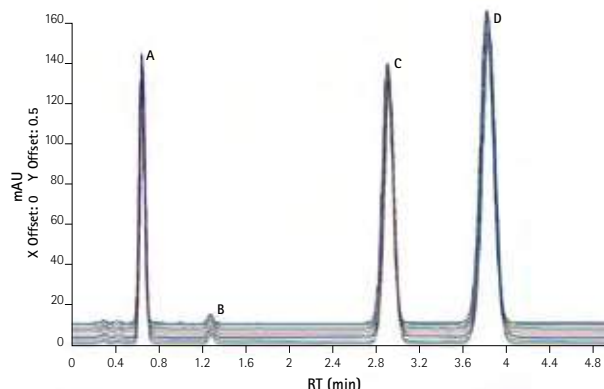


Achieve excellent signal-to-noise ratios with the highly sensitive, low noise, high light throughput UV-Vis detector. The above anthracene example shows a signal-to-noise ratio of 36.

Column: Varian Pursuit™ C8; Mobile phase: 85% acetonitrile, 15% water; Detection: UV at 251 nm; Flow: 0.3 mL/min

Accurate Column Temperature Control

A heated column compartment ensures rapid heating of the mobile phase for a consistent temperature profile along the column, providing retention time repeatability, and improved analytical reproducibility. The low delay volume pre-heater minimizes band broadening, maintaining chromatographic integrity.



Excellent reproducibility is made possible by the precise column heater, providing consistent retention times and the utmost confidence in your results. Above shows 12 sample injections of ibuprofen oral suspension. (A–D: polydatin, resveratrol, pterstilbene, emodin)

Column: Varian Pursuit XR8 C8; Mobile phase: 55% phosphoric acid, 45% acetonitrile; Detection: UV at 220 nm; Flow: 2 mL/min

VARIAN, INC.

Galaxie™ Chromatography Software

Simple. Flexible. Secure.

Software That Drives Productivity

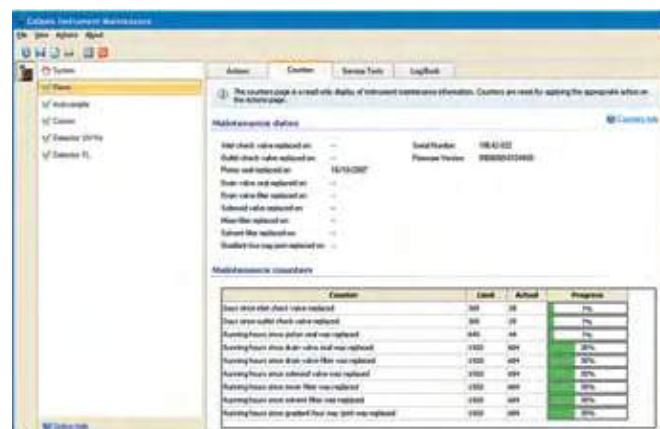
With Varian Galaxie Chromatography Software, control one or multiple Varian LCs, GCs, or third party chromatographs from a single PC. With an updated look and simple controls, Galaxie is easier than ever to use. It features:

- Automated method development, optimization and validation using optional Fusion AE™ (Automated Experiment) for Galaxie. Significantly improve productivity in R&D and QC laboratories.
- System Suitability software automatically monitors the quality of chromatographic analysis, such as peak asymmetry and column efficiency. It determines the best action to take to correct potential problems and ensure the integrity of results.
- Customized reports and powerful data handling capabilities, providing all the information you need in the format you want.
- User access control, audit trails and electronic signature capabilities for enhanced data security, assisting with operation in regulated environments, such as US FDA 21 CFR Part 11.
- An upgrade path to a Client/Server configuration to centralize system control and data handling.

Instrument Maintenance Scheduling

The Galaxie Instrument Maintenance window displays parameters such as pump strokes, number of injections and lamp intensity. As these parameters change, you can make informed decisions about when to perform maintenance on your instrument, for maximum uptime and peace of mind. You can also:

- Perform pre-defined instrument tests such as system noise, linearity, injection reproducibility, gradient accuracy, detector wavelength reproducibility and pressure integrity to ensure the highest confidence in instrument performance.
- Perform automated IQ/OQ tests to assist with operating in validated environments.



For an overview of the status of your Varian 920-LC, check the Instrument Status window. This dynamic, uptime enhancing window is an excellent diagnostic tool.

The Instrument Maintenance window lets you know when seals, valves and filters will require changing, so you are always prepared.



Depend on Varian for All Your Chromatography Needs...

From Microlitre to Litre Flows

Varian's unique capabilities in separation technologies extend from sample clean-up using Bond Plexa™, OMIX™, Bond Elut™ and Chem Elut™ extraction products, through analysis/identification and scale-up of the separation, all the way to pilot plant.

Our range of liquid chromatography systems provides microflow pumping on the Varian 320-MS LC/MS/MS systems, mL/min flow rates on the Varian 920-LC, Varian 940-LC analytical to preparative HPLC and SD-1 PrepStar™, to the ultimate in seamless scale-up with Varian expertise in pilot plant separations at L/min flow rates on our SepTech™ skid HPLC systems.

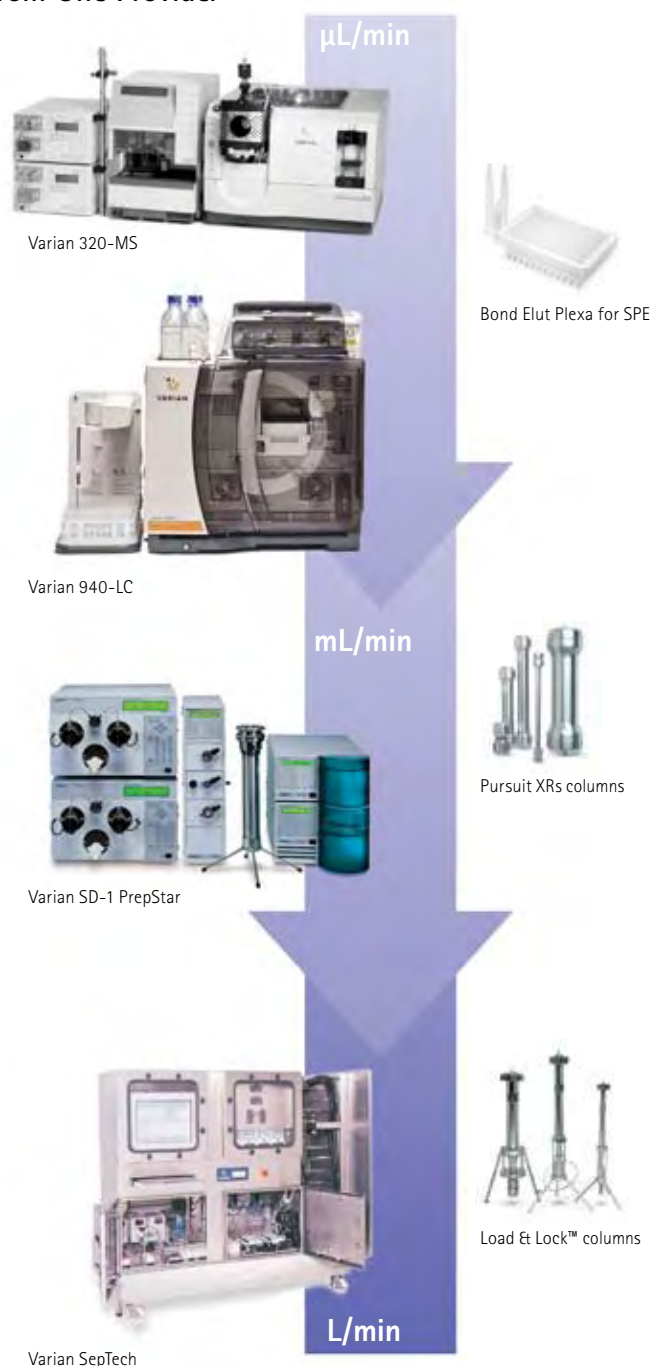
Varian Columns and Separation Media

Whether you need capillaries, 50 mm preparative columns or multi-kilo batches of prep and process chromatography packings for columns up to 150 mm ID, Varian can help. Our unique and exciting chemistries include Pursuit Diphenyl and PFP, Polaris™ and high performance Pursuit XRs C18 and C8 columns.

We manufacture every component of our proprietary phases, such as the world-famous Polymer Laboratories™ polymeric resins, and the pure silica gels in our Microsorb™ range. Our aim is to provide the highest quality columns, giving you better peak shapes, higher reproducibility and longer column lifetimes, all at an affordable price.

We are committed to meeting your needs with a full range of consumable products and supplies. Call today to request your free copy of our comprehensive analytical supplies catalog. Or, shop online at www.varianinc.com

Analytical to Process Scale Separation Solutions from One Provider



VARIAN, INC.

920-LC

ANALYTICAL LIQUID CHROMATOGRAPHY SOLUTIONS

Varian, Inc. – Supporting Customers Worldwide

All products are eligible for on-demand support from a worldwide network of specialists who can assist with any need. Varian, Inc. offers:

- Comprehensive programs that include a full range of services – from minor repairs, to complex applications development and training.
- Factory-qualified Field Support Representatives and Specialists, specifically chosen for each installation.
- Global support teams strategically located around the world.

To learn more about Varian's industry-leading customer support, visit our Web site at www.varianinc.com/support/

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AAnalyst 600 and AAnalyst 800 Atomic Absorption Spectrometers

System design

The AAnalyst™ 600 and AAnalyst 800 are the first fully-integrated benchtop design atomic absorption spectrometers, incorporating all spectrometer and atomizer components in a single instrument.

Optical system

Front-surfaced, reflecting optics with protective coating. Optical system sealed within protective cover.

AAnalyst 800 Real-time double-beam optical system (single-beam for Zeeman furnace operation).

AAnalyst 600 Single-beam optical system.

Monochromator Littrow design with motorized drive for automatic wavelength selection and peaking.

Wavelength range: 190-900 nm

Diffraction grating: 1800 lines/mm blazed at 236 nm and 597 nm

Grating area: 64 x 72 mm

Reciprocal linear dispersion: 1.6 nm/mm (nominal)

Focal length: 267 mm

Spectral bandwidths: 0.2, 0.7 and 2.0 nm, dual height (AAnalyst 800 only);
motorized slit drive for automatic slit selection

Detector Wide-range segmented solid-state detector, including a built-in low-noise CMOS charge amplifier array.

Automatic Lamp Selection 8-lamp holder with built-in power supplies for hollow cathode and electrodeless discharge lamps. Computer-controlled lamp selection and alignment via WinLab32™ software. Operating parameters are automatically set when using PerkinElmer® Lumina™ hollow cathode lamps.

Flame system (AAnalyst 800)

Gas Controls Fully computer-controlled with oxidant and fuel monitoring. Keyboard-actuated remote ignition system with air-acetylene. Acetylene flow is automatically adjusted prior to the oxidant change when switching to or from nitrous oxide-acetylene operation. TotalFlow™ control of the oxidant and fuel gases for constant fuel:oxidant ratio.

Safety Functions	Interlocks prevent ignition if the proper burner head, the nebulizer/end cap, or the burner drain system are not correctly installed; the liquid level in the drain vessel is incorrect; or gas pressures are too low. Interlocks automatically shut down gases if a flame is not detected, or if any of the other interlock functions are activated. Safe shutdown in the event of a power failure.
Burner System	Premix design that can be moved automatically into the sample compartment via software control and a motorized carriage. Alignment of the flame in the light beam is fully automatic and optimized, using a motorized burner mount for vertical and horizontal burner adjustments. The burner is equipped with a high-strength inert mixing chamber, angled to ensure proper drainage. Includes adjustable high-precision nebulizer and an all-titanium, 10-cm, single-slot burner head for air-acetylene operation.

Background correction

AC Zeeman-effect background correction using a modulated 0.8 Tesla magnetic field oriented longitudinally to the optical path. The magnet is automatically switched on during the atomization step only.

AAAnalyst 800 Built-in continuum source double-beam background correction for flame operation.

Graphite furnace

Built-in computer-controlled Transversely Heated Graphite Atomizer (THGA™). The graphite tube is transversely heated, providing a uniform temperature profile over the entire tube. An external protective gas stream around the graphite tube prevents the entrance of outside air to maximize tube life. An internal purge gas goes through the graphite tube to remove the volatilized matrix vapors during drying and thermal pretreatment. The two gas streams are independently computer-controlled. Pneumatic opening and closing of the furnace for easy tube change.

AAAnalyst 800 The graphite furnace can be moved automatically into the sample compartment and positioned via software control and a motorized carriage.

Furnace features

Program Flexibility	Analytical programs with up to 12 steps can be set up. Each step can be programmed with the following parameters:
	Temperature: Ambient up to 2600 °C in steps of 10 °C
	Ramp and Hold Time: 1 to 9 sec. in steps of 1 sec.
	Internal Gas Flow: 0, 50, or 250 mL/min; can be switched over to another type of gas
	Required Inert Gas: Argon. Inlet pressure 300 kPa (3 bar) minimum. Maximum gas consumption is 700 mL/min.
	Water Coolant: A circulatory cooling system is included with the AAAnalyst 800, optional for the AAAnalyst 600. When operating the AAAnalyst 600 without the circulatory cooling system, cooling water meeting the following specifications should be used: Sediment-free drinking water; 20-40 °C; flow rate not less than 2 L/min; pressure between 2.5 and 4.5 bar; pH between 6.5 and 7.5; hardness not greater than 14°dH or 100 ppm.

Furnace autosampler

Sampler Table	Removable sample tray with 88 and 146 sampling positions and 1 overflow container for pipet washing. Minimum sample requirement: ca. 0.1 mL.
Dispensable Volume	Sample and Reagent: 1-99 µL, selectable in increments of 1 µL
Electronics	The autosampler is powered from the spectrometer and is software-controlled.

Fume extraction system

AAAnalyst 600 Optional built-in device that removes all sample fumes generated during furnace drying and pyrolysis steps.

Data control system

Complete PC control using WinLab32 software. Provides complete control of the instrument and its major accessories plus data handling and storage.

Data Handling Instrument readings linear in absorbance (-0.500 A to +2.000 A), concentration or emission intensity. Integration times are operator-selectable from 0.1 to 60 sec. in increments of 0.1 sec. Reading modes include time-averaged integration, non-averaged integration (peak area), and peak height measurement. Includes built-in statistics. Up to thirty (30) standards and a choice of calibration equations. Reslope of the analytical curve using a single operator-selected calibration standard. Built-in IEEE-488 interface for computer connection and use of optional accessories.

Dimensions

110 cm wide x 65 cm high x 70 cm deep (104 cm deep with furnace autosampler)

Weight AAAnalyst 600: 175 kg (without controller and cooling system)

AAAnalyst 800: 187 kg (without controller and cooling system)

Power requirements

230 V ($\pm 10\%$), 50/60 Hz ($\pm 1\%$), 5000 VA (maximum)

Electrical Protection As defined in EN 61010-1; Insulation Class I; Installation Category II; Pollution Degree 2.

Technical standards

Certification Designed and tested to be in compliance with the legal requirements for laboratory instruments. The instrument was developed and produced in compliance with ISO 9001. The WinLab32 software provides required control parameters for GLP and instrument performance verification.

Safety Standards EN 61010-1, EN 61010-2-061, CSA C22.2 No. 1010.1, CSA C22.2 No. 1010.2.061. The instruments bear the CE Mark and the CSA/NRTL Certification Mark.

EMC Standards EN 61326, EN 55011, EN 61000-3-2, EN 61000-3-3

Environmental requirements

Ambient Temperature +15 °C to +35 °C

Relative Humidity 20% to 80%, non-condensing

Cooling system

Self-priming recirculatory system with fan-assisted heat exchanger (standard with the AAAnalyst 800, optional with the AAAnalyst 600) for constant cooling of the graphite furnace. Water temperature during operation approx. 36 °C; water flow 2.5 L/min.

Power Requirements 230 V ($\pm 10\%$), 50/60 Hz ($\pm 1\%$); approx. 140 VA

Dimensions 20 cm wide x 375 cm high x 50 cm deep

Weight 18 kg with coolant

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Model 7401/7401VR Alpha Spectrometer

Features

- Stainless steel vacuum chamber
- Accommodates samples up to 50 mm (2 in.) diameter
- Supports the use of alpha detectors up to 1200 mm²
- Optional reverse sample bias (standard with 7401VR)
- Built-in counter/timer
- Integral vacuum gauge with vacuum/bias interlock
- Bias supply variable to 198 V dc, positive or negative
- Digital display of:
Counter/Timer, Chamber Pressure, Detector Bias,
Leakage Current, Pulser Energy, Discriminator Energy

Description

The Canberra Model 7401 is a comprehensive alpha spectrometer that can accommodate samples up to two inches in diameter in a double-width NIM package. The versatile sample chamber and instrument electronics support Canberra's own PIPS Detectors, which combine high resolution and low backgrounds in a rugged alpha detector with active areas up to 1200 mm². In addition, the alternative use of most charged particle detectors is also supported. The Model 7401 fully integrates into one package a stainless steel vacuum chamber for low backgrounds and ease of cleaning, a vacuum gauge, detector bias supply, preamp/amplifier, pulser, discriminator, counter, and digital display. A stainless steel shelf and sample holder are included with each spectrometer, for reproducible detector/sample spacing, which is user selectable from 1 to 49 mm, in 4 mm increments.

The full functionality of the 7401 is enhanced by a microprocessor-managed user interface. Front panel controls allow the user to quickly set and easily display the bias voltage on the detector, the energy value of the calibrated internal pulser, the energy value of the discriminator and the preset time for the built-in counter. Additionally, the front panel display also monitors chamber pressure, detector leakage current, accumulated counts and elapsed time. To facilitate routine work and quick setup, the detector bias voltage, discriminator energy and pulser settings are retained in memory when the 7401 is switched off. For gross alpha counting, the counter can be started, stopped and reset using the simple front panel switches. For added convenience, the time display can be internally configured for either seconds or hours.

To support a variety of alpha detectors, the built-in detector bias supply is adjustable from 2 to 198 V dc, positive or negative. Premature and possibly damaging application of bias to the detector is avoided by a user-configured interlock. The interlock safely inhibits the bias supply until proper vacuum is attained, then the bias voltage is gradually ramped to the predetermined setting, over approximately one minute.

The precision preamp and amplifier provide the optimal pulse shaping and signal conditioning required for detectors used in alpha spectrometry. Gain and offset of the amplifier can be adjusted by means of front panel access to multi-turn controls. For reference, the internal test pulser can be set to mark energies from 0.1 to 10 MeV and can be used to calibrate the spectrometry system without the use of alpha emitting sources. The counter discriminator also is calibrated in energy units and is fully variable between 0.1 and 10 MeV. The discriminator output, indicating activity above the selected setting, is available at the



rear panel counts output. The rear panel also has a connector for signal input from an optional external test pulser. When combined with appropriate Canberra Mixer/Routers, Multiplexers and software products, a single multichannel analyzer (MCA) can easily support multiple 7401 Alpha Spectrometers in a complete data acquisition and analysis system.

Each Model 7401 Alpha Spectrometer has a pressure gauge with an operating range of 0-1000 μ m Hg (0-133 Pa). For those who need to operate at higher chamber pressures, the Model 7401VR Alpha Spectrometer has a pressure gauge range of 0-20 mm Hg (0-2.67 kPa). Chamber pressure is manually controlled by a three-position mechanical valve. To provide reliable performance with little maintenance, the stainless steel door of the chamber is equipped with hinges which automatically adjusts to and compensates for proper gasket compression. For added confidence, the vacuum chamber is helium leak tested to 10^{-10} cc/s during manufacture.

Reverse sample bias is available as an option in the 7401 Alpha Spectrometer as Model 7401-RSB. In applications requiring this option, reverse bias is provided by four 3-volt batteries. The Model 7401VR Alpha Spectrometer includes the 7401-RSB Reverse Sample Bias option.

Phone contact information

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For other international representative offices, visit our Web Site: <http://www.canberra.com> or contact the Canberra U.S.A. office.

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Specifications

INPUT

TEST INPUT – Accepts signal from external square wave or tail pulser; $Z_{in} = 93 \Omega$; gain nominally $\times 10$; rear panel BNC.

OUTPUTS

ENERGY OUTPUT – Provides positive, linear near-Gaussian shaped unipolar pulses proportional to energy, linear to $+10$ V; max output 12 V; dc restored; $Z_{out} = 10 \Omega$; short circuit protected; rear panel BNC.

TP (Test Point) – Replica of the energy output signal; isolated by $1 \text{ k}\Omega$ resistance; front panel mounted pin jack.

COUNTS OUTPUT – NIM-standard positive logic pulse available on rear panel BNC connector for driving external counter; pulse width nominally $3.5 \mu\text{s}$ for any event above discriminator setting; $Z_{out} \approx 50 \Omega$, dc coupled.

DISPLAY

Multi-purpose 5-digit LED display shows chamber pressure in $\mu\text{m Hg}$ (mm Hg on the 7401VR), detector leakage current (μA), gross counts, elapsed time, preset time, detector bias, discriminator level (MeV), and calibration pulser level (MeV); time readout in seconds or hours.

FRONT PANEL CONTROLS AND INDICATORS

BIAS ON/OFF – Toggle switch controls high voltage supply.

BIAS LED Indicator – Blinks when bias voltage is inhibited and while supply is increasing to preset value; steadily illuminated when supply approaches final value.

FUNCTION LED Indicators – One of eight LEDs is illuminated when corresponding function is selected for display; COUNTS LED blinks when counter is active; CAL LED blinks when calibration pulser is active.

INCREMENT/DECREMENT – Dual purpose momentary toggle switch selects display function and sets preset time, detector bias, calibration pulser level or discriminator level.

DIGIT SELECT – Pushbutton switch chooses display digit to be incremented or decremented; operable when setting preset time, HV bias, calibration pulser, or discriminator level.

START/STOP – Dual purpose momentary toggle switch starts or stops counter when counter functions are selected or starts/stops pulser when calibration pulser is selected.

RESET – Pushbutton resets counter and timer.

GAIN – Screwdriver adjustable multi-turn potentiometer adjusts amplifier gain.

OFFSET – Screwdriver adjustable multi-turn potentiometer adjusts amplifier offset.

PUMP/OFF/VENT – 3-position valve control; PUMP connects vacuum pump to chamber; OFF isolates pump from chamber and chamber from atmosphere; VENT vents chamber to atmosphere and isolates pump. Locks in pump position by turning handle one quarter turn counterclockwise.

REAR PANEL CONTROL

VACUUM/BIAS INTERLOCK – Locking toggle switch enables or disables bias inhibit; inhibit is triggered when chamber pressure exceeds threshold.

INTERNAL CONTROLS (Circuit board mounted)

VACUUM/BIAS INTERLOCK SET POINT – Dual position jumper chooses vacuum level at which bias is enabled. 7401 nominal trip level is 100 or $500 \mu\text{m Hg}$ (13 or 67 Pa); factory set to $500 \mu\text{m Hg}$ (67 Pa). 7401VR nominal trip level is 0.3 mm Hg (0.04 kPa) or 10 mm Hg (1.33 kPa); factory set to 10 mm Hg (1.33 kPa).

BIAS POLARITY – Toggle switch sets polarity of detector bias supply and internal pulser. Factory set for positive bias.

AMPLIFIER POLARITY – Jumper allows amplifier to accept positive or negative detector pulses. Factory set to process negative pulses.

TIME FORMAT – Jumper sets seconds or hours time display. Factory set for seconds display.

SYSTEM PERFORMANCE

(Based on use of a 450-20 AM PIPS detector with a good quality ^{241}Am point source.)

ENERGY RESOLUTION – $\leq 20 \text{ keV}$ (FWHM) with a detector-source spacing equal to the detector diameter.

DETECTOR EFFICIENCY – $\geq 25\%$ for detector-source spacing of less than 10 mm .

BACKGROUND – $\leq 1 \text{ count/hr}$ above 3 MeV .

ELECTRONICS PERFORMANCE

BIAS SUPPLY

Range – Nominal 1 V to $\pm 198 \text{ V}$ dc, adjustable in 2 V steps from 2 V to full voltage.

Stability – Better than $50 \text{ ppm}/^\circ\text{C}$.

Noise – $\leq 5 \text{ mV}$ peak-to-peak.

Display Resolution – 0.1 V .

CALIBRATION PULSER

Range – 0.1 to 10 MeV , adjustable in 0.1 MeV steps.

Stability – Better than $50 \text{ ppm}/^\circ\text{C}$.

Display Resolution – 10 keV .

DISCRIMINATOR

Range – 0.1 to 10 MeV .

Display Resolution – 10 keV .

DETECTOR CURRENT MONITOR

Range – 0 to $20.00 \mu\text{A}$.

Display Resolution – $0.01 \mu\text{A}$.

VACUUM GAUGE

7401 Range – 0 to $1000 \mu\text{m Hg}$ (0 to 133 Pa).

7401VR Range – 0 to 20 mm Hg (0 to 2.67 kPa).

COUNTER

Count Range – 0 to $99\,999$ counts.

Time Range – 0 to $99\,999$ seconds or 0 to 999.99 hours.

Preset Time Range – Same as Time Range.

Time base – 50 Hz or 60 Hz power line frequency or internal crystal, automatically selected.

PREAMPLIFIER/AMPLIFIER

Shaping – $0.5 \mu\text{s}$ unipolar, dc restored.

Integral Nonlinearity – $\leq 0.4\%$ of full scale.

Gain Range – 6 MeV to 13 MeV full scale (17 to 40 V/pC , 1 to 2.5 V/MeV).

Gain Drift – $\leq 200 \text{ ppm}/^\circ\text{C}$.

DC Drift – $\leq \pm 100 \mu\text{V}/^\circ\text{C}$.

Noise – $\leq 0.12 \text{ fC RMS}$ referred to input at 0 pF input capacitance.

Offset range – 0 to $\pm 200 \text{ mV}$.

CONNECTORS

TEST INPUT, ENERGY OUTPUT and COUNTS OUTPUT – BNC type UG-1094/U.

VACUUM – 9.5 mm ($\frac{3}{8} \text{ in.}$) O.D. aluminum fitting mounted through rear panel.

DETECTOR – Axial microdot.

POWER REQUIREMENTS

$+24 \text{ V}$ dc – 100 mA $+12 \text{ V}$ dc – 250 mA

-24 V dc – 50 mA -12 V dc – 50 mA

PHYSICAL

SIZE – Standard double-width NIM module $6.86 \times 22.12 \text{ cm}$ ($2.70 \times 8.71 \text{ in.}$) per DOE/ER – 0457 (1990).

NET WEIGHT – 2.5 kg (5.5 lb).

SHIPPING WEIGHT – 3.2 kg (7.0 lb).

VACUUM CHAMBER AND HARDWARE – 8.16 x 6.03 x 6.25 cm (3.25 x 2.375 x 2.5 in.) (height, width, depth). Stainless steel chamber, door, shelf and sample holder.

SAMPLE SIZE – Up to 51 mm (2 in.) diameter.

MAXIMUM DETECTOR SIZE – 1200 mm².

SAMPLE-DETECTOR SPACING – 1 to 49 mm in 4 mm steps.

SAMPLE HOLDER – One Model 7401SH-M sample holder for 32 mm (1.25 in.), 25 mm (1 in.) or 19 mm (0.75 in.) samples is supplied. Other sample holder sizes are available as extra cost options.

ENVIRONMENTAL

OPERATING TEMPERATURE – 0 to 50 °C.

OPERATING HUMIDITY – 0 to 80% relative, non-condensing. Tested to the environmental conditions specified by EN 61010, Installation Category I, Pollution Degree 2.

OPTIONS

Model 7401-RSB Reverse Sample Bias – Includes four 3 V batteries mounted on the sample shelf. The average battery life is 8 years.

Model 7401VR Alpha Spectrometer – Same as 7401 except the pressure gauge has a range of 0 to 20 mm Hg (0 to 2.67 kPa); also includes Model 7401-RSB Reverse Sample Bias option.

Model 7401SH-3 sample holder for 19 mm ($\frac{3}{4}$ in.) samples.

Model 7401SH-4 sample holder for 25 mm (1 in.) samples.

Model 7401SH-8 sample holder for 51 mm (2 in.) samples.



ORTEC[®]**SOLOIST™**
Alpha Spectrometer

- A versatile, integrated, alpha spectrometer for measuring low-activity samples that decay by alpha-particle emission
- Includes sample changer, detector, bias supply, preamplifier, amplifiers, and calibration pulser in a NIM-standard double-width module
- Accommodates horizontal samples up to 5.1 cm (2 in.) in diameter with adjustable sample-to-detector spacing
- Available with low-background ULTRA-AS™ Series detectors up to 1200 mm² in active area
- Easy access to vacuum chamber through hinged door featuring a high-reliability O-ring seal
- Removable, nickel-plated brass chamber simplifies decontamination
- Calibrated outputs and controls for selected energy ranges
- Complete, turn-key, multiple-unit alpha spectrometer systems available

The SOLOIST is an integrated spectrometer for measuring low-activity samples that decay by alpha-particle emission. It incorporates all the necessary functions within a NIM-standard double-width module. The module includes vacuum chamber, detector, bias supply for the detector, complete amplifying chain (preamplifier, amplifier, and biased amplifier), and calibration pulser.

The SOLOIST offers three flexible methods for recording the alpha emission activity. The simplest is to record the gross counting rate above the 2.5-MeV threshold using an external counter and timer. To achieve much lower detection limits, the linear amplifier output can be fed to a multichannel pulse-height analyzer (MCA) for quantitative analysis of specific isotope peaks in the 3- to 10-MeV energy spectrum. The biased amplifier output of the SOLOIST offers selection of a restricted energy range (containing only the peaks of interest) for analysis on the MCA. This feature allows a larger number of alpha spectrometers to be multiplexed into the limited memory size of a single MCA. A front-panel switch provides 6 selectable energy ranges at the biased amplifier output (3 to 8 MeV, 4 to 7 MeV, 3 to 5 MeV, 4 to 6 MeV, 5 to 7 MeV, and 6 to 8 MeV). Three front-panel adjustments permit precise calibration on any selected energy range.

The SOLOIST includes a robust, low-background, sample chamber. The chamber is cast in brass, then machined to close tolerances, before being nickel plated to ensure easy decontamination. In the event of severe contamination, the chamber may be easily isolated from vacuum, and then removed from the module. A compressed, high-performance O-ring, retained in a dove-tailed groove in the face of the chamber, provides an ultra-reliable vacuum seal for the chamber door. Nickel-plated brass sample trays slide into the chamber to provide an adjustable and precisely reproducible sample-to-detector spacing. Trays are available to handle sample sizes from 13 mm (0.5 in.) to 51 mm (2 in.), with sample-to-detector spacing selectable from 1 to 41 mm in increments of 4 mm. The front-panel PUMP/HOLD/VENT valve makes it easy to insert, count, and remove samples without disturbing the vacuum on other SOLOIST chambers attached to the same vacuum pump. A standard Swagelok® fitting on the rear panel simplifies



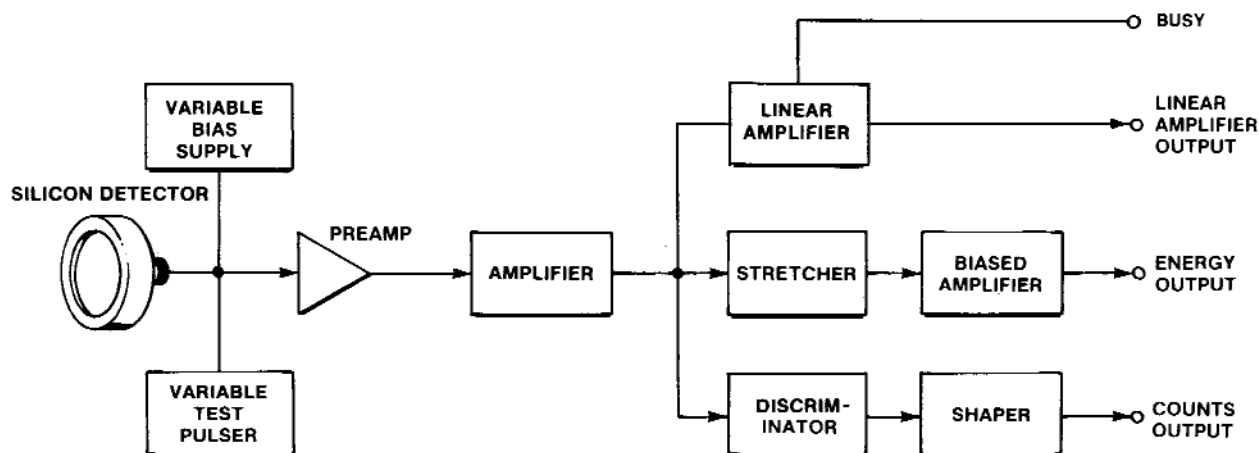


Fig. 1. A Simplified Block Diagram of the SOLOIST Electronics.

connection of the valve and chamber to an external vacuum pump. An optional pump station (Model ALPHA-PPS-115 or -230) is available for this function, and the Model 576-VM Vacuum Manifold can be added to connect up to four SOLOIST modules to the same vacuum pump.

The SOLOIST is available with an ULTRA-AS Series detector installed. These ion-implanted silicon detectors from ORTEC are specially designed and fabricated for low-background applications in alpha spectrometers. Detector sizes up to 1200 mm² in active area can be accommodated. The SOLOIST is also available without the detector to permit installation of alternative types of silicon detectors, such as ORTEC Ruggedized™ R-Series surface barrier detectors, or other ORTEC surface barrier detectors. A front-panel adjustment and internal jumpers accommodate detectors requiring positive or negative bias voltage in the range of 0 to 100 V.

A variety of single-input or multiplexed-input multichannel analyzers are available from ORTEC for use with the SOLOIST. Quantitative alpha-spectroscopy software is also offered with most of these MCAs.

Specifications

PERFORMANCE

Unless otherwise specified, the performance** is measured using a low-background 450 mm², ULTRA-AS Series detector, a good-quality ²⁴¹Am point source, and a detector-to-source spacing equal to the detector diameter.

MAXIMUM SAMPLE SIZE 51 mm (2.030 in.).

MAXIMUM SAMPLE-TO-DETECTOR SPACING 44 mm.

MAXIMUM DETECTOR SIZE 1200 mm².

ENERGY RANGES Biased amplifier (ENERGY) output: 3 to 8 MeV, 4 to 7 MeV, 3 to 5 MeV, 4 to 6 MeV, 5 to 7 MeV, and 6 to 8 MeV. Linear amplifier output (LIN AMP OUT): 3 to 10 MeV.

INTEGRAL NONLINEARITY $\pm 0.1\%$ of full scale in each energy range.

ENERGY RESOLUTION <20 kev.

DETECTOR EFFICIENCY >25% for a detector-to-source spacing <10 mm and a ²⁴¹Am point source.

BACKGROUND <24 counts in 24 hours above 3 MeV. Measured from the COUNTS output with no radioactive source in the chamber.

VACUUM CHAMBER

CONSTRUCTION Cast brass, with nickel plating for ease of decontamination. High-performance O-ring seal. Three-position PUMP/HOLD/VENT valve.

SAMPLE TRAYS Slide-in, nickel-plated brass sample trays are available to accommodate sample diameters from 13 mm (0.5 in.) to 51 mm (2 in.). (See Ordering Information). One sample tray (Model SOL-ST-1) is included with the SOLOIST.

SAMPLE-TO-DETECTOR DISTANCE Adjustable from nominally 1 mm to 41 mm in increments of 4 mm using slide-in

sample trays. Maximum distance from detector to bottom of chamber is approximately 44 mm.

DETECTOR SIZES The SOLOIST is available with high-performance, low-background, ULTRA-AS Series detectors. Select an active area of 300, 450, 600, 900, or 1200 mm². See Ordering Information.

CONTROLS

ENERGY RANGE Front-panel, six-position switch selects the energy range at the biased amplifier output. Selectable ranges for zero to full-scale amplitude at the ENERGY output are 3 to 8 MeV, 4 to 7 MeV, 3 to 5 MeV, 4 to 6 MeV, 5 to 7 MeV, and 6 to 8 MeV.

OFF/BIAS/PULSER Front-panel, three-position toggle switch controls the on/off conditions of the detector bias and the pulser.

SOLOIST™

Alpha Spectrometer

Switch Position	OFF	BIAS	PULSER
Detector Bias	off	on	on
Pulser	off	off	on

The associated red LED turns on when the bias voltage is on.

PULSER Front-panel 10-turn locking dial controls the pulser amplitude for energy calibration. Range: 0 to 10 MeV.

VACUUM PUMP/HOLD/VENT Front-panel, three-position valve controls the pumping or venting of the vacuum chamber. The HOLD position can be used to isolate the chamber from the vacuum pump when evacuating other chambers.

E BIAS Front-panel, 20-turn screwdriver control provides a $\pm 10\%$ adjustment of the biased amplifier threshold, to calibrate the lower limit of the energy range at the ENERGY output.

ΔE Front-panel, 20-turn screwdriver control adjusts the biased amplifier gain, to calibrate the upper limit of the energy range at the ENERGY output. The amplitude for the upper energy limit can be adjusted from 7.75 V to 10.25 V to match the input range of the ADC being used.

AMP GAIN Front-panel, 20-turn screwdriver control adjusts the full-scale calibration of the linear amplifier output (LIN AMP OUT) from 5 MeV to 10 MeV for a 10-V output pulse amplitude. Factory set for 10 MeV at 10 V.

DETECTOR POLARITY JUMPERS (+/-) Five printed circuit board jumpers select the polarity of the amplifier gain and the detector bias voltage to match the polarity of voltage required by the detector. Normally shipped in the "+" position for ULTRA-AS Series detectors.

DET BIAS ADJ Rear-panel, one-turn screwdriver control permits adjustment of the detector bias to the value specified for the installed detector. Variable from 0 to 100 V. Bias polarity is set to match the detector via the Detector Polarity Jumpers.

INPUTS

VACUUM Rear-panel vacuum connector (Swagelok connector for 0.25-in. O.D. tubing) for connecting the vacuum chamber in the module to a vacuum pump.

EXTERNAL PULSER Rear-panel BNC connector accepts external pulser signals. Input impedance is 100 Ω , dc-coupled. Input pulse polarity must be opposite that of the detector bias polarity.

OUTPUTS

COUNTS Rear-panel BNC connector provides a NIM-standard positive logic pulse for any detected particle having an energy greater than 2.5 MeV. Used for gross alpha counting, or routing in a multichannel analyzer. Pulse width is 3.5 μ s. Output impedance is 50 Ω , dc-coupled.

ENERGY Rear-panel BNC connector provides the linear output signal from the biased amplifier for connection to an ADC or multichannel analyzer. Output amplitude range is factory set for 0 to +10 V which corresponds to the energy ranges selected by the front-panel ENERGY RANGE switch. See E BIAS and ΔE controls for output range adjustment and calibration. Output impedance is 100 Ω , dc-coupled.

LIN AMP OUT Rear-panel BNC connector delivers the linear amplifier output signal for connection to an ADC or multichannel analyzer. Factory adjusted for 3 to 10 MeV, corresponding to a 0- to +10-V output pulse amplitude. See AMP GAIN control for calibration adjustment. Output pulse has a unipolar, semi-Gaussian pulse shape with a 1- μ s shaping time constant. Output impedance is 100 Ω , dc-coupled.

BUSY Rear-panel BNC connector produces a NIM-standard positive logic pulse whenever the module is busy processing a pulse. Can be supplied to an ADC or multichannel analyzer to assist in dead-time corrections when dead-time losses are significant. Output impedance is 10 Ω , dc-coupled.

DET/1.1 MEG OHM/HV Rear-panel test jacks permit monitoring the voltage of the detector bias supply, and the detector load current. The bias supply voltage is read at the HV test jack. The voltage measured between the two test jacks permits calculation of the detector load current flowing through the 1.1-M Ω resistor.

ELECTRICAL AND MECHANICAL

POWER REQUIRED The SOLOIST derives its power from a NIM-standard bin/power supply, such as the ORTEC

Model 4001A/4002A, or 4001A/4002D. The power required is +24 V at 120 mA, +12 V at 90 mA, -12 V at 45 mA, and -24 V at 75 mA.

WEIGHT

Net 2.4 kg (5.2 lb).

Shipping 2.3 kg (7.3 lb).

DIMENSIONS NIM-standard, double-width module 6.90 x 22.13 cm (2.70 x 8.714 in.) front panel per DOE/ER-0457T.

ACCESSORIES

SPARE CHAMBER GASKETS Replacement O-rings for the vacuum chamber door are available in quantities of 10 in a package. See Ordering Information.

SAMPLE TRAYS A variety of slide-in sample trays are available to hold different sample sizes. See Ordering Information.

VACUUM MANIFOLD The ORTEC Model 576-VM Vacuum Manifold and Control is recommended for connecting a common vacuum source to four SOLOIST modules.

PORTABLE PUMP STATION The ORTEC Model ALPHA-PPS-115 or -230 Portable Pump Station is recommended for evacuating the sample chamber in the SOLOIST. The pump station is available in both 115-V and 230-V ac version, and can be combined with the Model 575-VM Vacuum Manifold to serve multiple SOLOIST modules. The standard pump station is supplied with 1 m (40 in.) of 1-in. I.D. vacuum hose for connection to the 576-VM, and 0.9 m (36 in.) of 1/4-in. O.D. vacuum hose for coupling the larger hose to the SOLOIST. If different lengths are required, contact the factory for a special order.

MULTICHANNEL ANALYZERS WITH SOFTWARE The ENERGY output of the SOLOIST is intended for use with a multichannel pulse-height analyzer.

REPLACEMENT DETECTORS Detectors that have been severely contaminated or otherwise damaged beyond use can be replaced by ordering a new detector of the same size from the ULTRA-AS Series of detectors. Be sure to specify the ULTRA-AS detector with a B Mount.

SOLOIST™

Alpha Spectrometer

Ordering Information

To order, specify the following model numbers and descriptions:

Model Number	Description
SOLOIST	Alpha Spectrometer without detector
SOLOIST-U0300	Alpha Spectrometer with 300-mm ² ULTRA-AS detector
SOLOIST-U0450	Alpha Spectrometer with 450-mm ² ULTRA-AS detector
SOLOIST-U0600	Alpha Spectrometer with 600-mm ² ULTRA-AS detector
SOLOIST-U0900	Alpha Spectrometer with 900-mm ² ULTRA-AS detector
SOLOIST-U1200	Alpha Spectrometer with 1200-mm ² ULTRA-AS detector
Accessories	
ALPHA-PPS-115	115-V Portable Pump Station
ALPHA-PPS-230	230-V Portable Pump Station
SOL-CG	Spare O-rings for vacuum chamber door (pkg. of 10)
SOL-ST-KK	Set of Sample Trays: One each of all four sizes (.5 in. through 2 in.)
SOL-ST-1	Sample Tray for 3/4 in. (19 mm) and 1 in. (25 mm) diameter samples
SOL-ST-2	Sample Tray for 1/2 in. (13 mm) and 7/8 in. (22 mm) diameter samples
SOL-ST-3	Sample Tray for 1.25 in. (32 mm) and 1.5 in. (38 mm) diameter samples
SOL-ST-4	Sample Tray for 1.75 in. (44 mm) and 2 in. (51 mm) diameter samples
576-VM	Vacuum Manifold and Control for 115 V
576-VM-230	Vacuum Manifold and Control for 230 V

Specifications subject to change
042604



800-251-9750 • www.ortec-online.com

info@ortec-online.com • Fax (865) 483-0396
801 South Illinois Ave., Oak Ridge, TN 37831-0895 U.S.A. • (865) 482-4411
For International Office Locations, Visit Our Website

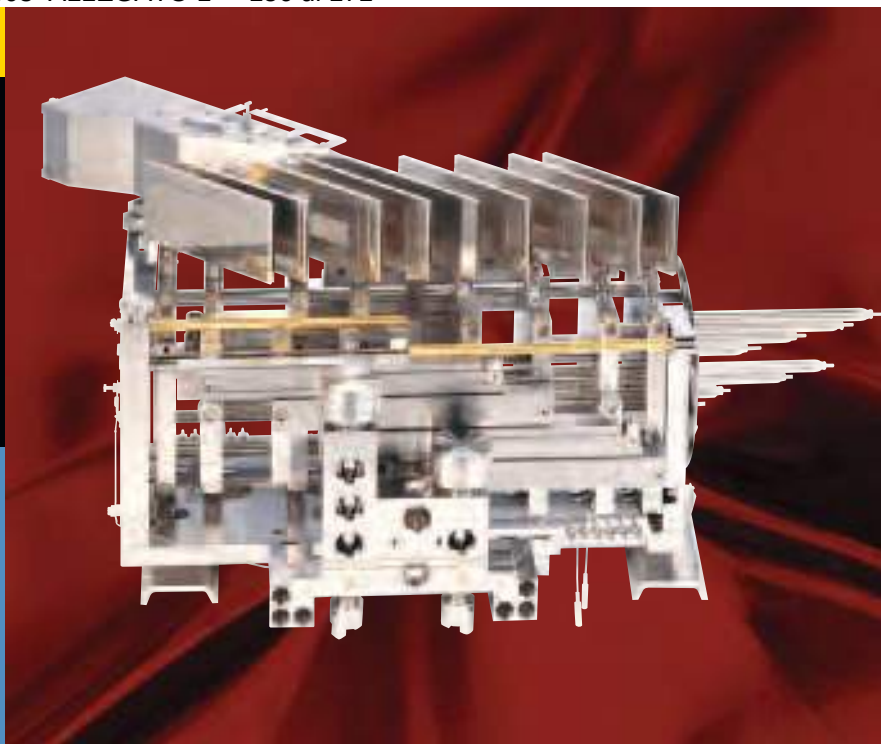


AMETEK
ADVANCED
MEASUREMENT
TECHNOLOGY

MASS SPECTROMETRY

**Thermo Scientific TRITON
Thermal Ionization MS**

**Thermo Scientific NEPTUNE
Multicollector ICP-MS**



*High Resolution
Multicollector Mass Spectrometers*

Thermo Scientific TRITON

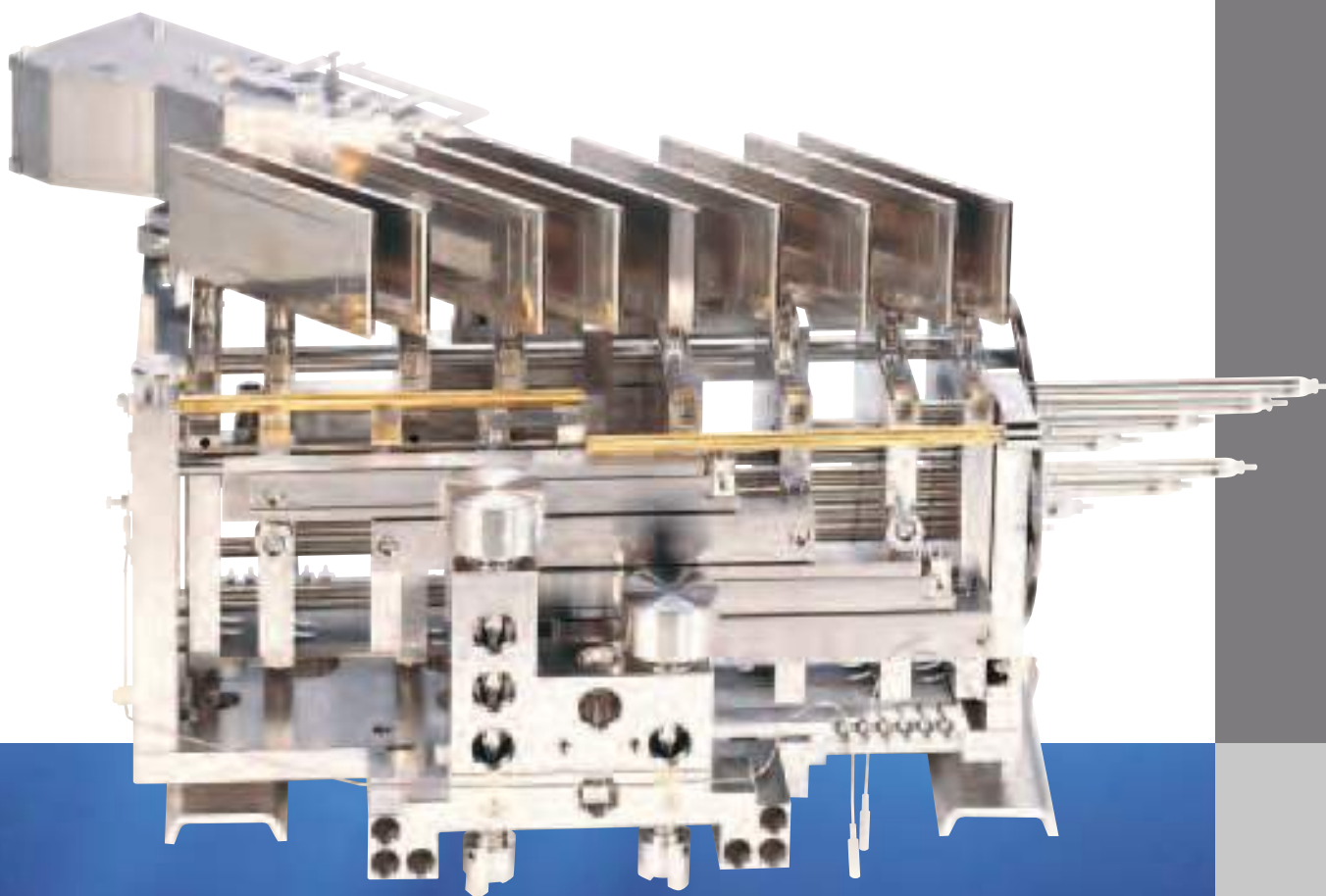
Thermo Scientific NEPTUNE

High Resolution Multicollector Mass Spectrometers

Based on more than 25 years experience in variable multicollector instrumentation, we have developed two instruments based on an innovative multicollector platform.

- High resolution ion optics corrected for second order image aberrations
 - Largest mass dispersion (812 mm)
 - Angular and energy focusing image planes are almost coincident
- Zoom optics to enhance dynamic multicollector measurements
 - Precise peak overlap for multi-dynamic measurements
- Field proven Faraday cups with largest aspect ratio
 - No cup factors
- Multiple Ion Counting (MIC)
 - Up to 8 moveable miniaturized SEMs in parallel
- Variable multicollector
 - Variable in position
 - Variable in detector type (Faraday/SEM)
 - Up to 17 collectors in parallel
 - "Plug-in" design of Faradays and SEMs
 - 17% relative mass range
- Virtual Amplifier system
 - No amplifier calibration bias
 - Linear response up to 50 V (positive ion mode)
- 10 kV acceleration voltage
 - Highest sensitivity
- All metal-sealed vacuum system
 - Ultra high vacuum system
 - High abundance sensitivity
 - Bakeable at high temperature
- Retardation lens (RPQ option)
 - Excellent abundance sensitivity
- Single focusing for thermal ionization source
 - Thermo Scientific TRITON
- Double focusing for inductively coupled plasma source
 - Thermo Scientific NEPTUNE

No Compromise
is the common philosophy



Thermo Scientific TRITON

The Thermo Scientific TRITON sets standards in high precision TIMS isotope ratio measurements. Its unique capabilities have earned it the reputation of the “natural choice” in TIMS instrumentation.

- Guaranteed external precision of Nd and Sr is 5 ppm (1 SD), both in static and multi-dynamic acquisition
- 2 ppm external precision has been shown
- Improved sensitivity
- 21 position sample turret for high throughput
- User friendly software with network capabilities



Thermo Scientific NEPTUNE

The Thermo Scientific NEPTUNE completes the our integrated product family for elemental and isotopic analysis. It shares the field proven ICP interface with the Thermo Scientific ELEMENT 2, the most advanced single collector high mass resolution ICP-MS. The NEPTUNE and the TRITON are using the same high precision multicollector platform.

The NEPTUNE defines a “third generation” Multicollector ICP-MS, combining, for the first time, the features of high mass resolution, variable multicollection, zoom optics and multiple ion counting (MIC).

- High mass resolving power with flat top peak sections
- Excellent short-term and long-term stability of signal intensity and mass bias
- Full sensitivity with standard sample introduction system
- Fully integrated software for unattended operation and high throughput

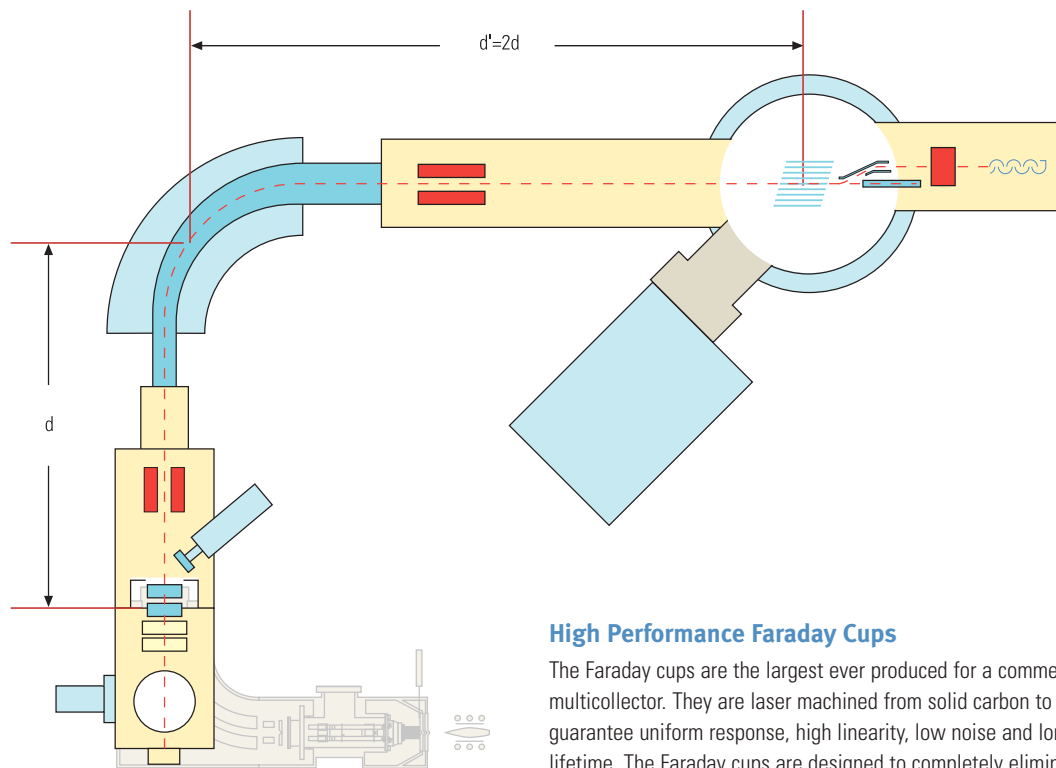


Key Technologies

Advanced Multicollector Ion Optics

Large mass dispersion using an ion optical magnification of 2:

The large mass dispersion of 812 mm provides generous space for the versatile collector array. The mass dispersion is achieved by an ion optical magnification of 2, which has the additional advantages of increased focal depth and improved cup performance



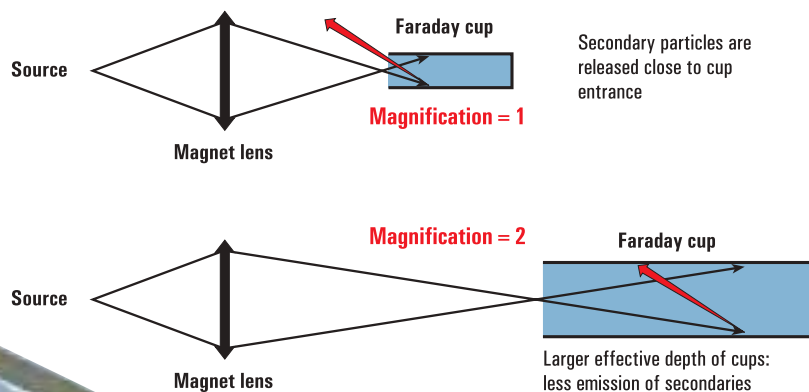
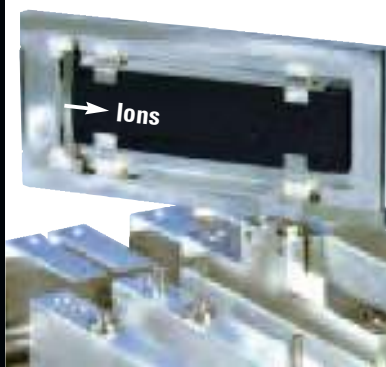
High Performance Faraday Cups

The Faraday cups are the largest ever produced for a commercial multicollector. They are laser machined from solid carbon to guarantee uniform response, high linearity, low noise and long lifetime. The Faraday cups are designed to completely eliminate the need for cup factors¹.

The effect of ion optical magnification on cup performance is depicted in the figure. With increasing ion optical magnification the divergence angles of the ion beams are reduced and the dispersion is increased. As a result, cups can be wider and deeper. Scattered particles released at the cup's side wall by the incoming ion beams are less likely to escape and do not alter the "true" ion current.

¹Patent No. US 6,452,165 B1

Inside view of a Faraday Cup



Multi Ion Counting



The Variable Multicollector

Eight moveable collector supports and one fixed center channel are installed on the optical bench of the high precision variable multicollector module. The center channel is equipped with a Faraday cup and optionally an ion counter with or without the retardation lens (RPQ) to achieve the ultimate abundance sensitivity.

The eight detector supports can be precisely positioned along the focal plane, according to the specific needs of the application. The maximum distance between the outermost channels corresponds to a relative mass range of 17% sufficient for the simultaneous measurement of ^6Li and ^7Li or ^{202}Hg to ^{238}U .

The variable detector supports are driven by motors. Beneath each variable detector platform there is a position sensor located inside the vacuum chamber. Precise in situ monitoring of the detector position directly at the optical bench of the variable multicollector ensures reliable positioning, which is a must for high precision isotope ratio measurements at high mass resolution.

Multiple Ion Counting (MIC)

Each moveable support can carry either a Faraday cup, or a miniature Secondary Electron Multiplier (SEM) or a combination of both in a package. All detectors are of 'plug-in' design² and can be readily exchanged. It is possible to equip one detector platform with a package of ion counters plus one Faraday cup. The above combination is perfect for counter packages for specific elements in the high mass range e.g. lead and uranium because the packages can be built very compact.

The configuration where the ion counter packages are attached to the outer moveable Faraday cups (H4, L4) keeps the full flexibility of the Faraday cup array. The insertion of the additional ion counters at these outer positions does not block any Faraday cup configuration. A fully equipped system can be loaded with a maximum of 17 channels: 9 Faraday cups plus 8 ion counters - all of which can be used in a simultaneous multicollector measurement.

²Patent No. US 6,949,732 B2

Key Technologies

The Amplifier

Each Faraday cup is connected to a current amplifier. The amplifier signal is digitized by a high linearity voltage to frequency converter with an equivalent digital resolution of 22 bits. This ensures sub-ppm digital resolution of all measured signals independent of the actual signal intensity. The amplifiers are mounted in a doubly shielded, evacuated and thermostated housing with a temperature stability of $\pm 0.01^\circ\text{C}$.

The dynamic range of the current amplifiers is extended to 50 V in positive ion detection mode. For negative ions it is restricted to 15 V. The extended dynamic range supports the measurement of large isotope ratios, and it directly leads to an improved signal to noise ratio for the minor isotopes.

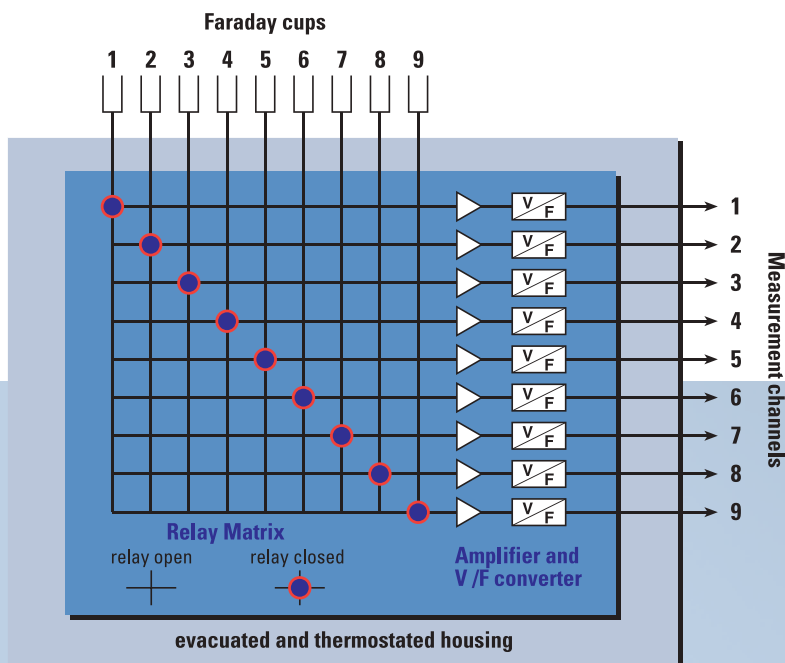
For classical systems the need for a precise cross calibration of the current amplifiers defines a precision barrier in static multi-collection. Even with perfect Faraday cups giving uniform response, results of static measurements are biased by the accuracy and reproducibility of the gain calibration. In the classical method of cross calibration, a high precision, constant current source is sequentially connected to all amplifiers. However, with this method, amplifiers cannot be calibrated to better than ~ 5 ppm per channel. For instance if one considers an isotope system consisting of three isotopes the best external precision can be estimated to be: $5 \text{ ppm} \times \sqrt{3} = \sim 9 \text{ ppm}$.

The Virtual Amplifier

The goal of the new multicollector development was to break through the 5 ppm precision barrier. The TRITON and the NEPTUNE use a patented measurement procedure, which completely eliminates gain calibration biases: the Virtual Amplifier concept³. In all previous multicollector systems the relation (connection) between individual Faraday cups and amplifiers was fixed. In the Virtual Amplifier concept all Faraday cups involved in a certain measurement are sequentially connected to all amplifiers. As a result all signals have been measured with the same set of amplifiers and for the calculation of the isotope ratios all calibration biases of the amplifiers are cancelled.

³Patent No. US 6,472,659 B1

- 50 V Dynamic Range
- Elimination of Amplifier Biases
- No Cup Factors
- Up to 17 Ion Beams can be detected simultaneously



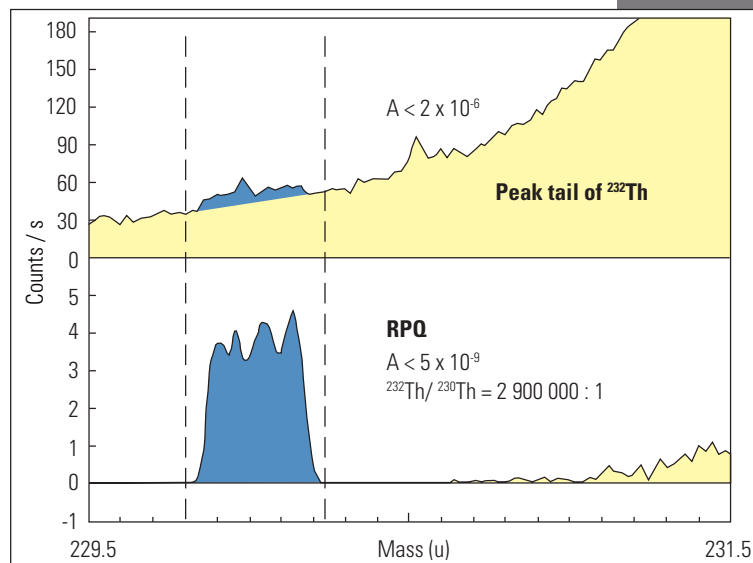
Measuring Large Isotope Ratios

The measurement of large isotope ratios is affected by scattered ions generated at slits and apertures, the flight tube walls and most importantly the interaction of ions with residual gas particles. Ions which suffered one of these interactions have lost kinetic energy and/or have changed their direction of motion. As a result, these ions appear at incorrect mass positions along the focal plane, typically increasing background at neighbouring masses. The TRITON and the NEPTUNE employ an optional Retarding Potential Quadrupole Lens (RPQ)⁴ that acts as a high selectivity filter for ions with disturbed energy or angle.

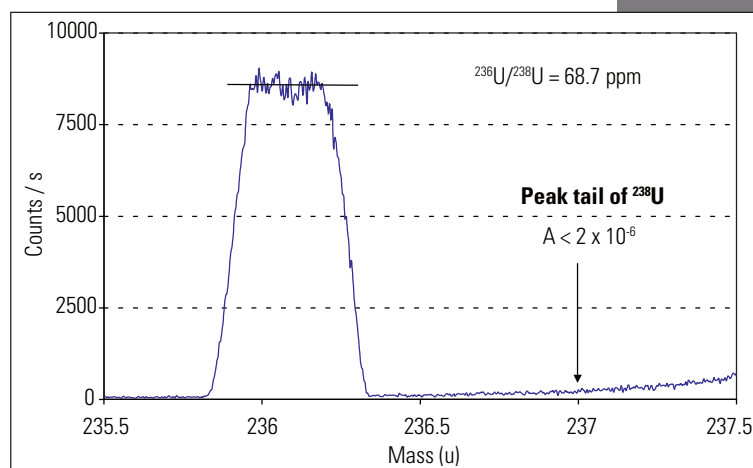
With the TRITON, whose thermal ionization source produces ions with a small energy spread (0.5 eV), the RPQ reduces the abundance sensitivity by two orders of magnitude from typical 2 ppm ($^{238}\text{U} \pm 1$ u) to 20 ppb. The dark noise of the ion counting system used in the RPQ is less than 10 counts per minute. This combination of low dark noise and high abundance sensitivity allows the determination of large isotope ratios with the highest accuracy. Combining the RPQ with the NEPTUNE, whose ICP source generates ions with an energy spread up to ~5 eV, improves the abundance sensitivity by one order of magnitude from guaranteed 5 ppm to 500 ppb with more than 90% transmission.

The abundance sensitivity of the NEPTUNE can be further improved by increasing the energy barrier of the RPQ filter: At 50% transmission, an abundance sensitivity of 150 ppb can be achieved. However, the stability of the system will be reduced.

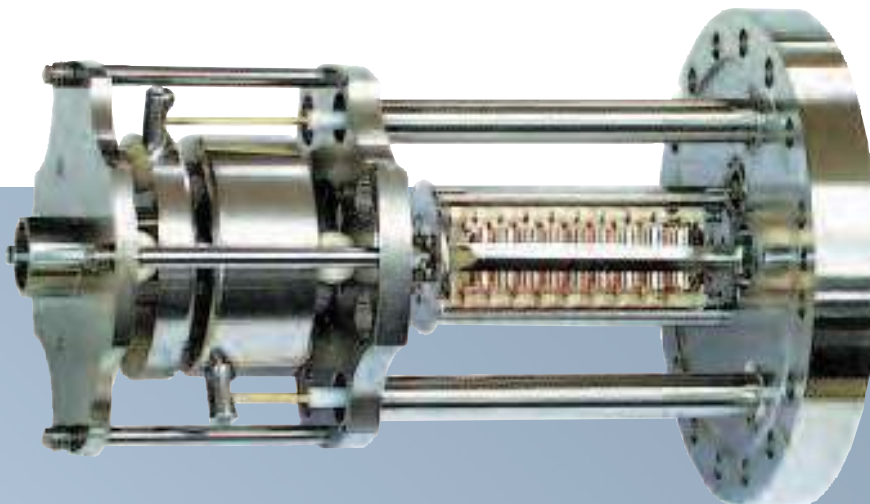
⁴Patent No. US 5180913



Thermo Scientific TRITON: abundance sensitivity with and without RPQ



Thermo Scientific NEPTUNE: abundance sensitivity without RPQ filter



Thermo Scientific TRITON

Thermal Ionization Source

The thermal ionization source is characterized by a very small (~ 0.5 eV) kinetic energy spread of the ions. Therefore, a single focusing geometry that focuses for angular divergence only is fully sufficient. Chromatic aberrations due to the initial energy spread of the ions can be neglected. In this configuration the magnetic sector lens focuses ions of different mass along an inclined focal plane with 45° angle. The magnet is laminated for high speed peak jumping and low hysteresis. The inner width of the flight tube is 14 mm, ensuring minimal scattering. Baffles are present along the flight path to directly catch any diverging ions and to minimize scattering at the side walls.

The New TI Source

The new ion source optics of the TRITON have been optimized for maximum ion transmission for both single and double filament techniques. It makes the TRITON about twice as sensitive as the MAT 262. The new sample turret holds 21 single or double filaments. The filaments can be easily exchanged without using any tools.

Special care has been taken by shaping the ion source lens elements so that the build up of contaminations and memory in the source are minimized. The lens stack is easily accessible by the user for inspection and maintenance.

The ion source is held at an acceleration potential of 10 kV to achieve optimum sensitivity.



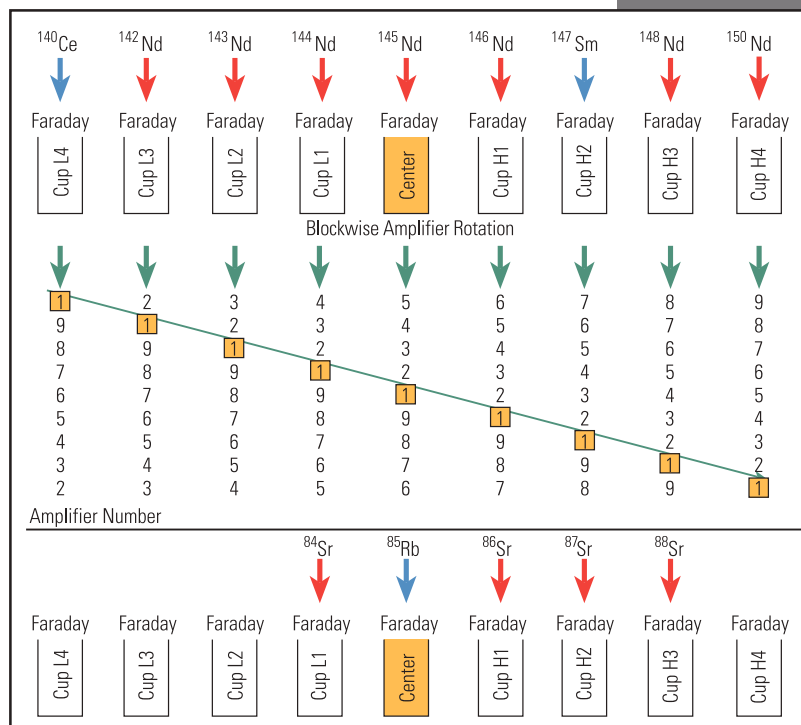
The Zoom Optics

Multi-dynamic measurements can be used to eliminate cross calibration biases of Faraday cup detectors or multiple-ion-counting (MIC) detectors. The philosophy of 'no compromises' led us also to achieve the ultimate performance using this procedure.

Historically, the collectors had to be set to compromise positions in order to fully catch the ion beams in all different cup configurations. The Zoom Optics is a tool to change mass dispersion. If used synchronously with switching the ion beams, perfect overlap of all peaks in all configurations is achieved. This scheme is fully integrated into the TRITON's automatic measurement.

For instance, the Zoom Optics allows measurement of all isotopes of UO in the same detector configuration as U without the need of mechanical readjustment of the detector positions.

Multicollector configurations for Nd and Sr, along with the amplifier rotation scheme (Virtual Amplifier)



Thermo Scientific NEPTUNE

Double Focusing High Resolution Multicollector ICP-MS

The kinetic energy distribution of ions generated in an ICP source is large (~20 eV), compared to ions from a thermal ionization source. A double focusing analyzer, focusing both ion energy and angular divergence, is the best technical solution for this challenge.

Reduced Energy Spread Using a CD-System

The NEPTUNE's ICP interface reduces the initial kinetic energy spread from ~20 to ~5 eV by capacitively decoupling (CD) the plasma from the load coil using a grounded platinum guard electrode. This low kinetic energy distribution, together with a wide energy acceptance of the mass analyzer and 10 kV ion acceleration voltage, eliminates all effects of ion energy spread on isotope ratios and mass bias.

Plasma Interface at Ground Potential

The plasma interface is held at ground potential, allowing easy access to the nebulizer, spray chamber and torch. Changing from solution to laser ablation is as easy as the connection of an autosampler.

The plasma interface can be isolated from the analyzer through an automatic gate valve. The ion transfer optics focus the ions from the plasma interface onto the entrance slit of the double focusing analyzer. Mass bias is mainly generated in the plasma interface and the ion transfer optics. The NEPTUNE's excellent mass bias stability, sensitivity and low background result from Thermo Fisher Scientific unique ion transfer optics⁵.

⁵ Patent No. US 5180913



Interference Free Measurements by High Mass Resolution Multicollection

High Mass Resolution

The ion optics of the the NEPTUNE achieve high mass resolving power on all detectors along the image plane. This capability is based on its refined ion optics with

- Almost coincident angular and energy image planes
- Large focal depth due to large ion optical magnification (see page 6)

The NEPTUNE can be operated in three different resolution settings: Low, medium and high resolution. In high resolution settings the resolving power can go up to $m/\Delta m = 10.000$. The $m/\Delta m$ is derived from the peak slope of the rising edge measured at 5% and 95% relative peak height.

For single collector sector field instruments the mass resolution is changed by switching both the source slit width and the detector slit width. For high mass resolution a small source slit and a small detector slit is used. This typically results into very narrow triangular shaped peaks in the mass spectrum and ensures safe peak separation of interfering species. However, for high precision isotope ratio measurements a wide peak flatness range is required and triangular peak shapes cannot be used. In order to separate molecular interferences from elemental peaks on a multicollector instrument a small source slit has to be selected as well, however, the detector slit can be kept at low resolution setting.

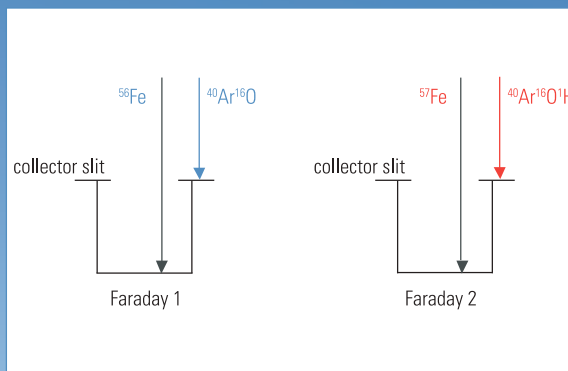
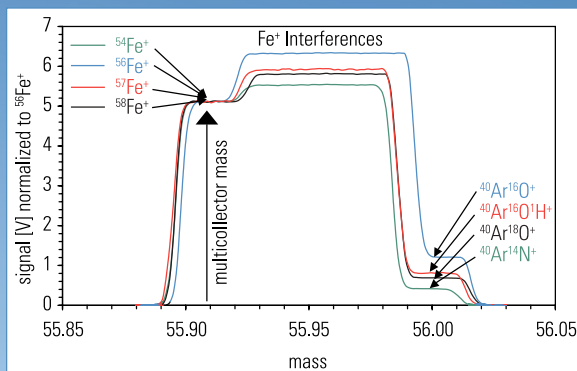
The individual detectors of the variable multicollector can be positioned such that just the elemental ions can enter the detector whereas the interfering ions are stopped on one side of the detector slit. The typical operation mode of a multicollector instrument is a static operation mode where the magnetic field remains constant and the interferences are stopped at the detector slit.

According to the systematics of the nuclear mass defect all molecular interferences in the low and medium mass range are heavier than the elemental species and all interferences can readily be stopped at the same side of the detector slit. The use of the wide detector slit for all resolution settings is the best choice because it guarantees the widest peak flatness at high resolving power, which is a must for high precision and accurate isotope ratio measurements.



Peakscan of all Fe isotopes and molecular interferences at high resolving power.

Fe isotopes can be measured free of any interferences in the first peak plateau at the low mass side. At the multicollector mass position indicated in the figure just the elemental ion beams enter the Faraday cups while the molecular interferences are stopped at one side of the detector slit (see right hand side Figure).



Software Package

The Thermo Scientific TRITON and NEPTUNE Software Package

Most of the software modules are common to both instruments:

- Cup configuration editor to define and select cup configurations
- Method editor to set up user-defined measurement procedures
- On-line and off-line data evaluation packages including statistical capabilities and display of the results in spreadsheet or graphical form
- Sequence editor for automatic, unattended acquisition and evaluation of samples including sample/standard bracketing and blank subtraction.
- Automated report generation of analytical results.

Tuning the Source

The TRITON (TI source)

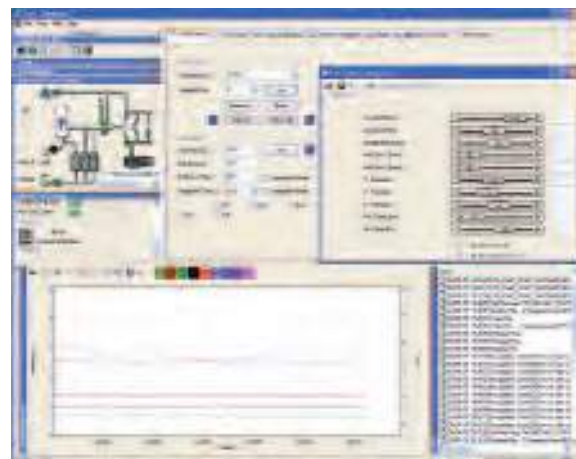
- Fully automated sample turret manipulation
- Configurable and automated filament heating
- Pyrometer readout of the filament temperature

The NEPTUNE (ICP source)

- Fully automated plasma start sequence
- Easy auto sampler setup

Method Setup

- Selection of cup configuration
 - Cup position
 - Faraday or SEM
 - Assignment of isotope masses to the detector
- Data collection strategy:
 - Static measurements
 - Dynamic measurements
 - Fast single collector peak jumping measurements
- Integration of sample heating program (TRITON)
- Selection of bias/fractionation corrections
- Definition of isotope ratios
 - Outlier tests
 - Interference correction
 - Equation editor for user-defined data reduction
- Switch key to synchronize start of data acquisition with laser ablation (NEPTUNE)



Thermo Scientific NEPTUNE Tune Window



Thermo Scientific TRITON Method Editor



Sequence Editor

Sequence Editor

- Automatic acquisition of samples, standards and/or blanks
- Computer control of autosampler
- Online blank subtraction and mass bias correction using an external standard
- Report of delta-values
- Online ASCII export
- Sequence accepts external trigger for starting (i.e. from laser system)



Result Display

Evaluation

- On-line and off-line evaluation
- User configurable display of results:
 - Spreadsheet
 - Graphical display
- Access to all raw data
- On-line monitoring of ratios, intensities, statistics vs. time



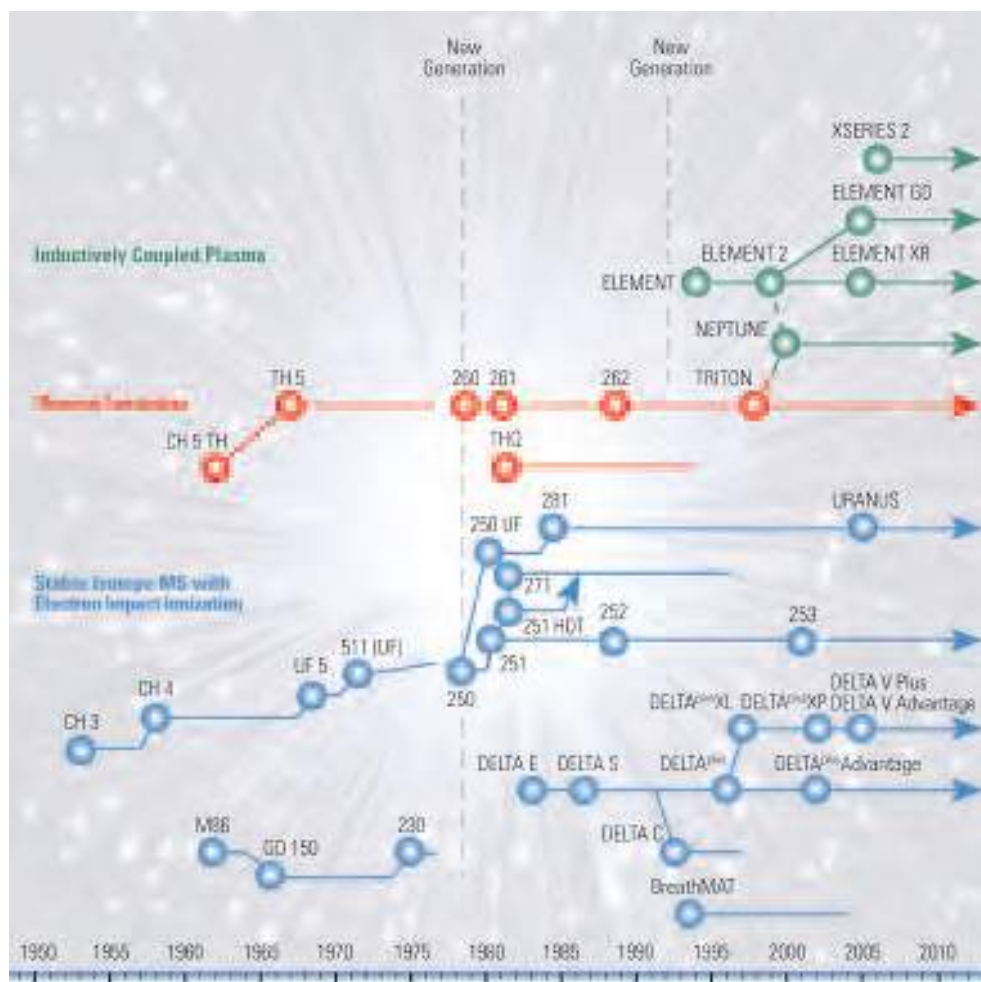
PCL Script Editor

Process Control Language (PCL)

- Script language based on C programming language
- Modification of existing procedures:
 - Baseline determinations
 - Gain calibration
- Definition of new procedures
 - Open for user-defined experiments
- Scripts can be:
 - Run individually
 - Combined with existing software modules

The software runs under the Microsoft Windows® operating system. The software package is optimized for stability, performance and is fully compatible with future operating systems. The software combines the strength of an optimized, Windows-based package written in C++ with the power and flexibility of a user-friendly open structure, realized in our unique Process Control Language, PCL. The Microsoft Windows® operating system allows the data system to be easily connected to a network, enabling data transfer and remote control of the instrument.

History of the Inorganic Product Lines



Laboratory Solutions Backed by Worldwide Service and Support

Tap our expertise throughout the life of your instrument. Thermo Scientific Services extends its support throughout our worldwide network of highly trained and certified engineers who are experts in laboratory technologies and applications. Put our team of experts to work for you in a range of disciplines – from system installation, training and technical support, to complete asset management and regulatory compliance consulting. Improve your productivity and lower the cost of instrument ownership through our product support services. Maximize uptime while eliminating the uncontrollable cost of unplanned maintenance and repairs. When it's time to enhance your system, we also offer certified parts and a range of accessories and consumables suited to your application.

To learn more about our products and comprehensive service offerings, visit us at www.thermo.com.

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Thermo
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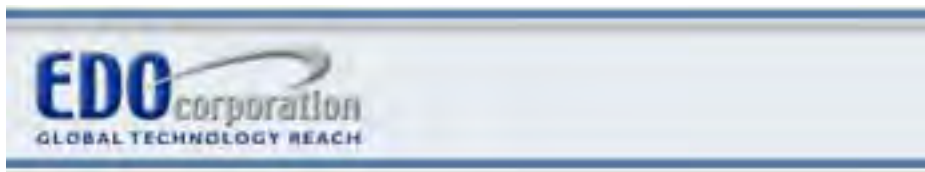


WM2211 Automated Waste Assay System

All of the features of the WM2200 plus:

- Conveyor rotator module for interface to automated conveyor line
- Automated batch processing software
- Complete conveyor lines available
- Optional bar code reader
- Optional dosimeter(s)





Nuclear Detection: System

GammaCam™ LT27 - Technology to Enhance Worker Safety

EDO's GammaCam™ represents a completely new dimension in assessing nuclear radiation fields by producing accurate two-dimensional images of gamma ray emitting objects. The portable system provides real-time pseudo-color gamma ray imagery superimposed on a conventional black and white video picture. Remote operation of the sensor head allows safe acquisition of gamma ray images in high radiation environments while minimizing worker exposure.



Sales and leases to both the Department of Energy (DoE) and commercial nuclear facilities demonstrate that the GammaCam™ is a useful tool in identifying gamma radiation sources and reducing exposure to personnel. The recorded gamma ray images can be used in multiple applications including survey management, job planning, inspection, and shielding evaluation. In addition to being a valuable ALARA tool, GammaCam™ improves the initial site characterization of Decontamination and Decommissioning job sites and characterization of unknown sources. By identifying the highest gamma radiation sources, the GammaCam™ provides valuable dose reduction information. Before and after images captured by the GammaCam™ are a useful tool in validating gamma radiation source elimination.

GammaCam™ Applications

COMMERCIAL NUCLEAR POWER PLANTS

- Streamline Critical Path Survey Management
- Safe, Remote Surveys of Large Areas
- Evaluation of Shielding Requirements and Implementation
- Monitoring of Dynamic Radiological Conditions
- Cost Effective Sorting of Radioactive Waste

HOMELAND SECURITY - NUCLEAR MATERIAL CONTROL

- Homeland Security
 - Counter Terrorism
 - Treaty Verification
 - Security/Inspection Camera
- Emergency Responders
- Port of Call/Border Protection
- [Characterize Suspect Vehicles, Containers](#)

DECONTAMINATION AND DECOMMISSIONING (SITE CLEANUP) - ENVIRONMENTAL RESTORATION APPLICATIONS

- [Expedite Site Characterization Using Remote Surveys](#)
- High Radiation Environments
- Source Term Determination in Curies
- Survey Hard to Access Areas
- Evaluate Effectiveness of Decontamination Activity

NUCLEAR NAVY

- Safe Evaluation of Radiological Areas
- ALARA Tool to Reduce Personnel Exposure
- Clarify Complex Radiological Conditions

PUBLIC HEALTH

- Fugitive Sources Located
- Validates DOT Guidelines
- Characterize "Mystery" Sources
- Medical safeguards
- Medical imagery
- Nuclear Medicine Control

GammaCam™ Model LT27 Sensor Module Specifications

Spectral Range	< 50 keV to > 1.5 MeV
Detector	High density terbium-activated scintillating glass
Sensitivity	1 µR integrated dose for Cs-137 point source and 7:1 SNR (6 µR/hr above background at sensor head)
Exposure Time	User selectable, 1 millisecond - 10 minutes, Software Summing for >10 minutes
Field of View (FOV)	25 degrees Narrow FOV Mode, 50 degrees Wide FOV Mode
Spatial Resolution	1.3 degrees Narrow FOV Mode, 2.6 degrees Wide FOV Mode
Dynamic Range	Instrument: >10E8, Single Image: >20:1
Color or B&W Video FOV	73 degrees Horizontal, 55 degrees Vertical
Temperature	Operation: 5 degrees C - 40 degrees C, Storage: -20 degrees C- 50 degrees C
Humidity	0 - 99% noncondensing
Detection Head	Weight: 45 Pounds, Size: 20 in. Length, 10 in. Width, 10 in. Height, Tripod Mountable
Processor (Optional)	Rugged Laptop Computer (IBM PC Compatible), Intel Pentium CPU, 256 Megabytes RAM (min), Active Matrix LCD Color Display, Internal Hard Drive, CD-RW
Standard Software	GammaSoft™
System Power	120 Watts, 110 - 240 VAC 50/60 Hz



Multi-Group Analysis for Uranium

Features

- Determines uranium enrichment in non-destructive assay applications
- Uses spectra collected with HPGe detectors optimized for high resolution at low energies
- Sophisticated peak fitting and multiplet deconvolution to provide analysis results
- In the normal mode, requires no efficiency calibration for matrix density, matrix type, or container characteristics
- In the enrichment meter mode, does require one calibration measurement with known container characteristics
- Integrated into Canberra waste and safeguards instruments to perform sophisticated analysis with minimal operator interaction
- Developed in collaboration with top experts in safeguards NDA applications

Description

The non-destructive assay of uranium bearing samples to determine uranium enrichment is one of the most common measurements in waste management, fuel cycle process control and safeguards applications. However, varying container shapes, container wall thicknesses, uranium chemical forms and other complications have historically made it one of the more difficult measurements in the nuclear field.

Multi-Group Analysis for Uranium (MGAU) was designed to improve the accuracy of these measurements over traditional methods, while simplifying or eliminating the setup and calibration steps necessary with other methodologies. Thus it can be used in applications involving routine, repetitive measurements taken with relatively unskilled operators.

In the normal mode, MGAU uses information from either two or three regions of the energy spectrum, depending on the specific application. For most applications, two regions that lie within an energy range of approximately 0-300 keV are used. The primary enrichment information is derived from the ^{235}U and ^{238}U gamma peaks in the 88-100 keV energy range. Additionally, the K-beta region is used to develop a local intrinsic efficiency curve – to establish the detector efficiency as a function of energy, the amount of attenuation caused by the sample container and the amount of self-absorption in the uranium material itself. This process eliminates the need for an efficiency calibration prior to making sample measurements.

In the enrichment meter mode, MGAU requires one calibration measurement with a standard of known enrichment and known container wall thickness. The results of this calibration measurement are automatically stored for further use on any samples with known container wall thicknesses. The enrichment meter mode is useful for very thick container walls where the normal mode may not have enough data to provide good results.

The Canberra LEGe is the detector of choice for MGAU work due to its exceptional low energy peak shape and resolution characteristics over a wide range of count rates. Such a high performance detector is recommended as MGAU is dealing with regions of the spectrum where very complex gamma/x-ray multiplets are encountered.

Test data (summarized in Table 1) shows excellent correlation between MGAU results in the normal mode and known standard values. Accuracies in the 1-2% range for most common samples are typical. MGAU can measure enrichment ranges from depleted up to 93% ^{235}U with optimum accuracies in the 3-20% enrichment range. Measurements require only short acquisition times (a few minutes) and only seconds of analysis time. Similar accuracies can be achieved in the enrichment meter mode as long as the walls are well characterized.

Ordering Information

- Model S507 MGAU for Windows® 95/98/NT®.
- Model S348 MGAU for DOS and Windows 3.1.

Table 1 MGAU Results vs. Standards			
Standards	Measured % ^{235}U	% Err	Difference %
Small UO_2 Powder	0.488	3.6	+1.0
Metal (0.087 kg)	0.709	3.0	-0.1
Small UO_2 Powder	0.993	1.5	+0.2
Small UO_2 Powder	2.993	1.0	-0.5
UF ₆ (0.055 kg)	3.442	1.3	-0.5
Small UO_2 Powder	4.949	1.1	+1.4
Small UO_2 Powder	10.09	0.6	+0.2
Small UO_2 Powder	49.35	0.7	+0.0
Metal Disk (0.3 kg)	90.99	9.7	-2.3
U_3O_8 (0.05 kg)	95.66	2.0	+2.3



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Phone contact information

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Multi-Group Analysis Software

Features

- Determines relative plutonium isotopic abundances in nondestructive assay applications
- Determines the relative amounts of other non-plutonium actinides
- Uses spectra collected with HPGe detectors which are optimized for high resolution at low energies over a wide range of count rates
- Incorporates a sophisticated peak fitting and multiplet deconvolution algorithm to improve the accuracy in samples with complex isotope mixtures
- Requires no efficiency calibration for matrix density, thickness or container characteristics
- Operates in either one or two detector mode
- Integrated into Canberra waste and safeguards instruments to perform a sophisticated analysis with minimal operator interaction
- Developed in collaboration with top experts in non-destructive safeguards applications

Description

The non-destructive assay of plutonium bearing samples to determine relative plutonium isotopic concentrations is one of the most common measurements in waste management and safeguards applications. However, complex samples, varying container shapes and materials and other complications have historically made it one of the more difficult measurements in the nuclear field.

Multi-Group Analysis (MGA) was designed to improve the accuracy of these measurements over traditional methods. In addition to the primary application of measuring Pu isotopics, MGA can be used to determine other actinides such as ^{235}U , ^{238}U , ^{237}Np and ^{241}Am as well.

Early public domain versions of MGA were primarily used in safeguards applications. More recently, Canberra has added its exclusive enhancements to improve the measurement results obtained under the difficult conditions encountered in waste applications – specifically low activities and poor counting statistics. Additional enhancements have simplified or eliminated the numerous setup and calibration steps necessary with earlier MGA versions and other methodologies. Thus it can be used in a broader range of applications involving routine, repetitive measurements taken with relatively unskilled operators.

In the single detector mode, MGA uses information from several regions of the energy spectrum that lie within an energy range of approximately 0-300 keV. In the two detector mode, MGA uses information from the low energy spectrum which has a range of 0-300 keV and from a high energy spectrum which has a range of about 0-1000 keV. The primary analysis in both cases is performed using the multiplet region at 94-104 keV. This region is a very complex multiplet, consisting of gamma ray peaks from plutonium and its progeny as well as numerous x-rays. But it is in this region where the most intense gamma ray emissions occur, thus

providing the best possible detection sensitivity. MGA also uses the characteristic plutonium lines at 129 keV and 208 keV which must also be present.

To be able to unfold this complex multiplet region, MGA automatically adjusts the energy and peak shape calibration for each spectrum using peaks that are characteristic of all plutonium samples – 59 keV, 129 keV, and 208 keV. To take into account the physical processes that affect the observable gamma ray intensities at different energies, such as the detector efficiency as a function of energy, and gamma ray attenuation in absorbing materials between the sample and the detector as well as within the plutonium sample itself, MGA internally develops an intrinsic efficiency curve by evaluating 10 peaks from three isotopes.

Using the energy, shape and intrinsic efficiency information, MGA calculates a response spectrum consisting of peak energies (positions), relative peak intensities and an accurate peak shape of each peak in the 94-104 keV peak region. Accommodation is made for the Gaussian broadening of gamma ray peaks and the Lorentzian shape of the x-ray peaks. Isotopic concentrations are directly calculated for all Pu isotopes, except ^{242}Pu which is derived from the other isotopes.

Most common applications can be accommodated with a single detector. The Canberra LGe is the detector of choice in such cases due to its exceptional low energy peak shape and resolution characteristics over a wide range of count rates. Such a high performance detector is recommended for optimum performance with MGA.

In some applications, particularly those involving thick or dense container walls, the high energy spectrum collected with a typical coaxial detector is recommended to supplement the low energy MGA spectrum. In this case, in addition to the normal low energy spectrum peak regions, three high energy regions are examined and evaluated. While this results in a more complex system implementation, Canberra systems designed around this technique can still be operated by routine operating personnel.

Test data (summarized in Table 1) shows excellent correlation between MGA measurements and CBNM standards used in one series of tests. Accuracies shown in Table 1 are typical for safeguards samples. For waste applications, the accuracies are typically in the 20-30% range but the accuracy and whether the analysis can be performed at all is highly dependent on the waste matrix, the amount of plutonium present, and the count time used. We have shown the ability to determine the isotopic composition of a 10 mg Pu sample with a 30 minute count in a waste container.

Ordering Information

- Model S508 MGA for Windows® 95/98/NT®.
- Model S349 MGA for DOS and Windows 3.1.
- Model 48-0714 MGA for VMS™ and AXP.

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VMS is a trademark or registered trademark of Hewlett-Packard Corporation.

Phone contact information

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Table 1 Comparison of MGA Results with Declared Values of CBNM Standards										
CBNM Source	²³⁸ Pu		²³⁹ Pu		²⁴⁰ Pu		²⁴¹ Pu		²⁴¹ Am	
	Declared	% Diff	Declared	% Diff	Declared	% Diff	Declared	% Diff	Declared	% Diff
93	0.0119	−4.4 (4.0)	93.42	0.03 (0.05)	6.32	−0.5 (0.7)	0.223	0.3 (0.5)	0.1047	0.4 (0.8)
84	0.0704	−0.6 (1.4)	84.33	−0.5 (0.07)	14.21	0.3 (0.4)	1.028	−0.1 (0.5)	0.2173	0.5 (0.4)
70	0.847	0.5 (0.8)	73.32	−0.5 (0.8)	18.30	1.6 (1.6)	5.457	−0.8 (0.5)	1.171	−0.8 (0.5)
60	1.198	1.2 (1.2)	62.21	−0.5 (0.5)	25.40	0.9 (1.4)	6.68	1.0 (1.0)	1.445	0.5 (1.0)
Counting time = 10 minutes; sample = 6 g Measurement uncertainty (%) in parentheses.										



X-RAY SECURITY INSPECTION SYSTEM

SISTEMI A RAGGI-X AD ELEVATA CAPACITÀ PER RILEVARE ESPLOSIVI, ARMI E NARCOTICI

I sistemi AUTOCLEAR® sono scanner a raggi-X con capacità e penetrazione elevate. Robusti e trasportabili, sono studiati per ispezionare borse a mano, bagagli, valige ventiquattrore, corrispondenza e pacchi postali.

Luoghi di utilizzo

- Aeroporti • Porti marittimi e commerciali • Tribunali • Dogane
- Edifici governativi • Uffici postali • Penitenziari • Stazioni nucleari
- Checkpoints a eventi speciali, ospedali, stazioni ferroviarie e autobus, stazioni di polizia, basi militari • Musei

MAILGUARD



Sistema per il controllo a raggi-X di lettere e piccoli pacchi. Adatto a spazi ristretti, in postazione fissa o su carrello. È la soluzione ideale per controllare rapidamente la presenza di narcotici, esplosivi e armi all'interno di lettere, vestiti, dispositivi elettronici, borse, macchine fotografiche e pacchetti.

AUTOCLEAR® 4025



Il sistema a raggi-X 4025 è un dispositivo compatto, leggero ed ergonomico, facile da spostare. Il controllo avviene attraverso un tunnel a nastro trasportatore, il contenuto è visualizzato sullo schermo in tempo reale. Ideale per individuare parti di munizioni, lame, esplosivi e liquidi infiammabili in tempi brevi.

AUTOCLEAR® 5333



Il sistema a raggi-X 5333 è un dispositivo compatto e leggero. Con pannello di controllo ergonomico e facile da usare. Il controllo di borse e pacchi avviene attraverso un tunnel a nastro trasportatore, il contenuto è visualizzato sullo schermo in tempo reale. Ideale per individuare esplosivi, armi e narcotici.

AUTOCLEAR® 6040



Il sistema a raggi-X 6040 è un dispositivo mobile compatto e leggero. Pannello di controllo ergonomico e facile da usare. Il controllo avviene attraverso un tunnel a nastro trasportatore, il contenuto è visualizzato sullo schermo in tempo reale. Ideale per individuare esplosivi, armi e narcotici all'interno di bagagli a mano, valige, pacchetti e carrelli per la posta.

AUTOCLEAR® 6848



Il sistema a raggi-X 6848 è un dispositivo mobile compatto e leggero. Pannello di controllo ergonomico e facile da usare. Il controllo avviene attraverso un tunnel a nastro trasportatore, il contenuto è visualizzato sullo schermo in tempo reale. Ideale per individuare esplosivi, armi e narcotici all'interno di bagagli, pacchi e carrelli per la posta.

AUTOCLEAR® 7555



Il sistema a raggi-X 7555 è un dispositivo compatto e leggero. Il pannello di controllo è ergonomico e facile da usare. Il controllo avviene attraverso un tunnel a nastro trasportatore con ampia capienza. Ideale per controllare la presenza di esplosivi, armi e narcotici all'interno di pacchi di medie dimensioni.

AUTOCLEAR® 10080T



Il sistema a raggi-X 10080T è un dispositivo compatto e resistente. Il controllo avviene attraverso un ampio tunnel a nastro trasportatore. Ideale per controllare la presenza di armi, esplosivi e narcotici all'interno di pacchi e bagagli di grandi dimensioni.

AUTOCLEAR® 100100B



Il sistema a raggi-X 100100B è un dispositivo resistente e mobile. Il controllo avviene attraverso un ampio tunnel a nastro trasportatore. Ideale per controllare la presenza di armi, esplosivi e narcotici all'interno di bagagli e pacchi di grandi dimensioni.

AUTOCLEAR® 100100T



Il sistema a raggi-X 100100T è un dispositivo compatto e resistente. Il controllo avviene attraverso un ampio tunnel a nastro trasportatore. Ideale per controllare la presenza di armi, esplosivi e narcotici all'interno di bagagli e pacchi di grandi dimensioni.

CARATTERISTICHE TECNICHE

Generatore a raggi-X Testata tubo a raggi-x autocontenuta e serbatoio protetto. Raffreddamento: 100% bagno d'olio sigillato

Detector a raggi-x Detector a "elle" per uno screening del pacco al 100%. Detector a stato solido, a montaggio dei componenti in superficie, multistrato, totalmente integrato, ad alta frequenza, con l'uso di processori ad alta velocità, e un'elaborazione di immagine Pentium 4 con colore a Single Energy o Multi-Energy (M) opzionale.

Opzioni • Colorazione e stripping di materiale organico e inorganico in modalità Multi-Energy • Gruppo di continuità UPS • Cavo VCR stampante o a distanza • autoMatalert® • Copertura tavolo e monitor a bloccaggio • Trasportatore ad alta velocità • Threat Image Protection (TIP) • Estensione della piattaforma a rullo o del trasportatore autoNet • Kv, contatore mA o contatore oggetti • LCD, schermi doppi o più lunghi • TipNet • Kit per l'umidità tropicale • Footpad oppure on/off ottico • Archivio delle immagini • Supporto variabile per regolare l'altezza della tastiera

Caratteristiche standard • RealClear® • autoDensalert® • autoTracking® • autoSensing® • autoOutline® • autoScale® • autoCal® • 64X zoom intelligente • Migliora il chiaro-scuro • DensityScan • Colore, inversione B/W • alta densità • Help • Density & Stripping Alto/Basso • direzione del trasportatore reversibile • riscaldamento iniziale veloce (25 sec.) • funzionale, robusto, basso profilo

Possibilità di fornire sistemi con tunnel di ispezione da cm. 150 x 150 - 150 x 180 - 200 x 220 oppure sistemi a raggi-X con tunnel 100 x 80 installati su mezzi furgonati.

	Mailguard
Dimensioni (cm.)	77.5 x 57.2 x 59.7
Dimensione scomparto (cm.)	45.7 x 53.3 x 35.6
Penetrazione del materiale	11 mm. di acciaio
Potenza nominale ad alto voltaggio	90 kV
Metodo di osservazione	diretto
Corrente	1 mA massimo
Formato schermo fluoroscopico di controllo (cm.)	43.2 x 43.2
Risoluzione	40 AWG
Tensione in ingresso e alimentazione	110-130 volt o 210-250 volt, una fase AC, 50/60 Hz, inferiore 250 Watt
Raffreddamento	bagno d'olio sigillato, aria
Sicurezza	doppi interruttori di sicurezza - interruttore di funzionamento del pannello - doppio vetro schermato - sicurezza interruttore di alimentazione
Opzionale	carrello per il trasporto - noleggio - estensione di garanzia

	4025	5333	6040	6848	7555	10080T	100100B	100100T
Dimensioni (cm.)	109.1 x 58.4 x 103.6	125.4 x 72.1 x 111.4	154.60 x 80.9 x 26.4	185.4 x 88.1 x 132.7	191 x 95.3 x 139.5	317 x 129.3 x 172.9	314.2 x 129.3 x 192.9	318.8 x 131.1 x 186.4
Dimensione Tunnel (cm.)	40 x 25	53 x 33	60 x 40	68 x 48	75 x 55	100 x 80	100 x 100	100 x 100
Penetrazione del materiale	10 mm. / 28-29 mm. di acciaio		28-29 mm. di acciaio					
Risoluzione	cavo da 40 AWG							
Elaborazione immagine	adattabile a 32 bit con un minimo di 128 Mbytes, 2.4 + processore GHz							
Velocità del trasportatore	24 cm al secondo, lunghezza d'entrata variabile e piattaforma d'uscita, completamente reversibile							
Trazione del peso	150 Kg (disponibile con una maggiore trazione dei pesi)							
AutoTracking	il nastro autoTracking è garantito a vita							
Sicurezza della pellicola	Garantita per pellicole ad alta velocità fino a 1600 ISO (33 DIN)							
Testata del tubo a raggi-x	Autocontenuta, serbatoio protetto							
Potenza nominale ad alto voltaggio	90 kV, 160 kV		160 kV			160 kV, 140 kV		
Orientamento del raggio	Diagonale					Diagonale (80° divergenza raggio)		
Ritmo di dose per esame	0.1 mR sono disponibili anche dosi più basse							
Video	Standard monitor da 17 pollici a colori SVGA. Alta risoluzione, senza tremolio, distanza tra punti 21, monitor a radiazioni basse, scheda video 1280x1024							
Peso	186 Kg 254 Kg (prodotto)	236 Kg 313 Kg (prodotto)	352 Kg 442 Kg (prodotto)	403 Kg 517 Kg (prodotto)	454 Kg 589 Kg (prodotto)	590 Kg 862 Kg (prodotto)	726 Kg / 998 Kg (prodotto)	
Condizioni ambientali	Temperature: 32 -104 F (0 - 40). Umidità 20% - 95%, a scappamento libero. Immagazzinamento a 65 C (149 F). Possibilità di sistema tropicalizzato							

Disegnati, prodotti e rigorosamente testati negli Stati Uniti in conformità con ISO9001 (International Standard Organisation) e relativi standard di controllo EC, EEC, EN, IEC, USBRH, 21 CFR 1020.40 e FAA Standard 14 CFR 108.17 e 129.26. Questi sistemi a raggi-X sono sicuri da radiazioni, non presentano pericoli di radiazioni al pubblico e seguono i requisiti "Standards Handbook 93 for Exempt Protective Installation" garantendo la sicurezza per gli operatori e sono conformi alla direttiva europea n°781/2005 sulla penetrazione dei materiali ispezionati.



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rev. 02-230807

IPAN™/GEA: Crate

Imaging passive-active neutron/gamma energy assay crate system

- Fast, accurate and efficient analysis of large TRU and low level waste items allowing selection of appropriate waste disposal option.
- Measures fissile material in crated waste with dimensions up to 8' x 8' x 20'.
- Isotopic identification and real-time assay capability.
- Automatic identification and matrix correction for Pu and enriched U contaminated wastes.
- User friendly Windows™ NT and Windows 95™ compatible software.
- <10n Ci/g performance.



Features

- Active neutron imaging using pulsed neutron source and differential dieaway analysis.
- Passive neutron imaging.
- Active and passive neutron multiplicity analysis using BII PMCCM electronics.
- Advanced systematic error correcting algorithms significantly improve assay accuracy.
- Passive HPGe high resolution gamma energy analysis.
- Active and passive NaI low resolution gamma energy analysis.
- Innovative and proven waste matrix correction techniques.
- Automatic and manual data diagnostics package.
- Determines spatial location of radioactive constituents.

Designed and built to your fixed crate dimensions

- Standard systems optimized for B25, SWB, 4' x 4' x 8' and 5' x 5' x 8' boxes.
- Optional systems configured for any crate size up to 8' x 8' x 20'.
- Protection against a wide range of electrical interference which may occur in an industrial plant environment.
- Automatic data quality checking.
- Large dynamic range (1 mg-1 kg Pu) – fully deadtime corrected.
- System configuration comprehensively meets nuclear safety requirements.
- Operationally proven – complies with applicable disposal regulations.
- Designed for ease of decontamination.

Control and Interface

- Network compatible.
- Compatible with most recognized PLC systems.
- Full diagnostic capabilities.
- Standard and user defined report formats.

Applications

The BII IPAN™/GEA Crate System uses active and passive neutron imaging techniques combined with HPGe and NaI gamma spectrometry to accurately and quickly measure the uranium and transuranic content of miscellaneous wastes enclosed in crates with dimensions up to 2.5m x 2.5m x 6.5m (8' x 8' x 20').

The wastes presented to the system may include low level and decommissioning wastes of various sizes and shapes, and of differing chemical and isotopic compositions.

The computer controlled system requires little operator input, no prior knowledge of sample characteristics (such as isotopic composition). Accurately assays a wide range of waste matrix categories, such as soil, concrete rubble, metal and combustibles in crates of varying sizes.

Operationally proven and installed at DOE waste management sites.

Operation

While inside the main neutron counting chamber, the crate passes an array of NaI and HRGS detectors. Data taken is automatically combined with the neutron imaging and multiplicity counting data to enable matrix and isotopic corrections and provide an accurate assay of all radioactive constituents.

Isotopic Inventory Analysis

Integrated array of NaI and HPGe detectors permit the identification and quantification of many fission products, activation products and actinides.

System Self Checks

The performance and integrity of the entire system is regularly checked with gamma and neutron sources.

Calibration Checks

At preset intervals the monitor prompts the operator for a calibration check. Approved calibration standard is loaded into the measurement chamber and the calibration routine is automatically carried out.

Operator Interface

A user friendly operator interface is provided.

All measurement parameters are automatically stored to disk and may also be directly printed. Diagnostic and maintenance operations are password protected.

Specifications

Crate size: Standard systems for B25, SWB, 4' x 4' x 8' and 5' x 5' x 8' boxes.
Optional systems for all sizes up to 8' x 8' x 20'.

Detectors: Multiple polyethylene moderated ³He detectors distributed in several independent detection modules.
Multiple HPGe detectors.
Multiple NaI detectors

Performance

Detection limit (under typical operating conditions): <10nCi/g

Assay time: Typically 30min to 1 hr for a standard system.

Assay accuracy: ±25% total uncertainty

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Email: bii@bnfl-instruments.com





Features

- Designed for quantitative passive neutron multiplicity analysis
- Optimized for assay of inventory containers within shipping drum
- Performance exceeds that from most multiplicity well counters
- Accommodates 200 liter drums
- Moderate neutron detection efficiency for ^{240}Pu fission neutrons: 19.4%
- Composite Die-Away Time: 80 μs
- Fast Amptek electronics
- Dead-time: 200 ns
- Sensitivity – detection levels of <50 mg W.G. Pu
- All HDPE moderator enclosed within metallic skins
- Modular detector assemblies
- Operated using JSR-12, 2150 or JSR-14 shift registers
- Available with NDA 2000 software
- Options
 - Automation
 - Add-A-Source matrix correction
 - Alternate detector configurations
 - Drum rotator
 - Automated load/unload mechanism
 - Larger container sizes

WM3100 Series Passive Neutron Coincidence Waste Drum Assay System

Description

The WM3100 series of passive neutron coincidence counters, based on the successful Waste Drum Assay System (WDAS)¹, is designed to perform accurate quantitative assays on neutron emitting nuclides found in Transuranic (TRU) wastes. The WM3100 measures the plutonium content of the waste drum by detecting coincidence neutrons

from the spontaneous fission of the even numbered isotopes of plutonium. The standard system configuration provides a 4π passive neutron detection efficiency of 19% for ^{240}Pu spontaneous fission neutron emitted with in the center of the assay cavity. The WM3100 is designed to assay 208 liter (55 gallon) drums and provide detection levels on the order of approximately 3 mg of ^{240}Pu effective in a 1800 second count time.

Components of the proposed system include the neutron counter with ^3He detectors, Amptek-based fast preamplifier/discriminator circuit boards (Model JAB-01), coincidence electronics, computer hardware, and application software. The turnkey system is designed for ease of operation and minimal maintenance.

Spontaneous fission neutrons from the even isotopes of plutonium will be measured using passive neutron coincidence or optional multiplicity counting techniques. The neutron counter consists of a High-Density Polyethylene (HDPE) moderator with ^3He tubes embedded in the HDPE on all six sides of the counter with optimal spacing for maximum efficiency. The moderator assemblies are surrounded by an additional 100 mm (4 in.) thick HDPE shield to minimize the impact of neutron background on the measurement and the impact of nearby neutron sources.

The measured neutron coincidence rate is converted to a ^{240}Pu -effective mass and then to total plutonium mass using the plutonium isotopic abundances associated with the waste stream (or measured directly if an appropriate isotopics system is available).



Phone contact information

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WM3100 Series Passive Neutron Coincidence Waste Drum Assay System

Performance

The accuracy of a given measurement is determined primarily by the following factors:

Counting Statistics:

The statistics are typically associated with the precision of the assay. The limits on the precision are count time, efficiency, SNM content, and background. The WM3110 series still has an advantage over the competition because of its lower background response. This is derived from shielding and superior electronics. The background of our counters is typically half that of other counters of the same size and efficiency. This leads to lower limits of detection for the CANBERRA drum counters.

The Lower Limit of detection of the counter is 3 mg of ^{240}Pu effective corresponding to 10 mg of high burn-up Pu. For Pu contents exceeding one gram this uncertainty drops to about 3.5% and at 30 grams Pu this further decreases to less than 1%.

Uniformity of the Chamber Response:

The variation of the response with source location in the chamber can have a significant impact on the assay results. The flat response of the WM3100 series of counters combined with the averaging effect of the turntable essentially eliminate this effect for most sample matrices. The RSD variation in response for the WM3100 is approximately 2% throughout the normal sample volume.

Matrix Effects:

Neutron counters are most impacted by the hydrogen content of the sample. Samples containing significant quantities of water or oil can be significantly impacted. This impact is seen as a lowering of the neutron response. The WM3100 series of counters include the Add-A-Source (AAS) Matrix correction to reduce this effect as an option.

Distribution of the Pu in the Drum:

For homogeneously distributed samples the AAS correction is highly accurate, providing values of $\pm 2\%$ (not including the effects of counting statistics). However, drums containing large quantities of hydrogen and localized concentrations of Pu will incur larger errors due to positioning effects.

Overall accuracy for a typical drum with a hydrogen content less than 10% of water (e.g. paper and process clothing) will be better than 20% for a sample with more than one gram of high burn-up Pu. (For samples with greater than one gram high burn-up Pu the counting statistics become negligible compared to other sources of error.)

Software

The WM3100 systems are provided with CANBERRA's S529 Non-Destructive Assay Software (NDA 2000).

CANBERRA's NDA 2000 software, is a multipurpose application software package intended to operate all CANBERRA waste and safeguards assay systems. The software supports several neutron coincidence and multiplicity analysis modes. Such as:

Passive Neutron Coincidence Analyses including:

- Polynomial Calibrations.
- Known Alpha Multiplication Correction.
- Add-A-Source Matrix Correction.

Multiplicity Analyses including:

- Known Efficiency.
- Known Alpha.
- Known Multiplication.
- Curium/Californium Discrimination.
- Cosmic Ray Rejection.
- Truncated Histogram Analysis.

Note: the system hardware must support the selected analyses.

Requires:

- S529C – NDA 2000 Software.
- S500C – Genie 2000 Basic Multi-Input.
- S505C – Quality Assurance Software.

Options

Automation

The WM3100 series of counters is available with various options for drum handling and automation. For example, the counter can be provided with either unpowered or powered conveyor rollers for drum handling and can be provided with a second powered door to allow for in-line operation of the system.

The base system, the WM3110, is provided with a single powered door, automatic drawbridge assembly and unpowered load/unload conveyor. The general operating sequence for the WM3100 can be summarized as:

- The drum is placed at the end of the unpowered conveyor and manually moved into the assay chamber.
- The Assay is begun when the operator signals that the drum is in position.

WM3100 Series Passive Neutron Coincidence Waste Drum Assay System

- The drawbridge automatically raises and the counter door closes.
- The operator enters the pertinent information on the sample.
- The rotation motor is automatically switched on.
- A passive neutron count is performed for the preset time interval.
- Add-A-Source Option: Following the passive count the AAS measurement begins.
- The AAS source movement is automatically controlled by the PLC and IBM/PC.
- Upon completion of the assay the door opens and the drawbridge lowers.
- The sample is then manually removed from the counter.

The most common system configurations are listed in the following table.

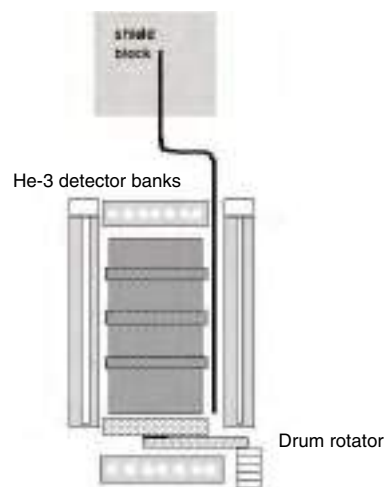
Model	Powered Doors	Powered Conveyors
WM3110	Input only	None
WM3111	Input only	Single In/Out
WM3112	Input and Output	Input and Output

Multiplicity Analysis Option

For traditional waste assay, the total fissile mass is less than a few grams total so that traditional multiplicity analysis offers little benefit to waste assay. However, multiplicity analysis offers advantages in reduction of the neutron coincidences caused by the interaction of cosmic-ray with the structure of the neutron counter and the high-Z materials within the waste.

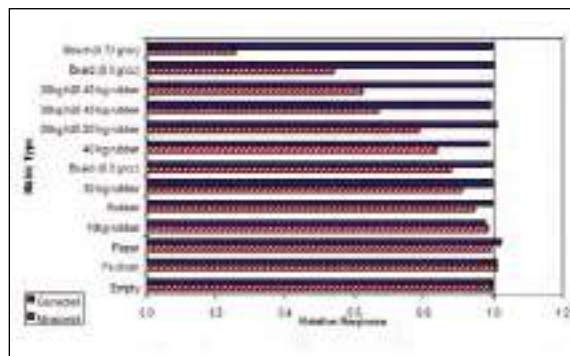
Add-A-Source Matrix Correction Option

The Add-A-Source technique provides a means of measuring the impact of the waste matrix on the neutrons emitted within the drum. In practice a small ^{252}Cf source (about 20 000 n/s) is introduced into the assay cavity with no sample in the counter. The measurement is repeated after the sample is loaded and the results compared. The difference in the measured count rates can be used to correct the measured sample rate. An illustration of the AAS measurement is shown in the figure below.



Schematic diagram of the side scanning AAS.
(Other configurations are available.)

For homogenous distributions of Pu in the drum the AAS correction results in a typical error of $\pm 2\%$ from the expected values. Without the correction the errors can exceed 50%. The effectiveness of the AAS correction is illustrated in the following figure.



WM3100 Series Passive Neutron Coincidence Waste Drum Assay System

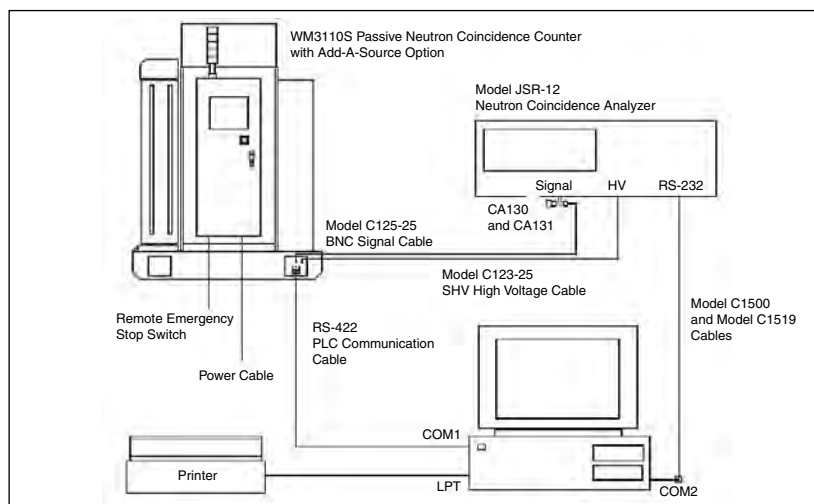


Illustration of the set-up of the HNMC with shift register and computer and the optional AAS correction module

Specifications

NEUTRON DETECTION

- 64 ^3He proportional tubes arranged in a single layer of tubes in a 4π detection geometry.
- Outer diameter 25.4 mm (1 in.).
- ^3He partial Pressure: 4.5 atm.
- Neutron Detection Efficiency: 19.4%.
- Die-Away Time: 28 μs .

COINCIDENCE COUNTING DETECTION LEVELS

<3 mg ^{240}Pu effective (<50 mg weapons grade plutonium) under the following conditions:

- 30 minute acquisition time.
- Non-moderating matrix.
- Operation at sea-level.
- Neutron background – natural sources only.

PHYSICAL

Counter Dimensions (with AAS Module)

- LENGTH – 3520 mm (139 in.).
- WIDTH – 2750 mm (108 in.) (with drawbridge).
- HEIGHT – 2460 mm (97 in.).
- CONVEYOR HEIGHT – 690 mm (27.2 in.).

Maximum Container Dimensions

- DRUM DIAMETER – 610 mm (24 in.).
- HEIGHT – 840 mm (33 in.).

RELATED SYSTEMS

WM3112-HE High Efficiency Neutron Counter (HENC) – The HENC extends the capability of the WM3100 series offering higher neutron detection efficiencies and lower detection levels.

Hexagonal Neutron Multiplicity Counter (HNMC) – The HNMC is a variant of the HENC offering greater flexibility than the HENC but is better suited for manual operations.

Integrated Waste Assay System (IWAS) – The IWAS combines high efficiency passive neutron counting, active neutron interrogation and high resolution gamma-ray spectroscopy into a single assay system for 200 and 320 liter drums.

REFERENCES

1. "A New 208 Liter Drum Neutron Coincidence Counter with Add-A-Source Matrix Correction", D.R. Davidson, R.D. McElroy, D. Brochu and M. Villani, Proceedings of the 36th Annual Meeting for the Institute of Nuclear Materials Management, Desert Springs, California, July (1995).
2. "Operator Experience Measuring Pu-bearing Waste at PNC Using the Waste Drum Assay System", S. Terakado, T. Asano, D.R. Davidson, R.D. McElroy, and H.O. Menlove, ESARDA, France, May 12-16, (1997).
3. "Total Measurement Uncertainty Analysis for an Integrated Waste Assay System", R.D. McElroy, Jr., S. Croft, B. Gillespie and B. Young, Proceedings of the Institute of Nuclear Materials Management, 44th Annual Meeting, Phoenix (2003).





Model JCC-51 Active Well Neutron Coincidence Counter

Features

- Designed for active neutron interrogation of uranium.
- Variable sample cavity size.
- Fast Amptek electronics.
- 42 ^3He detectors.
- Passive counting of plutonium when the AmLi sources are removed.
- Optional transport containers.

Description

Isotopes of uranium (^{235}U and ^{238}U) do not spontaneously fission at a significant rate like the even-numbered isotopes of plutonium. For this reason, uranium assays utilize an external neutron interrogation source to induce fission in the sample. This is referred to as an active assay.

The JCC-51, which is based on a technology transfer from Los Alamos National Laboratory, is used to make active neutron measurements on items such as bulk UO_2 samples, high-enrichment uranium metals, UAl alloy scraps, LWR fuel pellets and ^{238}UTh fuel materials. Americium-Lithium (AmLi) neutron sources (one in the top plug and one in the bottom plug) induce fission in the uranium sample and the coincidence neutrons are counted. If the AmLi sources are removed, the counter can be operated in a passive mode to assay plutonium. Two AmLi neutron sources (JNS-01), JSR-12 Neutron Coincidence Analyzer, a computer and analysis software are required for neutron coincidence counting but are not included with the JCC-51.

Forty-two ^3He tubes are embedded in the high-density polyethylene surrounding the sample well. They are arranged in two concentric rings to



maximize efficiency. The tubes are divided into six groups of seven, and each group is wired together and connected to one JAB-01 Amplifier/Discriminator circuit board. The six JAB-01s are mounted inside a sealed junction box, with LED indicators placed externally on the junction box to indicate proper operation of each JAB-01 channel. Electrical connections between the JCC-51 and the JSR-12 Neutron Coincidence Analyzer include +5 V, HV, and single "ORed" output signal.

The sample well height can be increased by removing one or both of the polyethylene discs in the top and bottom plugs. Enlarging the sample well will increase the absolute efficiency because the ends of the ^3He tubes are not as shielded, but decrease the precision because the random background from the AmLi source is increased.

A cadmium sleeve is wrapped around the outside of the counter to reduce the background and to reduce personnel exposure.

The counter can be operated in two active modes: thermal mode and fast mode. Thermal mode is used for low-enrichment material such as UO_2 pellets, U_3O_8 powder and low content scrap ($<50 \text{ g } ^{235}\text{U}$), high-enrichment material including ^{235}UTh and ^{233}UTh (HTGR fuels) and samples with large quantities of hydrogenous materials such as scrap with plastic bags, uranyl nitrate (few g/L to few hundred g/L) and plutonium solutions (few g/L to few hundred g/L). The fast mode is used for high-enrichment uranium metal. For thermal mode, the internal cadmium sleeve and cadmium in the end plugs are removed.

For assay of large samples such as fuel rods or plates, the counter is turned on its side, the end plugs are removed and an MTR Insert (JWI-11) is positioned inside the counter. The cart is used to support the counter in the horizontal position.

The counter sits on a cart that is designed so that one person can move the unit.

Specifications

PERFORMANCE

- **HV Setting** – 1680 V.
- **Required AmLi Source Strength** – $5 \times 10^4 \text{ n/s}$. (not included with JCC-51)
- **Gate Setting** – 64 μs .
- **Detector Efficiency** – 26% for smallest sample configuration.
- **Detection Limit**¹ (smallest sample configuration; all for ^{235}U):

	Thermal Mode	Fast Mode
Low Enrich. U_3O_8	11 cps g	0.15 cps g
High Enrich. Metal	n/a	0.10 cps
Sensitivity Limit ²	1 g	23 g
Precision	1.5%/20 g	3.8%/200 g

PHYSICAL

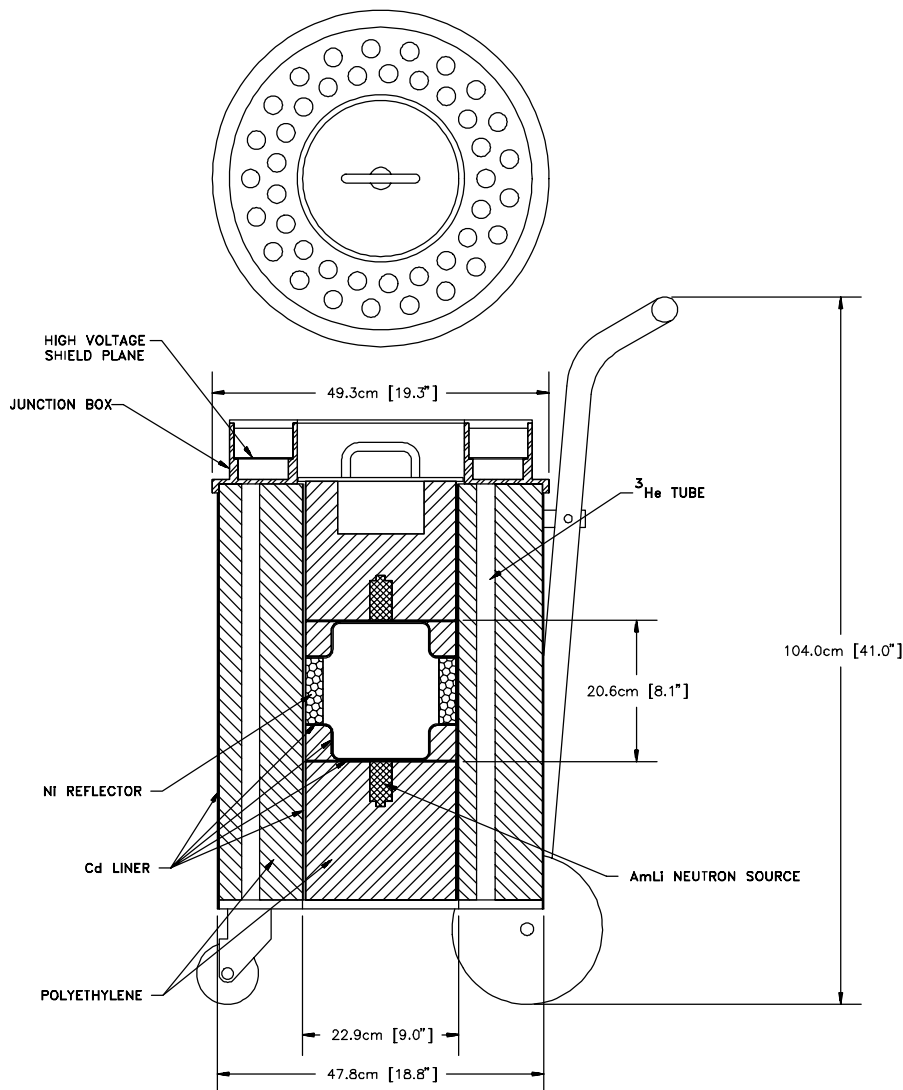
- **Counter Size** – 73.7 x 49.3 cm (29 x 19.4 in.) H (excluding cart handle) x Dia.
- **Weight** (including cart) – 125 kg (275 lb).
- **Sample Cavity Size** (Three sample cavity configurations depending on which polyethylene discs are removed from the counter):
 - **Full Discs** – 20.6 x 22.9 cm (8.1 x 9 in.) H x Dia. A 2.54 cm (1 in.) thick nickel reflector is positioned in the center of the sample cavity for the smallest configuration to give a more penetrating neutron interrogation.
 - **Small Discs Removed** – 24.9 x 22.9 cm (9.8 x 9 in.) H x Dia.
 - **Both Discs Removed** – 35.1 x 22.9 cm (13.8 x 9 in.) H x Dia.
- **^3He Tubes** – 42.
- **^3He Rings** – 2.
- **^3He Active Length** – 50.8 x 2.54 cm (20 x 1 in.) H x Dia.
- **Cladding** – Aluminum.
- **AmLi Source Holder** – 5.7 x 3.2 cm (2.25 x 1.25 in.) H x Dia.

OPTIONS

- ^3He tube wiring to provide separate outputs from both rings of detectors.
- Model JWI-11 MTR Insert.
- Transport Container.
- Top and bottom end plugs without tungsten source bottles for passive neutron measurements. This eliminates the need to remove sources from the end plugs normally supplied with the counter if passive measurements will be made often.

REFERENCES

1. Menlove, H.O. (1979). *Description and Operation Manual for the Active Well Coincidence Counter*. Report LA-7823-M. Los Alamos, New Mexico: Los Alamos National Laboratory.
2. Net coincidence signal equal to three sigma times the background for a 1000 second count.





Features

- Designed for neutron coincidence measurement of uranium in PWR, BWR and CANDU fuel assemblies, or plutonium in MOX fuel assemblies.
- Variable sample cavity size (Model JCC-71).
- Fast Amptek electronics.
- ^3He detectors.
- Transportable.
- Optional transport container.
- Authorized for routine inspection use by the International Atomic Energy Agency (IAEA) as the Uranium Neutron Collar (UNCL and UNCL II).

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Model JCC-71, 72 and 73 Neutron Coincidence Collars

Description

The Model JCC-71 Neutron Coincidence Collar is based upon technology transfer from the Los Alamos National Laboratory. It is a passive/active neutron counter for the measurement of the ^{235}U content per unit length in fresh PWR, BWR and CANDU fuel assemblies in the active mode, and the plutonium content of MOX fuel in the passive mode. In the active mode, an AmLi source is required to interrogate the fuel, and coincidence counting of the induced fission neutrons from ^{235}U is performed. To measure the ^{238}U content, the AmLi source is removed, a fourth bank of ^3He detectors is added,



Model JCC-72 (Active).

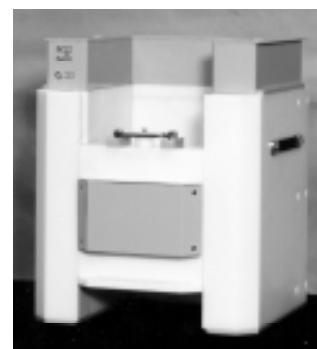
and the counter is operated in a passive mode, counting the coincidence neutrons from spontaneous fission of ^{238}U . The collar measures the ^{235}U and ^{238}U content along the axis of the assembly, not the enrichment. Since the ^{235}U content is of primary interest for safeguard purposes, only the active measurement is necessary. Pu-containing fuel rods are measured in the passive mode because of the high spontaneous fission rate. A JSR-12 Neutron Coincidence Analyzer, a computer and analysis software are required for coincidence counting but are not included with the JCC-71, 72 and 73.

For the passive mode, there are four counter banks composed of high-density polyethylene for moderation of the fission neutrons. If operated in the active mode, one bank of detectors is replaced with a polyethylene bank containing the AmLi interrogating source. The AmLi source is ordered separately.

The JCC-71 Neutron Coincidence Collar is designed to allow modification of the geometry to close-couple the detectors with the fuel type. For the smaller BWR fuel, the side detector banks are moved into the inner screw hole position.



Model JCC-71 (Passive).



Model JCC-73 (Active).

Model JCC-71, 72 & 73 Neutron Coincidence Collars

The fourth bank of tubes (passive mode) is hinged to facilitate placing the counter around fuel assemblies. For the active mode, the fourth side of the counter is a polyethylene moderator with a tungsten source bottle for the AmLi source. The AmLi neutrons are thermalized in the polyethylene and induce fission in the ²³⁵U.

The average energy from the induced fission is higher than the moderated AmLi neutrons and gives fast neutron multiplication which allows the measurement to penetrate into the interior of the fuel assemblies. For HEU fuel, cadmium liners can be added to improve neutron penetrability.

The Neutron Coincidence Collar is designed to be insensitive to parameters such as open channels for control rods, enrichments, angular orientation of the fuel in the Collar, fuel pellet density, and any protective bagging. Cladding type (zinc alloy or stainless steel), different fuel pellet diameters, and neutron absorbers (Gd₂O₃) can affect the measurement.

Since more neutron collars are being installed at facilities for measuring designated fuel types (BWR or PWR), the Neutron Coincidence Collar was redesigned by Los Alamos National Laboratory to make two separate counters: the JCC-72 for BWR and CANDU fuel assemblies and the JCC-73 for PWR fuel assemblies.

Specifications

PERFORMANCE

- **HV Setting** – 1680 V.
- **Required AmLi Source Strength** – JCC-71, 5×10^4 n/s; JCC-72 and JCC-73, 1×10^5 n/s. (not included with counter)
- **Gate Setting** – 64 μ s.
- **Efficiency** – JCC-71 (Passive, PWR Configuration), 11.5% $\pm$ 10%; JCC-72 (Active), 13.5% $\pm$ 10%; JCC-73 (Active) 12.5% $\pm$ 10%.
- **Sensitivity (JCC-71)^{1,2}** – 2.2 rods for iron substitution; 2.8 rods for empty substitution.

PHYSICAL

- **Weight** – JCC-71, 38 kg (84 lb).
- **Sample Cavity Size**
 - **PWR Assemblies** – 41.4 x 23.4 x 23.4 cm (16.30 x 9.21 x 9.21 in.) H x L x W.
 - **BWR/CANDU Assemblies** – 41.4 x 16.5 x 23.4 cm (16.30 x 6.5 x 9.21 in.) H x L x W.
- **³He Tubes**
 - **JCC-71 (Passive Mode)** – 24.
 - **JCC-71 (Active Mode)** – 18.
 - **JCC-72 (Active Mode)** – 16.
 - **JCC-73 (Active Mode)** – 20.
- **³He Active Length** – 33 x 2.54 cm (13 x 1 in.) L x Dia.
- **Cladding** – Aluminum.

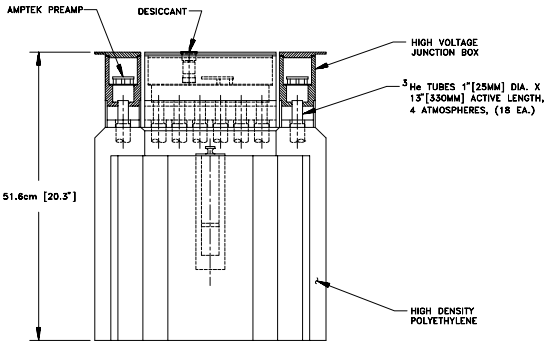
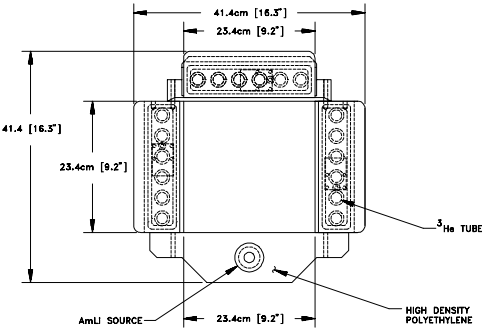
OPTIONS

- Passive fourth bank for JCC-72 and JCC-73.
- ²⁵²Cf neutron source for verifying proper operation.
- Cart to vary the vertical and horizontal position of the counter.

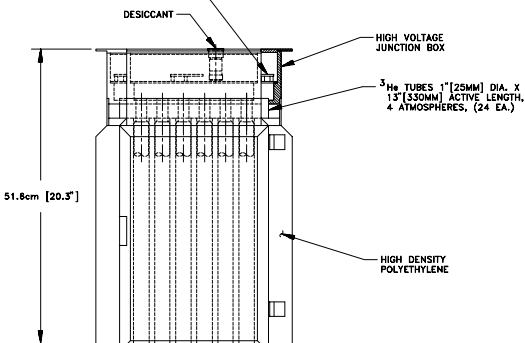
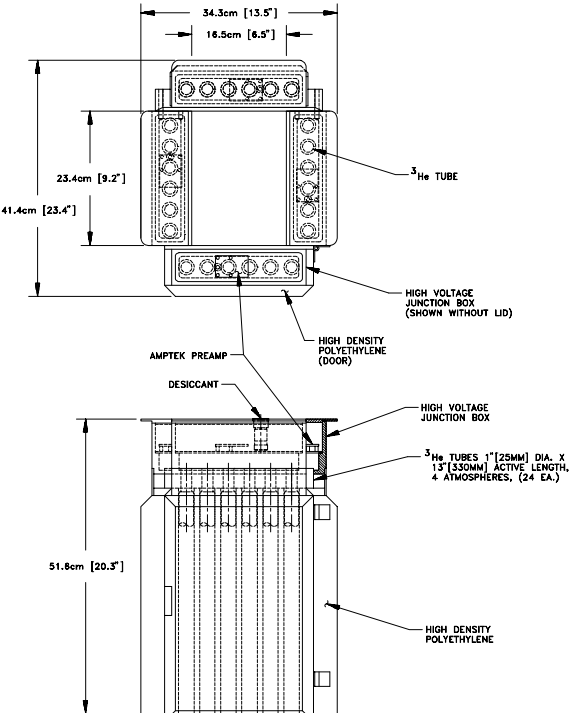
REFERENCES

1. Menlove, Howard A. (1981). Description and Performance Characteristics for the Neutron Coincidence Collar for the Verification of Reactor Fuel Assemblies. *Los Alamos National Laboratory Report LA-8939-MS*. Los Alamos, New Mexico.
2. Sensitivity is defined as the minimum number of rods that can be substituted and detected in a 1000 second count at a confidence level of 2 sigma.

Model JCC-71, 72 & 73 Neutron Coincidence Collars



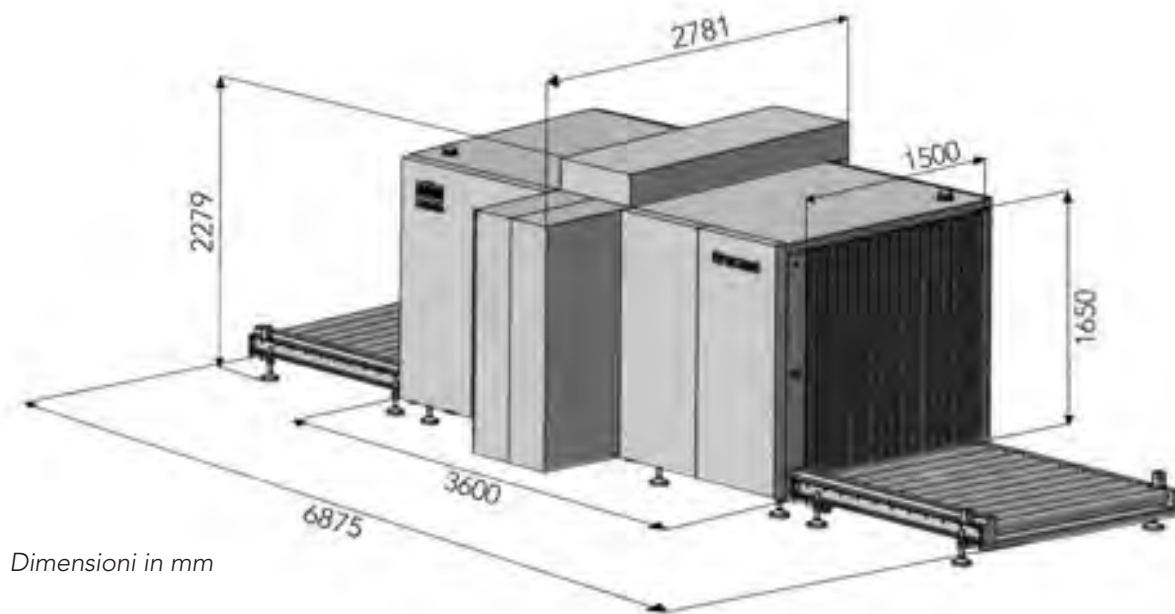
JCC-71, PWR Active Configuration.



JCC-71, PWR Passive Configuration.

FEP ME CARGO

FEP ME CARGO



Dimensioni in mm

Con riserva di modifiche e miglioramenti

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FEP ME CARGO

SISTEMA DI ISPEZIONE DI NUOVA CONCEZIONE. IDEALE PER IL CONTROLLO DI MERCI PALLETTIZZATE E DI COLLI DI GRANDI DIMENSIONI. UTILIZZA LE PIÙ MODERNE TECNOLOGIE IN AMBITO DI DISPOSITIVI DI DETEZIONE, ELETTRONICA DI ACQUISIZIONE, GESTIONE DATI SOFTWARE A MEZZO COMPUTER. LA CONSOLE DI COMANDO ERGONOMICA CONSENTE LA RIDUZIONE DEI TEMPI DI ISPEZIONE.

- *Trattamento immagine real-time a 24-bit*
- *Risoluzione e penetrazione ai massimi livelli*
- *Visualizzazione immagine b/n e colore su unico monitor switchabile*
- *Implementazione dei principali enhancements "on the fly"*
- *Innovativo sistema di archiviazione digitale delle immagini*
- *Possibilità di registrazione digitale della sessione di lavoro.*

SPECIFICHE TECNICHE

Unità d'ispezione

- Dimensioni: 6875 mm (L) x 2781 mm (W) x 2279 mm (H)
- Dimensioni tunnel: 1550 mm (W) x 1650 mm (H)
- Peso: 2400 kg
- Dimensione max bagaglio: 1500 mm (W) x 1650 mm (H)
- Altezza nastro: 350 mm (regolabile)
- Velocità nastro: 0,1-0,2 m/sec
- Carico massimo: 3000 kg
- Tensione d'alimentazione: monofase 230 VAC o 110 VAC +/- 10%
- Frequenza d'alimentazione: 50/60 Hz +/- 3 Hz
- Duty cycle: 100%

Postazione di controllo

- Dimensioni tavolo: 900 mm (L) x 800 mm (W) x 750 mm (H)
- Peso: 30 kg
- Controlli:
 - Chiave d'accensione
 - Pulsanti movimento nastro
 - Pulsanti di processing
 - Pulsanti di zoom
 - Pulsanti di allarme
 - Stop di emergenza
- Monitor: 19" SVGA, 1600 x 1200

Generatore raggi X

- Monoblocco ad alta frequenza: 30 kHz
- Tensione al tubo radiogeno: 150 kV
- Corrente al tubo radiogeno: 1 mA

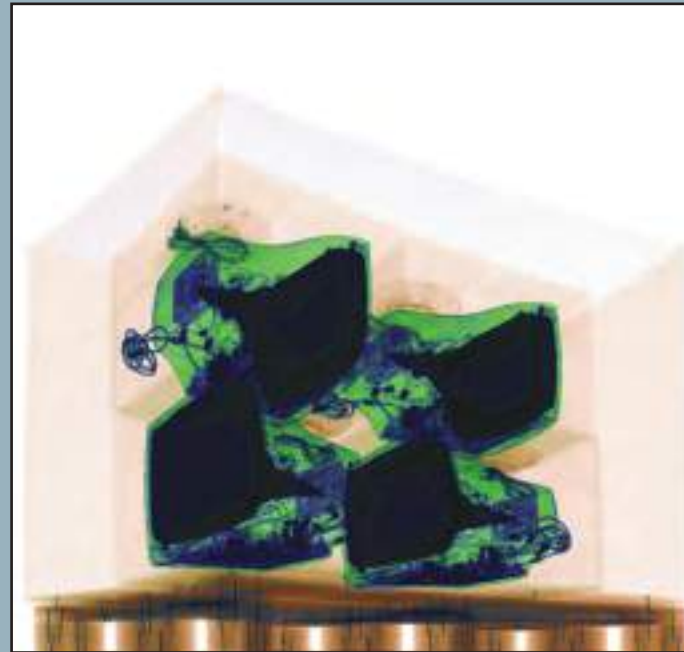


Immagine a colori di un imballo palletizzato in cui i materiali sono rappresentati con le seguenti colorazioni: arancio per organico, blu per inorganico, verde per materiali amorfi



Immagine in bianco e nero dello stesso imballo palletizzato

Caratteristiche del sistema di detezone

- Risoluzione:
 - 36 AWG garantito
 - 38 AWG tipico
- Penetrazione:
 - 26 mm acciaio garantito
 - 28 mm acciaio tipico
- Fotodiodi: doppio array ad "L"; 2240 fotodiodi

Elaborazioni d'immagine standard

- Evidenziazione famiglie di materiali
- Ottimizzazione del contrasto
- Esaltazione dei contorni
- Negativo dell'immagine
- Rimozione "low color levels"
- Energy stripping
- Hystogram equalization
- Pseudo colori
- Zoom x2 ... x64
- Elaborazioni "on the fly"

Funzionalità avanzate

- Allarme oggetti ad alta densità (soglia tarabile)
- Allarme masse organiche (soglia tarabile)
- Archiviazione digitale immagini

Fattori esposimetrici

- Gli impianti sono conformi alle normative internazionali vigenti
- Dose media al bagaglio:
 - <1,4 μSv / ispezione (con velocità del conveyor pari a 0,2 m/sec),
 - <2,5 μSv / ispezione (con velocità del conveyor pari a 0,1 m/sec)
- Dose sfuggente a 10 cm:
 - <1,0 μSv / h (0.1 mR/h)
- Film safety: garantita fino a ISO 1600/33 DIN

Requisiti ambientali

- Temperatura di funzionamento: da 0° C a +40° C
- Temperatura di stoccaggio: da -20° C a +60° C
- Umidità: 95 % senza condensa





Features

- Complete tool for *in situ* cartography, saving time, money, and dose
- Real-time acquisition and display
- Two dimensional gamma mapping
- High level of portability
- Compact detection head
- Compatible with hot cell applications
- Detection Head easily protected against contamination and easily cleaned
- Doserate estimation of hot spots
- Excellent spatial resolution for localization of gamma-ray emitters
- Perfect superimposition of gamma and visible images
- High detection sensitivity
- Remote control and operation
- User-friendly software on industrial PC
- Emergency response tool

Cartogam

Real-Time Portable Gamma-Ray Imaging System

Description

The Cartogam real-time portable gamma-ray imaging system is specially designed for *in situ* gamma measurements to locate radioactivity at nuclear sites.

It can be used to provide radiation intensity maps of areas during normal operations, to evaluate radiological source location when planning for maintenance or decommissioning operations and to quickly evaluate source positions during incidents, accidents, or emergencies.

Cartogam also provides input to quantitative gamma spectroscopy measurements of radioactive wastes or *in situ* radioactivity.

The high level of portability and the possibility of remote operation of Cartogam lead to a significant reduction of human exposure complying with the ALARA principle.

Cartogam is easy to carry, easy to use, and can be easily decontaminated, therefore making it practical for use in contaminated areas during equipment maintenance activities.

Cartogam is the perfect tool for real-time mapping of gamma emitting sources – it allows fast localization of radionuclides within contaminated areas.

The Cartogam system is composed of a small detection head and a portable PC. Acquisition, image analysis and data storage are managed through the GammaView software.

The detection head has been specially designed for taking into account the harshest environmental constraints of operations within hot areas of nuclear sites.

The Cartogam head is splashproof, fully decontaminable and is both light weight and portable, making it perfectly suited for an extended range of applications.



Phone contact information

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Cartogam

The user-friendly operation of Cartogam drastically reduces the exposure time of operators in accordance with the ALARA principle – the detection head can be remotely adjusted via a Pan and Tilt or specific remote manipulator devices. The PC to detection head distance can be up to 200 m (600 ft).

The Cartogam operation is very simple – full control is made from the GammaView software. Control of acquisition, analysis of scenes and data storage are particularly user-friendly and use a standard Windows® “Look and Feel” man-machine interface.



In situ radiological inventory prior to decontamination with Cartogam detection head mounted on Pan and Tilt and tripod.

After selection of the area to be mapped and the acquisition mode (low or high counting rate), the operator starts the automatic sequence of acquisitions.

At the end of the exposure time, Cartogam generates a composite image of the gamma map, superimposed on the visible image. The gamma image intensity is automatically normalized to full scale.

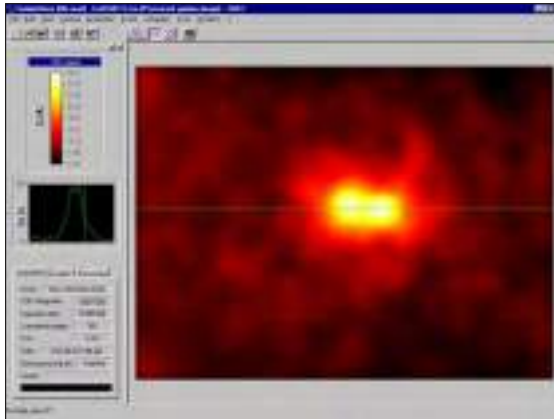
The hot spots may also be evaluated in dose rate according to a user-defined nuclide or energy.

The acquired raw data (composed of visible and gamma images, and other various parameters) is stored to ensure data integrity. Enhanced storage functions are available (key words associated to acquired images, etc.).

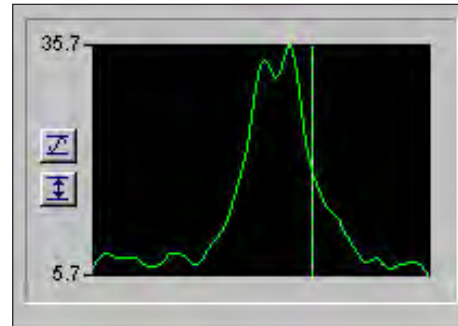
Cartogam Typical Applications

- Printed image showing radioactive source locations to workers.
- Source localization in waste removal activities.
- Monitoring of decontamination activities.
- Reduced exposure with improved job planning (according to the ALARA principle).
- Planning for maintenance during outages of nuclear power reactors.
- Precise location of sources for improved ISOCS measurements.
- Cartogam and ISOCS outputs provide input to Mercurad modeling and doserate calculation software.
- Remote survey of radiological conditions.
- Evaluation of shielding.
- Cost-effective sorting of nuclear wastes.
- Emergency situations such as: spills, transportation accidents, fires, terrorist “dirty bombs”, etc.

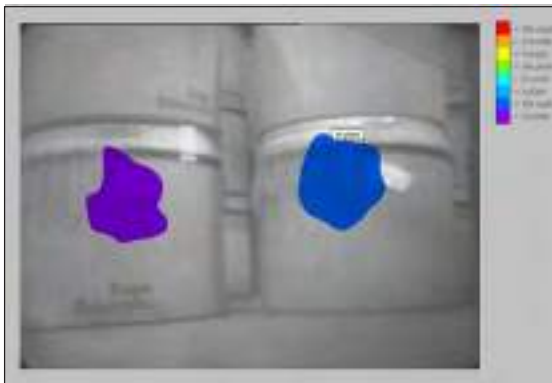
Cartogam



Histogram mode of a processed gamma image.



Projection of the gamma intensity on the X axis.



Heterogeneous source in a 220 liter drum – doserate mode.



Cartogam – superimposition of visible and gamma images without parallax. Gamma hot spots are quantized using a color scale.



Cartogam in association with ISOCS and Mercurad for easy localization and activity measurements of hot spots.

Cartogam

Specifications

IMAGING

ENERGY RANGE – 50 keV to 1.5 MeV and higher.

ACQUISITION MODES:

- High Count rate mode (up to 20 R/h at detector head).
- Low Count rate mode (allows real-time signal processing for improved spatial resolution).

DISPLAY MODES:

- Counts vs. position.
- Doserate according to user-defined nuclide or energy.

DETECTOR TYPE – CsI(Tl).

DETECTOR SENSITIVITY* – Can detect in 30 minutes a point source of ^{137}Cs that generates a doserate of 100 nGy/h (10 $\mu\text{R/h}$) at the detector, when used in low count rate mode.

EXPOSURE TIME – From 40 ms to 100 hours.

FIELD OF VIEW – Typically $43^\circ \times 33^\circ$ (H x V) for a collimator of 50° (30° collimator available on request).

SPATIAL RESOLUTION* –

Collimator	662 keV	1332 keV
50° (standard)	2.5°	4.5°
30° (optional)	1°	2°

PHYSICAL

OPERATING TEMPERATURE – -10°C to 35°C (14°F to 95°F).

STORAGE TEMPERATURE – -20°C to 50°C (-4°F to 122°F).

DETECTION HEAD:

- WEIGHT – 17.7 kg (39 lb).
- LENGTH – 414 mm (16.3 in.).
- DIAMETER – 80 mm (3.2 in.).
- Delivered with dedicated transport case.

HUMIDITY – 0 to 100%.

DETECTION HEAD TO PC CABLE – 30 m (90 ft) long (supplied with system), additional cables up to 200 m (600 ft) (see options).

MODEL NUMBER

Cartogam 50 – EM71267

- Real-time portable Gamma-ray imaging system.
- Standard unit as described.

Cartogam 30 – On specific request

- Similar unit, but with 30° collimator.

COMPUTER

DATA RECORDING:

- Gamma image, video image, and composite.
- Gamma/video images may be stored on disk, printed or transferred via a network.

STANDARD SOFTWARE – GammaView, based on Windows 2000 operating system.

PROCESSING UNIT – Includes portable industrial PC with integral card slots for data acquisition and processing units.

POWER SUPPLY – 110-230 V, 44-440 Hz.

OPTIONS AND ACCESSORIES

TM/TRI/CG – EM73416:

- Pan and Tilt mechanism mounted on heavy duty tripod.
- Manual control unit.
- Requires 220 V ac or 110-220 V transformer.
- 30 m cable between Pan and Tilt head and control unit.

SPT/CG – EM48052:

- Tabletop tilt-stand to support Cartogam.

SC/CG – EM71451:

- Shielded support bucket and stainless steel chain for crane.

CL/DH-PC/X – EM67186X:

- Additional cable between detection head and PC.
- Replace X with length between 10 m and 200 m.

CL/PT-CT/X – EM54881X:

- Additional cable between Pan and Tilt head and control unit
- Replace X with length between 10 m and 200 m.

CCPT-CG – EM72155:

- Aluminum lightweight carrying case for Pan and Tilt and tripod.

BLC-CG – EM49090:

- Annular tungsten shielding for increased protection against sources outside the field of view.

**Performances values are for a standard unit at 25°C (77°F).*

DrumScan® HRGS

Modular Segmented Gamma Scanner

- Fast accurate assay of waste containing gamma-emitting nuclides, allowing selection of appropriate waste disposal options
- Identification and quantification of radionuclides in near real-time
- Configurable for the measurement of fission and activation products, uranium and plutonium
- Modular approach to meet customer's specific needs
- Applications include disposal assay of operational, historic, or decommissioning waste contained in drums and boxes, through to fully plant integrated systems for monitoring high level wastes
- System supply backed up by BIL extensive experience to provide the 'total solution' to your nuclear waste monitoring needs

Features

- Wide range of selectable options to ensure that the system matches the customer's unique requirements
- Configurations range from stand alone manually operated units, through to full automated plant integrated systems
- Unique fingerprinting algorithms for the quantification of non-measurable isotopes. This technique was especially designed for dealing with the LLW arising from commercial reactor sites
- Configurable to all standard drum or container sizes including 1 liter, 100 liter, 200 litre (55 gallon) and 500 litre
- Large dynamic range – fully deadtime corrected
- Advanced and approved waste matrix correction techniques



- Transmission source option
- Full diagnostics and measurement control procedures
- Microsoft Windows™ NT based software
- Protection from all forms of electrical interference which may occur in an industrial plant environment
- Operationally proven

The DrumScan® HRGS is a modular Segmented Gamma Scanner which builds on the comprehensive range of waste assay systems offered by BIL. The system employs the very latest in advanced technology and is based on the unrivalled experience of BIL, gained in over twenty five years of the design, supply and operation of advanced radiometric instrumentation systems.

Applications

The DrumScan® HRGS offers reliable and efficient assay of waste arising from commercial nuclear reactors, allowing classification of wastes according to disposal category based

on activity, half-life and/or radiotoxicity. The system can be configured to identify which drums have below de minimus levels of activity for disposal as non-radioactive waste. The system is designed for ease of use and can be operated safely and confidently by staff with minimum training requirements.

System configurations

Modularity is the key to the flexibility offered by DrumScan® HRGS. This modularity extends through a choice of rotational platforms, with air drive motors, electric motors or stepper drive motors, and platforms capable of handling a wide range of container sizes. A range of detector types are available with either electrically cooled or LN2 cooled options.

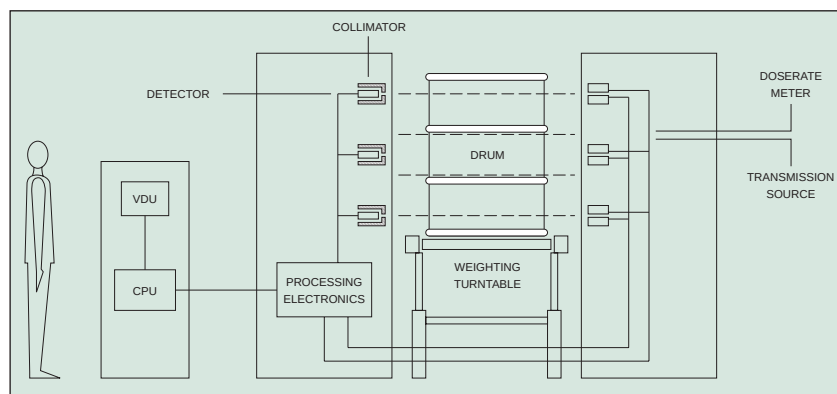


The range of detector options includes a single scanning detector or multiple detectors for a high throughput system.

A variety of matrix correction techniques are available with the use of a transmission source being optional. The choice of the appropriate techniques for use in a customer specific application can be made by BIL physicists based on the waste stream characteristics and the range of matrices that will be encountered by the system.

Matrix correction is by the 'intelligent combination' of any of the following options:- by weight, by differential peak absorption, use of a transmission source and the transweight approach. In operation, the system automatically selects the appropriate technique on the basis of density and the level of radioactivity determined by the system. The transmission source technique when combined with the stepper motor drive provides optional tomographic plots of both the density and radioactive distributions within the drum.

A bar code reader can be supplied as an option enabling the drum isotopic inventory to be automatically assigned to the drum identifier and also to allow automatic waste stream identification. To ensure that the system can handle a variety of wastes covering a broad dynamic range the system can be offered with an automated variable aperture collimator. Drum loading options offered include manual loading of drums, manual conveyor or fully automated conveyor.



A typical 3 detector configuration including transmission based matrix correction

Software and electronics

The software runs under Microsoft Windows™ NT, and is written to provide the operator with a familiar and friendly user interface.

Password protection is provided to allow controlled access to system manager functions, such as system calibration constants.

The software includes comprehensive error handling functions and diagnostics facilities with on-line help available to the system operator.

The system can provide hard copies of drum inventories to an optional external printer, save the inventory file to disc or transfer the file over an Ethernet link to a central computer database.

Operator interface

Routine operator interactions are carried out via the PC based control system from where all measurement and control procedures are initiated. Non-routine measurements and fault diagnostics are carried out via password protected menus. The system features in-built automatic standardization routines which check performance automatically either prior to every drum measurement or at preset time intervals.

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A BNFL Group Company



FEP ME 1000

- Trattamento immagine real-time a 24-bit
- Risoluzione e penetrazione ai massimi livelli
- Visualizzazione immagine b/n e colore su unico monitor switchabile o su doppio monitor
- Implementazione dei principali enhancements "on the fly"
- Innovativo sistema di archiviazione digitale
- Possibilità di registrazione digitale della sessione di lavoro

Sistema di ispezione di nuova concezione. Ideale per il controllo del bagaglio da stiva o di colli di medie e grandi dimensioni.

Utilizza le più moderne tecnologie in ambito di dispositivi di detezione, elettronica di acquisizione, gestione dati software a mezzo computer.

Predisposto per l'implementazione di software di riconoscimento di materiali pericolosi o vietati.

La console di comando ergonomica consente la riduzione dei tempi di ispezione.

SPECIFICHE TECNICHE

Unità d'ispezione

- Dimensioni: 3000 mm (L) x 1395 mm (W) x 1960 mm (H)
- Peso: 1000 kg
- Dimensione max bagaglio: 1000 mm (W) x 1000 mm (H)
- Altezza nastro: 350 mm (adjustable)
- Velocità nastro: 0.2 m/sec
- Carico massimo: 240 kg
- Tensione d'alimentazione: Monofase 230 VAC or 110 VAC +/- 10%
- Frequenza d'alimentazione: 50/60 Hz +/- 3 Hz
- Potenza assorbita: < 1.5 kVA
- Duty cycle: 100%

Postazione di controllo

- Dimensioni tavolo: 900 mm (L) x 800 mm (W) x 750 mm (H)
- Peso: 30 kg
- Controlli:
 - Chiave d'accensione
 - Pulsanti movimento nastro
 - Pulsanti di processing
 - Pulsanti di zoom
 - Pulsanti di allarme
 - Stop di emergenza

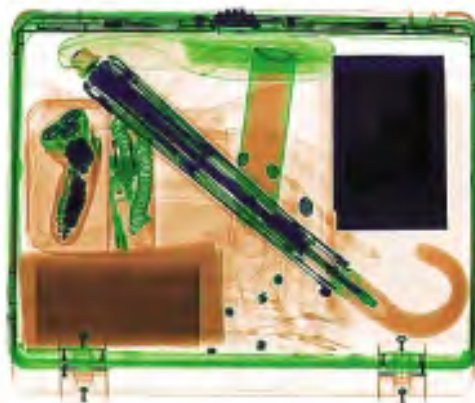
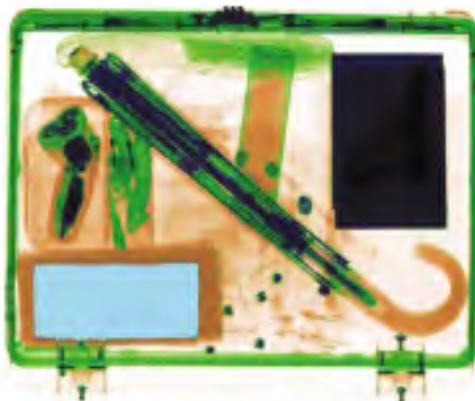


Immagine a colori in cui i materiali sono rappresentati con le seguenti colorazioni: arancio per organico, blu per inorganico, verde per materiali amorfi.



Esempio di segnalazione automatica di masse organiche ad alto assorbimento (con soglia tarabile)



Esempio di segnalazione automatica di masse metalliche ad alto assorbimento (con soglia tarabile)

- Monitor: 17" SVGA, 1024 x 768 (standard)

Generatore raggi X

- Monoblocco ad alta frequenza: 30kHz
- Tensione al tubo radiogeno: 150 kV

Caratteristiche del sistema di detezione

- Risoluzione:
 - 36 AWG garantito
 - 38 AWG tipico
- Penetrazione:
 - 23 mm acciaio garantito
 - 25 mm acciaio tipico
- Fotodiodi: doppio array ad "L"; 1400 fotodiodi

Elaborazione d'immagine standard

- Evidenziazione famiglie di materiali
- Ottimizzazione del contrasto
- Esaltazione contorni
- Negativo immagine
- Rimozione "low colour levels"
- Rimozione stripping
- Histogram equalization

- Pseudo colori
- Zoom x2 x64
- Elaborazioni "on the fly"

Funzionalità avanzate

- Allarme oggetti ad alta densità (soglia tarabile)
- Allarme masse organiche (soglia tarabile)
- ADS (optional)
- TIP (optional)
- Archiviazione digitale immagini

Fattori esposimetrici

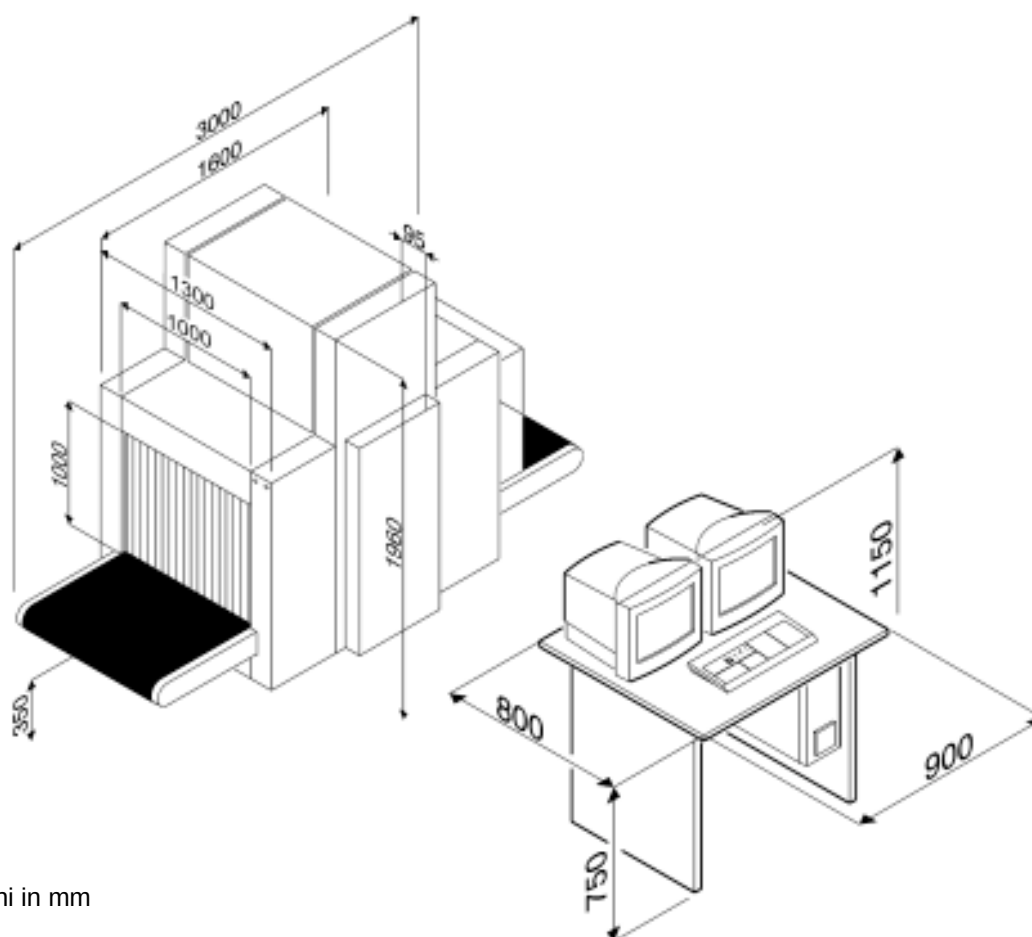
- Gli impianti sono conformi alle normative internazionali vigenti.
- Dose media al bagaglio: $<1.4 \mu\text{Sv}$ / ispezione (0.14mR)
- Dose sfuggente a 10 cm: $<1.0 \mu\text{Sv}$ / h (0.1mR/h)
- Film safety: garantita fino a ISO 1600/33 DIN

Requisiti ambientali

- Temperatura di funzionamento: 0°C / $+40^{\circ}\text{C}$
- Temperatura di stoccaggio: -20°C / $+60^{\circ}\text{C}$
- Umidità: 95% senza condensa
- Classe di protezione: IP22
- Rumore aereo prodotto: $<60\text{dB}$ (A)



FEP ME 1000



Dimensioni in mm

Con riserva di modifiche e miglioramenti

LABORATORI DI RICERCA riconosciuti "altamente qualificati" con D.M. 9-10-1985 – L.46/82 art.4

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Export department: tel. (+39) 0341-705.224 - 0341-705.281

NORME DI RIFERIMENTO

EC, IEC, FAA, ICRP, marcatura CE



Cod. 64804147 - Rev. 2 - IV/06 - Grafica Comense

FEP ME 990



- ✓ Trattamento immagine real-time a 24 bit
- ✓ Risoluzione e penetrazione ai massimi livelli
- ✓ Visualizzazione immagine b/n e colore su unico monitor switchabile o su doppio monitor
- ✓ Implementazione dei principali enhancements "on the fly"
- ✓ Innovativo sistema di archiviazione digitale delle immagini
- ✓ Possibilità di registrazione digitale della sessione di lavoro

Sistema di ispezione di nuova concezione. Ideale per il controllo del bagaglio da stiva o di colli di medie e grandi dimensioni.

Utilizza le più moderne tecnologie in ambito di dispositivi di detezione, elettronica di acquisizione, gestione dati software a mezzo computer.

Predisposto per l'implementazione di software di riconoscimento di materiali pericolosi o vietati.

La console di comando ergonomica consente la riduzione dei tempi di ispezione.

SPECIFICHE TECNICHE

Unità di ispezione

- Dimensioni : 3000 mm (L) x 1200 mm (W) x 1945 mm (H)
- Peso : 950 kg
- Dimensione max bagaglio : 900 mm (W) x 900 mm (H)
- Altezza nastro : 350 mm (regolabile)
- Velocità nastro : 0.2 m/second
- Carico massimo : 240 kg
- Alimentazione : Monofase 230 VAC or 110 VAC +/- 10%
- Frequenza : 50/60 Hz +/- 3 Hz
- Potenza assorbita : < 1.5 kVA
- Duty Cycle : 100%

Postazione di controllo

- Dimensioni tavolo : 900 mm (L) x 800 mm (W) x 750 mm (H)
- Peso : 30 kg
- Controlli : Chiave d'accensione
- Pulsanti movimento nastro
- Pulsanti di processing
- Pulsanti di zoom
- Pulsanti di allarme
- Stop di emergenza
- Monitor : 17" SVGA, 1024 x 768

Generatore raggi X

- Monoblocco ad alta frequenza (30 kHz)
- Tensione al tubo radiogeno : 150 kV

Caratteristiche del sistema di detezione

- Risoluzione : 36 AWG garantito
- 38 AWG tipico
- Penetrazione : 23 mm acciaio garantito
- 25 mm acciaio tipico
- Fotodiodi : Doppio array ad "L", 1248 fotodiodi

Elaborazioni d'immagine standard

- Evidenziazione famiglie di materiali
- Ottimizzazione del contrasto
- Esaltazione dei contorni
- Negativo dell'immagine
- Rimozione "low colour levels"
- Energy stripping
- Histogram Equalization
- Pseudo colori
- Zoom x 2 x 64
- Elaborazioni "on the fly"

Funzionalità avanzate

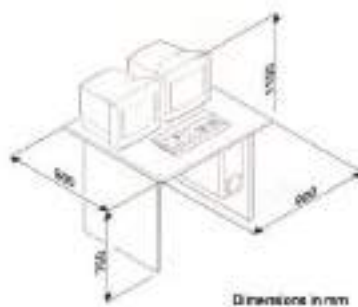
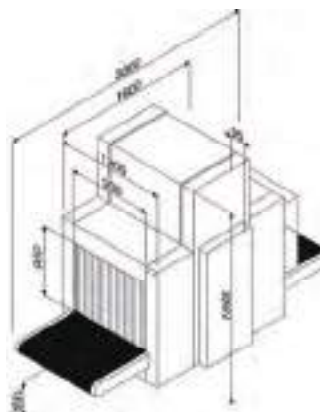
- Allarme oggetti ad alta densità (soglia tarabile)
- Allarme masse organiche (soglia tarabile)
- ADS (optional)
- TIP (optional)
- Archiviazione digitale immagini

Fattori esposimetrici

- Gli impianti sono conformi alle normative internazionali vigenti
- Dose media al bagaglio : <1.4 µSv / ispezione (0.14 mR)
- Dose sfuggente a 10 cm : <1.0 µSv / h (0.1 mR/h)
- Film safety : garantita fino a ISO 1600/33 DIN

Requisiti ambientali

- Temper. di funzionamento : 0° C - +40° C
- Temper. di stoccaggio : -20° C - +60° C
- Umidità : 95 % senza condensa
- Classe di protezione : IP 22
- Rumore aereo prodotto : < 60 dB (A)



Con riserva di modifiche e miglioramenti

LABORATORI DI RICERCA riconosciuti "Altamente Qualificati" con D.M. 9-10-1985 - L.46/82 art.4

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NORMATIVE DI RIFERIMENTO

Direttive CEE, Norme IEC, TSA, Marcatura CE



FRAM

Features

- Determines relative plutonium isotopic abundances or uranium isotopic abundances in non-destructive assay applications
- Uses spectra collected with HPGe detectors
- Incorporates a sophisticated peak fitting and multiplet deconvolution algorithm to analyze complex peak regions
- Requires no efficiency calibration for matrix density, thickness or container characteristics
- Developed by Los Alamos and licensed to Canberra

Description

FRAM (Fixed-Energy, Response Function Analysis with Multiple Efficiency) is a code developed by Los Alamos to analyze pulse-height spectra generated by high-resolution gamma-ray detectors. It has been used primarily to determine the isotopic composition of plutonium in special nuclear materials. Its design and flexibility allow it to easily measure ratios and distributions of isotopes other than plutonium in arbitrary items.

In nuclear safeguards, FRAM complements calorimetry and neutron coincidence counting by allowing measurements to be interpreted in terms of total plutonium mass.

Table 1. Material Types Measured with FRAM

^{240}Pu (2% – 95%) of total plutonium
^{241}Pu – ^{237}U (nonequilibrium)
Am/Pu in heterogeneous combinations
^{241}Am (0.01% to >50%)
$^{235}\text{U}/\text{Pu}$ mixed (MOX) ratios from 0.005 – 35
^{243}Am – ^{239}Np
^{244}Cm
^{237}Np
^{234}U , ^{235}U , ^{238}U relative abundances, (no plutonium present), 0.2 to >97% ^{235}U
^{238}Pu (80%)
Materials in shielded or heavy-walled containers (≥ 13 mm Pb for plutonium, ≥ 16 mm steel for uranium)

Measurement Principles

In its principal application, FRAM analyzes photopeaks in the spectrum of plutonium gamma rays detected by a high-purity germanium detector. This spectrum contains peaks from the plutonium isotopes $^{238-241}\text{Pu}$, ^{241}Am and often other isotopes such as ^{235}U or ^{237}Np . FRAM combines this information to produce isotopic ratios independent of sample size, shape, physical and chemical composition, measurement geometry, and container characteristics. The results are obtained using only the spectral data and known fundamental nuclear branching fractions and half lives and do not require calibration with standards.

A requirement that the plutonium in the sample has one isotopic composition is usually satisfied. However, certain important cases in which the ^{241}Am is not homogenous with the plutonium can also be analyzed using the “multiple efficiency” characteristics built into the FRAM code. This allows FRAM to improve the results on elementally (Am/Pu) heterogeneous pyrochemical residues. The multiple efficiency feature of FRAM can also be applied to other types of elementally heterogeneous materials. The physical and chemical characteristics of the measured item need not be uniform or even well known. Items may contain mixtures of solids and powders with no ill effect as long as the plutonium is isotopically uniform.

FRAM is primarily an analysis package, although it is capable of simple control of data acquisition hardware as well (see below). The end results are displayed in their own window as shown in Figure 1. It is also possible to display the spectrum in various ways, including showing the fitted results on each peak region. FRAM also contains an MCA emulator display and displays the spectrum during data acquisition.

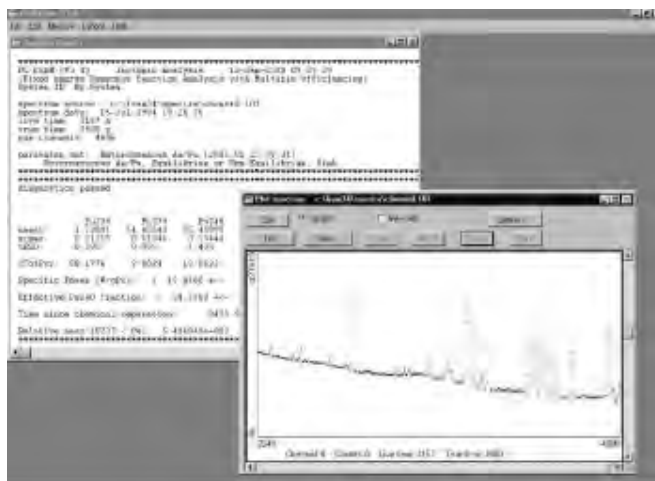


Figure 1.
Example of spectrum display and analysis result
printout capabilities

Phone contact information

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For other international representative offices, visit our Web Site: <http://www.canberra.com> or contact the Canberra U.S.A. office.

5/03 Printed in U.S.A.

Performance

The isotopic fractions themselves are usually the desired result for quality control and process measurements. For nuclear safeguards, two additional quantities are most often the end results of the isotopic measurement process. These integral quantities, the effective specific power P_{eff} (W/g Pu) and the effective ^{240}Pu fraction $^{240}\text{Pu}_{\text{eff}}$, are derived from the measured isotopic fractions, and known nuclear constants. They are used to interpret calorimetry measurements (P_{eff}) and neutron coincidence counter measurements ($^{240}\text{Pu}_{\text{eff}}$) respectively.

Over a wide range of measurement and sample conditions FRAM performance falls into ranges shown in Table 2.

Table 2. Typical Ranges of FRAM Measurement Characteristics	
Measurement Time	20 min to 1 hr
Sample Size	100 mg to many kg (limited by criticality)
Precision (relative standard deviation)	$P_{\text{eff}} - 0.2\%$ to 0.5% $^{240}\text{Pu}_{\text{eff}} - 0.8\%$ to 3.0%
Bias	$P_{\text{eff}} - <0.3\%$ $^{240}\text{Pu}_{\text{eff}} - <1.0\%$ Individual isotopes – $<1.0\%$ (^{238}Pu to ^{241}Pu)

MEASUREMENT HARDWARE

While FRAM is primarily an analysis package, it does include a simple method for data acquisition. It can set the preset, start and stop spectrum acquisition, and save the spectra to a file using the following Canberra MCA devices:

DSA-2000 Digital Spectrum Analyzer
Model 556A AIM with ICB NIM
InSpector Portable MCA
InSpector 2000 DSP Portable MCA
AccuSpec Boards
System 100 Boards

The details of the MCA setup are defined with the Genie 2000 MID Editor Setup Wizard. This utility program leads the user through a simple set of selections to define the MCA configuration. More complex cases are defined using the MCA Input Definition Editor itself.

If the front end electronics are not programmable, the use of the MID Editor Setup Wizard, or the MID Editor itself is usually all that is required to define the configuration. The FRAM code can then be used as a stand-alone package. If the front end electronics are programmable, they need to be setup using the Genie 2000 software since FRAM does include any controls for such adjustments.

OPERATING PLATFORMS

FRAM is available to work with the Genie 2000 software suite on the Windows® 95, Windows 98 and Windows NT® operating systems.



GammaModeler™, 3-D Gamma Ray Imaging Technology

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AIL Systems Inc.
455 Commack Road
Deer Park, NY 11729

ABSTRACT

The AIL GammaModeler™ 3-D visual and gamma-ray imaging system was successfully demonstrated at the DOE Hanford Site 221-U facility as part of the Canyon Disposition Initiative (CDI). Measurements were taken of canyon equipment from several viewing directions using the GammaModeler™ camera. The combined radiation and visual data were rendered as 3-D drawings that allow the user to view the representation from any angle. The gamma-ray sources are color coded to represent the radiation intensities. The known coordinates and intensities of the sources allow calculations of dose estimates to be performed for any position relative to the canyon equipment. These positional and intensity data allow better dose mapping in the canyon area that should improve planning decision-making with respects to the goals of the CDI.

INTRODUCTION

The Canyon Disposition Initiative (CDI) is a jointly funded project at the Department of Energy's Hanford site, which is located in the southeastern Washington State. Participating Environmental Management (EM) offices include the Office of Waste Management (EM-30), the Office of Environmental Restoration (EM-40), The Office of Science and Technology (EM-50), and the Office of Nuclear Material and Facility Stabilization (EM-60). This partnership is evaluating the feasibility of utilizing the five massive fuel-reprocessing facilities (canyons) in the 200 Areas as waste repositories, among other disposition alternatives. The 221-U Facility is the "pilot" project for the CDI. As part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Remedial Investigation/Feasibility Study, extensive characterization of the 221-U Facility is underway. The characterization data collected, measured, derived, etc. are required to support a Performance Assessment , which will lead to a Record of Decision.

OBJECTIVE

The 3-D GammaModeler™ visual and gamma ray imaging system was developed by AIL Systems Inc. to remotely survey large areas for gamma-ray emissions and display the results as combined 3-D representations of the radiation sources and the equipment. The objective of the demonstration of the 3-D GammaModeler™ system at the

Department of Energy Hanford site 221- U Facility is to identify potentially beneficial technologies for the Canyon Disposition Initiative (CDI). During the demonstration, the GammaModeler™ system was used to survey a portion of the facility and provide visual and radiation measurements of contaminated equipment located within the facility. The system provides information on source locations interior to the visual objects and provides a better estimate of the source intensities. The use of 3-D visual and gamma ray information supports improved planning decision-making, and aids in communications with regulators and stakeholders. The demonstration was performed from August 18 – August 26, 1999. Measurements were taken during four of those days.

PROJECT DESCRIPTION

The 3-D GammaModeler™ system consists of four modules: a sensor head, a portable PC compatible computer, a pan and tilt controller, and a 3-D workstation. The sensor head, shown in figure 1, incorporates a coded aperture gamma ray imaging detector, a high-resolution video camera, a laser range finder, and a pan and tilt assembly. For the demonstration the sensor head was wrapped in plastic to prevent contamination and mounted via a special adapter to the facilities crane hook. The PC and pan and tilt controllers were located in the crane cab for remote operation of the sensor head. By mounting the sensor head on the crane hook, the sensor head could be remotely positioned anywhere in the canyon and could point in any direction using the pan and tilt assembly. However, the tilt angles were restricted to +/- 73 degrees so looking straight down on an object was not possible. The video field of view (FOV) was 73° horizontal by 55° vertical and the gamma FOV was 25° by 25° degrees with an angular resolution of 1.3 degrees. The sensor head has a spectral range from ~100 keV to > 1.3 MeV with a sensitivity for ^{137}Cs of one microR dose with the highest sensitivity in the center of the FOV. The system is able to operate in both low level (< 15 microR/hr) and high level (>100 R/hr) radiation environments with no shielding required.



Figure 1. 3-D GammaModeler™ Sensor Head

AIL personnel operated the GammaModeler™ system and the crane operator positioned the sensor head near the objects to be surveyed for gamma radiation sources. A pseudo-

color image of gamma ray emitting sources is displayed as a composite picture with the video picture of the scene. The gamma ray intensities above a detection threshold are automatically scaled to indicate the highest radiation level as red and the lowest level as blue. The video picture has a wider FOV than the gamma FOV so the boundaries of the gamma images are indicated in the composite picture by a rectangular box. Parallax corrections are applied in positioning the gamma ray image with respect to the video image so the gamma sources appear at the proper visual location. The exposure time required to obtain a gamma image is dependent upon several factors including gamma ray energy, the distance to the source, and the shape and distribution of the source. Additional images taken by the operator provide vector range to key references in the scene. These marker images are used to locate the position of the sensor head. The system software, *GammaSoft*TM, produces a single file that contains all the images and the system measurement parameters. This file is copied to a disk for transfer to the 3-D workstation located outside the canyon area.

For those objects with detectable radiation, *GammaSoft*TM is used to generate files that are used by the 3-D processing software in addition to the images in graphic format. The files used by the 3-D processing software are marker files and the gamma ray count file for the gamma ray image. The marker files contain an ordered list of the range and direction to each reference point for a given sensor head location. For each sensor head location, the reference points are cross-referenced to reference points for other sensor head locations. From these data, the relative positions of the sensor head locations can be determined. If a reference point is on the object being surveyed, that position can be determined also. From the gamma radiation image data, location in the image corresponds to a direction from the gamma detector axis. For extended sources, line sources, etc., the 2-D image can be deconvolved into a series of point sources using our knowledge of the point-spread function for the detector. The locations in the image of the resulting point sources are the directions to the true locations for the sources. The deconvolution analysis also provides the intensity of the source at the sensor head. This intensity can be converted to a dose at the sensor head for the source. Similar to the reference points the sources seen in a 2-D view must be cross-referenced to the sources seen in another 2-D view. By knowing the sensor head positions, the pointing directions for the sensor head, the directions of the radiation sources for each view, and the cross-referencing of the sources, the 3-D location of the sources can be calculated along with their source strengths. The source strengths are calculated from each image in which the source is detected. If there is no differential attenuation between the views, then the calculated source strengths agree. If there is a difference, then the largest value for the source strength is reported. The results are stored to a file that can be used by *GammaCad*TM to merge these results with the visual representations in AUTOCAD.

RESULTS

A total of 20 objects were imaged during the demonstration period at the 221-U Facility. Seven of these objects had observable gamma radiation and measurements were taken at several viewing angles to support the 3-D rendering of the objects.

The high rad tank on Cell 35 was the first object imaged during the demonstration and was observed to have gamma emissions. This object was measured from four viewing directions. In addition to the four gamma images, a total of 27 marker images were obtained. The four gamma images are shown in figures 2 – 5. In figures 2,4,and 5, the source is observed to be an elongated source rather than a point source. The view from the side does not show the source strongly. This is probably due to some internal structure that attenuates the gamma radiation. The source seen in fig. 3 is treated as an ambiguous source that cannot be triangulated with other views. The gamma FOV for these figures is indicated by the rectangular outline within the figure. For sensor head position 1, the source is clearly seen to be near the bottom of the object. However, for sensor positions 3 and 4, the source is not near the bottom but does change location with the viewing angle.



Figure 2. Sensor Position 1



Figure 3. Sensor Position 2



Figure 4. Sensor Position 3



Figure 5. Sensor Position 4

In the coordinate system of the object, the y direction is along the canyon length, and the x direction is across the canyon. In figure 2 (sensor head position 1), the sensor is located in the positive y direction and in the negative x direction relative to the tank. Sensor positions 3 and 4 are behind the tank in the negative y direction. Sensor position 4 was taken from a higher elevation than sensor position 3 with the sensor head tilted down more to keep the tank in the FOV.

For each 2-D image, the extended source was deconvolved into five point sources. The direction from the sensor head to the source locations was determined and the intensity at

the sensor head. Knowing the sensor head locations and the directions to the sources, the source positions are determined by the positions of closest approach for the source ray traces. Figure 6 shows a 3-D plot locating the sensor head locations (small labeled boxes), the direction ray traces from the sensor locations, the locations of closest approach, and the source position for each pair of ray traces. In this figure, the sensor head locations have been adjusted so that the coordinate (0,0,0) corresponds to the bottom center of the tank. The same program that generates this plot generates the file, which contains the source locations and the 30-cm dose values.

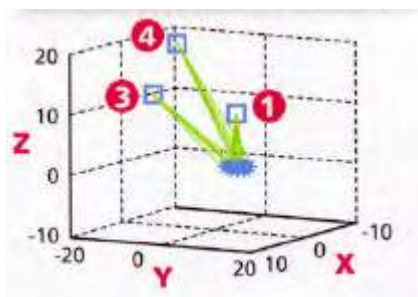


Figure 6. Calculated sensor positions, source positions

A 3-D representation of the object was generated using AUTOCAD. From the marker image data, it was determined that the tank diameter was 10 feet. The tank's center was positioned at $x=0$ and $y=0$. There the visual representation coordinate system is the same as that for the gamma radiation analysis. The tank was made transparent so that the sources located interior to the tank can be seen in the merged drawing. *GammaCadTM* is used to merge the gamma radiation data with the visual representation. *GammaCadTM* opens the AUTOCAD drawing of the visual object and the file containing the gamma radiation source information. The program creates color spheres for each of the point sources. The color of the spheres is related to the strength of the source. Red corresponds to those sources in the highest 1/3 intensity. Green corresponds to the middle third. Blue corresponds to the lowest third. Figures 7 and 8 show the merged 3-D visual and gamma radiation results as an AUTOCAD representation. AUTOCAD allows the object to be viewed from any direction. The two figures represent different rotations of the same object. Five colored spheres represent the extended source; their color relates to the 30-cm dose strength. The center sphere is red and corresponds to 810 mR/hr (the most intense source). In figure 7, the sphere on the right is blue representing 200mR/hr (within the lowest third strength). The other spheres are green and have values between 290 and 550 mR/hr.

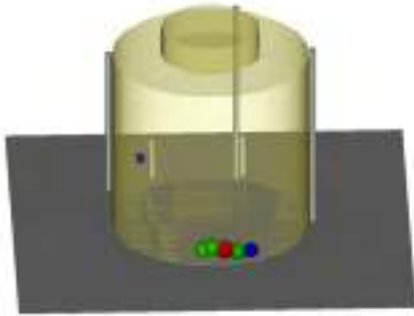


Figure 7. 3-D rendering of high rad tank.

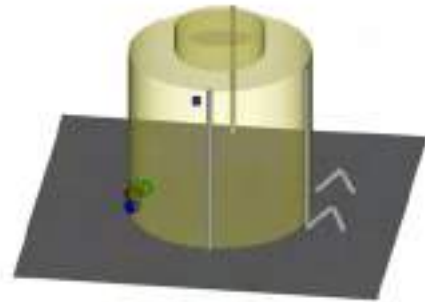


Figure 8. 3-D rendering of the high rad tank. Rotated approximately 90 degrees from the previous view.

A program called DOSE that can calculate the dose at any position in the coordinate system reads the file of the radiation sources. Figure 9 shows a screen capture of a dose calculation for the high rad tank. The program requests the file name and then the coordinates for the point where the dose is desired. The coordinates correspond to a location near the edge of the radiation exclusion zone. The calculated dose is 21 mR/hr. The calculation can be repeated for another location. Another program called MDOSE can calculate the dose resulting from multiple objects by combining files resulting from the analyses of additional objects and absolute canyon coordinates for each object.

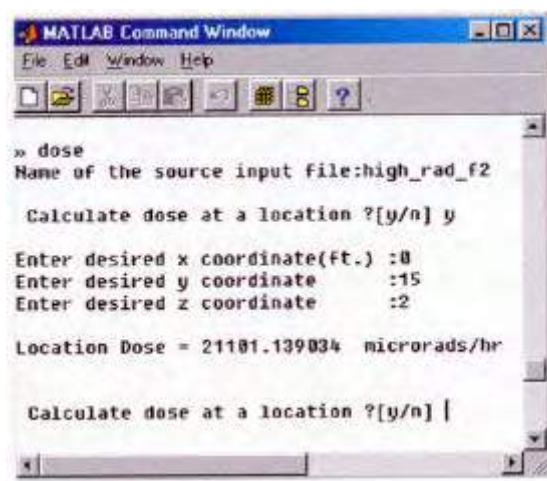


Figure 9. Typical dose calculation.

TECHNOLOGY APPLICABILITY

The applicability and benefits of AIL's 3-D GammaModeler™ Gamma Ray Imaging technology at the U-Facility includes:

- Characterization with minimum exposure to personnel
- Rapid characterization via imaging of large areas from a safe standoff distance
- Characterization in a high radiation environment
- Characterization of radiation environment internal to the equipment
- Characterization that provides a visual electronic records
- 3-D localization of sources provides better estimates of radiation intensities, which leads to cost effective D&D planning and operation.
- Pan and Tilt capability allows measurements from new directions previously not available.



Summary Report DOE/EM-0593

GammaModeler™

3-D Gamma-Ray Imaging Technology

Deactivation and Decommissioning Focus Area
and Characterization, Monitoring, and Sensor
Technology Crosscutting Program



Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

August 2001



GammaModeler™

3-D Gamma-Ray Imaging Technology

OST/TMS ID 2402

Deactivation and Decommissioning Focus Area
and Characterization, Monitoring, and Sensor
Technology Crosscutting Program

Demonstrated at
U. S. Department of Energy
Hanford Site, 221-U Facility
Richland, Washington



Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.ost.em.doe.gov/ost under "Publications."

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SECTION 1

SUMMARY

Technology Summary

Project Background

The Canyon Disposition Initiative (CDI) project is evaluating the feasibility of using the DOE Hanford site processing facilities as assets for disposal of low-level wastes. As part of the study, an extensive characterization of the 221-U facility is underway as the “pilot” facility. In support of CDI characterization project objectives, the GammaModeler™ system was comprehensively demonstrated to facilitate deployment of 3-D Visual and Gamma-Ray Imaging technology, and to compare performance and cost of the GammaModeler™ to the GammaCam™ (2-D system). The GammaModeler™ system was used to survey a portion of the facility and provide 3-D visual and radiation representation of contaminated equipment located within the facility.

The 3-D GammaModeler™ system software was used to deconvolve extended sources into a series of point sources, locate the positions of these sources in space and calculate the 30 cm. dose rates for each of these sources. Localization of the sources in three dimensions provides information on source locations interior to the visual objects and provides a better estimate of the source intensities. The three dimensional representation of the objects can be made transparent in order to visualize sources located within the objects. Positional knowledge of all the sources can be used to calculate a map of the radiation in the canyon. The use of 3-D visual and gamma ray information supports improved planning decision-making, and aids in communications with regulators and stakeholders with only a minimal cost increase (<10%).

System Description

The 3-D GammaModeler™ visual and gamma ray imaging system was developed by AIL Systems Inc. to remotely survey large areas for gamma-ray emissions and display the results as combined 3-D representations of the radiation sources and the equipment. The GammaModeler™ system is an upgrade of the AIL GammaCam™ system that provides 2-D images of the radiation environment overlaid on the video picture of the scene. The 3-D GammaModeler™ system consists of four modules: a sensor head, a portable PC compatible computer, a pan and tilt controller, and a 3-D workstation. The sensor head, shown in figure 1, incorporates a coded aperture gamma ray imaging detector, a high-resolution video camera, a laser range finder (new), and a pan and tilt assembly (new). The sensor head is controlled remotely by the PC and the pan and tilt controller. The pan and tilt assembly allows the sensor head to be panned a full 360 degrees and tilted ± 73 degrees. The sensor head was mounted the canyon crane hook with a special interface mount. Remote operation and control of the sensor head allows for safe image acquisition in high radiation environments, minimizing operator exposure. During image taking operation, a pseudo-color image of gamma ray emitting sources is overlaid on the video picture of the scene.



Figure 1 GammaModeler™ Sensor Head

At each camera location with observed gamma ray emissions, additional images are taken of key reference features in the scene along with the measured range, and pan and tilt directions to these features. Viewing the same features from another location allows the relative camera positions to be calculated. These calculated camera positions are adjusted to place the object at a desired position or an absolute position if known. Knowledge of the camera locations is essential to triangulating the observed gamma sources in the 2-D images in order to position the sources in three dimensions.

The baseline 2-D GammaCam™ has also been mounted from the crane hook. However its mounting fixture allows only downward looking images to be taken. This prevents measurements of objects obscured by any shielding above the object or obtaining measurements from other viewing angles.

Without the ability to pan and tilt, 3-D rendering is not possible without entering the canyon and changing the mounting fixture for the GammaCam™.

The GammaModeler™ system with its ability to pan and tilt the sensor head and measure range has extended the uses of gamma imaging systems in highly contaminated areas. First, the GammaModeler™ system with its remote pan and tilt capability allows the sensor head to completely scan of an area without requiring a radiation worker to change the sensor head direction. This reduces the potential exposure for the radiation worker. Second, the GammaModeler™ system with its range and direction measurement capability, allows analysis of the radiation environment in 3-D. The localization of sources and calculation of dose environment can substantially reduce exposure to the radiation worker and allow improved execution of any D&D operation.

Demonstration Summary

The objective of the demonstration of the 3-D GammaModeler™ visual and gamma-ray imaging system at the Department of Energy Hanford site is to identify potentially beneficial technologies for the Canyon Disposition Initiative (CDI). The Canyon Disposition Initiative (CDI) is a jointly funded project at the Department of Energy's Hanford site, which is located in the southeastern Washington State. Participating Environmental Management (EM) offices include the Office of Waste Management (EM-30), the Office of Environmental Restoration (EM-40), The Office of Science and Technology (EM-50), and the Office of Nuclear Material and Facility Stabilization (EM-60). This partnership is evaluating the feasibility of utilizing the five massive fuel reprocessing facilities (canyons) in the 200 Areas (B Plant, T Plant, U Plant, Plutonium Uranium Extraction Facility, and the Reduction Oxidation Plant) as waste repositories, among other disposition alternatives. The 221-U Facility is the "pilot" project for the CDI. As part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Remedial Investigation/Feasibility Study, extensive characterization of the 221-U Facility is underway. The characterization data collected, measured, derived, etc. are required to support a Performance Assessment (PA), which will lead to a Record of Decision (ROD).

The demonstration was performed from August 18 – August 26, 1999. Measurements were taken during four of those days.

The key results of the demonstration are as follows:

- The AIL GammaModeler™ system could be mounted on the U-Facility's crane hook and positioned to any location within the canyon. The pan and tilt assembly allows fine pointing of the sensor head at the equipment of interest. The laser range finder provided distance measurements to the objects being surveyed.
- The pan and tilt capability allowed the system to view objects that may have been blocked if a fixed viewing direction system was used.
- The system performed well during the demonstration and obtained data on 21 objects of interest to the CDI study. Real time display of the gamma ray images to the operator showed that seven of these objects had detectable emissions. For these objects, additional views were obtained to allow 3-D rendering. The 3-D rendering showed the sources in relationship to the visual objects.
- During the demonstration, 3-D renderings were generated for several of these objects and were presented during the outbrief presentation. Post demonstration analyses refined the 3-D rendering results but did not substantially change any of the results.
- Operation of the GammaModeler™ system is relatively simple and some training is required to assure relevant data are obtained. Currently, the use of the 3-D rendering software requires experience in modeling the source distributions.
- Several of the U-Facility cells were imaged. Even with the limited viewing angles that could be obtained for these cases, the 3-D rendering software still allowed 3-D representations of the source locations and strengths to be determined.

- For one U-Facility cell, the system was able to determine the source distributions and intensities at distances greater than forty feet. These sources are of high intensities and would not be accessible to RCTs using hand-held instrumentation.
- The cost of using the GammaModeler™ is approximately ten percent greater than that for the baseline GammaCam™. The difference is due to the cost of equipment rental and 3-D rendering of an object. However only the GammaModeler™ system with its ability to measure sensor head pointing direction and range can produce a 3-D rendering of an object or region. From multiple views obtained using the GammaCam™ the location of sources can be inferred but not accurately determined.

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Licensing

No licensing activities were required to support the demonstration.

Permitting

No permitting activities were required to the support the demonstration.

Other

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST reference number for GammaModeler™ is 2402.

SECTION 2 TECHNOLOGY DESCRIPTION

Overall Process Definition

The 3-D GammaModeler™ system consists of four modules; a sensor head, a portable PC compatible computer, a pan and tilt controller, and a 3-D workstation. The demonstration setup is schematically shown in figure 2. For the demonstration, the sensor head was attached to the 221-U facilities 10-ton crane hook using an AIL designed crane hook interface. The PC compatible computer and the pan and tilt controller were located in the crane cab. Two 100 foot cables (a system cable and a pan and tilt cable) were routed along the crane bridge from the sensor head to the equipment in the crane cab. The 3-D workstation was located in the office portion of the U facility.

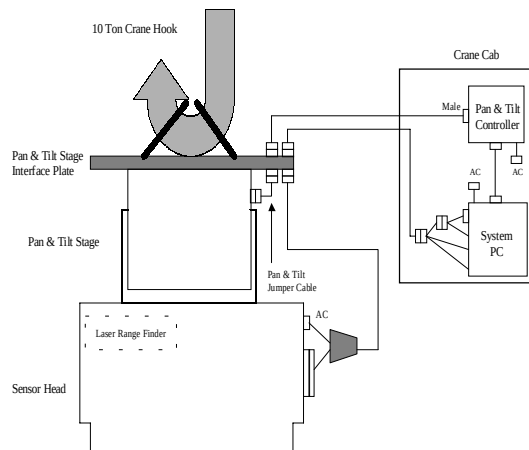


Figure 2 GammaModeler™ Setup

The sensor head has a gamma ray imaging detector, a high-resolution video camera, a laser range finder, and a pan and tilt assembly. The gamma ray imaging detector belongs to a class of cameras called spatially coded aperture cameras. The gamma ray photons passing through the coded aperture in the sensor head cast a complicated gamma shadow on a gamma detector (scintillator). This shadow created by the gamma ray flux is detected by the scintillator, which converts the gamma shadow into a visible shadow. The visible shadow is amplified through an optical system and is detected by a low-noise charged coupled device (CCD) imaging camera. The signals representing the gamma shadow are read out by the CCD camera and are then digitally processed by the computer. A gamma ray image of the objects is reconstructed by applying a decoding process on the gamma shadow of the coded aperture. The reconstructed image is displayed over a video image of the observed scene obtained with the video camera. The pan and tilt assembly provides the ability to point the sensor head in any direction.

The sensor head was wrapped in plastic prior to canyon entry to protect it from airborne contamination. The plastic wrap did not cover the video/laser range finder window but was taped to its edges to assure the seal. For the demonstration, the sensor head was inverted when attached to the crane hook. During installation of the sensor head to the crane hook, the slack in the cable was looped and rigidly secured to the crane hook. This prevented the sensor head from being lowered below the canyon deck and into the open cells. By mounting the sensor head on the crane hook, the sensor head could be remotely positioned anywhere in the canyon and could point in any direction using the pan and tilt assembly. However, the tilt angles were restricted to ± 73 degrees so looking straight down on an object was not possible. The video field of view (FOV) was 73° horizontal by 55° vertical and the gamma FOV was 25° by 25° degrees with an angular resolution of 1.3 degrees. The sensor head has a spectral range from ~ 100 keV to > 1.3 MeV with a sensitivity for ^{137}Cs of one microR dose with the highest sensitivity in the center of the FOV. The system is able to operate in both low level (< 15 microR/hr) and high level (> 100 R/hr) radiation environments with no shielding required.

The crane operator positioned the sensor head near the objects and AIL personnel operated the GammaModeler™ system during the survey measurement for gamma radiation sources. A pseudo-color image of gamma ray emitting sources is displayed as a composite picture with the video picture of the scene. A four sigma detection threshold of the statistical image noise is used to suppress displaying noise fluctuations. The gamma ray intensities above this detection threshold are automatically scaled to indicate the highest radiation level as red and the lowest level as blue. The video picture has a wider FOV than the gamma FOV so the boundaries of the gamma images are indicated in the composite picture by a rectangular box as seen in figure 3. Parallax corrections are applied in positioning the gamma ray image with respect to the video image so the gamma sources appear at the proper visual location. The exposure time required to obtain a gamma image is dependent upon several factors including gamma ray energy,

the distance to the source, and the shape and distribution of the source. Additional images taken by the operator provide vector range to key references in the scene. These marker images are used to locate the position of the sensor head. The system software, *GammaSoft™*, produces a single file that contains all the images and the system measurement parameters. This file is copied to a disk for transfer to the 3-D workstation located outside the canyon area.

The demonstration test plan defined the data to be acquired, the data analysis and reporting. BHI personnel provided a list of objects they desired to have imaged.

For the data to be acquired, two-dimensional (2-D) image data files will be obtained of selected objects from three or more angles using the 3-D GammaModeler™ system suspended from the crane. These 2-D images will provide visual information on the object as well as gamma source information on/within the objects. Other demonstration data will consist of information needed to evaluate costs the GammaModeler™ system relative to those for the GammaCam™ system.

For the data analysis, the captured 2-D images and supporting data of selected object are imported into the 3-D workstation. The visual/gamma images and data are then processed and used to create the 3-D renderings of the selected objects with the location(s) of the radiation source(s) indicated. The radiation source(s) will be display in color indicating the source(s) strength(s). The 3-D renderings are provided in AutoCAD 14 compatible format with gamma sources located.



**Figure 3 Gamma Image #4
obtained for the High Rad
Tank on cell 35**

System Operation

For the demonstration in support of the characterization project objectives of the CDI, a list of objects on the canyon deck that needed to be surveyed was provided by BHI. During the demonstration period, open canyon cells were added to the list (indicated by *italic*). The objects contained in the list were the following:

- REDOX Pulsar on cell 4.
- High Rad Equipment and PUREX Centrifuge on cell 6
- Fuel carriers on cell 15
- REDOX Dissolver on cell 15
- Transport Box on cell 19
- Fuel carriers on cells 19 and 20
- T-Plant Ventilators on cell 21 (there are 5 stacked)
- Column (thimble across from cells 23 and 24
- Vessel on pipe trench side across from cell 26
- Empty dissolver on cell 32
- High Rad Tank on cell 35
- Shipping casks located on cells 31 through 35
- *Deep cell 10*
- *Pump equipment in cell 7*
- *Equipment in cell 25*
- *Equipment in cell 39*

The high rad tank on Cell 35 was the first object imaged during the demonstration and took the longest to acquire the complete image set because this object served as a training experience for the operator. The positioning of the sensor head and the acquisition of all the images required a total of 1 1/2 hours. The greatest amount of time was required to precisely position the laser range finder at the reference point. This object was measured from four viewing directions. In addition to the four gamma images, a total of 27 marker images were obtained. Later, other objects will detectable radiation required about 30 minutes to acquired the completed set of data for the 3-D rendering. Objects with no detectable radiation required about 10 minutes of data acquisition.

For each object, the crane hook and sensor head are positioned so the object is in the gamma FOV and an initial gamma image is taken. The typical exposure time for the image is a few minutes. The captured image is displayed on the PC computer screen to the system operator in the crane cab. If no gamma radiation is detected, the crane hook and sensor head can be positioned to characterize the next object on the list. If a gamma radiation is detected above threshold, the operator needs to obtain two or more images of the object from several additional angles in order to generate a 3-D rendering of the object.

For those objects with detected radiation and before the crane hook can be translated to a new location, the operator must obtain some "marker images" to allow the sensor head location to be determined. For each "marker image", the sensor head is panned and tilted in order to point the laser range finder at a reference point in the scene. The reference points are selected to be points seen from more than one viewing angle or are unique locations on the object being surveyed. The composite gamma-ray image and the "marker images" are stored in a single file for later analysis on the 3-D workstation. For each viewing direction, gamma images and additional "marker images" are obtained. The new "marker images" must contain some common reference features so the relative sensor head positions can be determined. The coordinate system for the 3-D rendering can be relative to the sensor head positions or some position in or on the object surveyed. If the absolute canyon position of a reference can be determined then the 3-D rendering can be adjusted to be in the canyon coordinate system if desired.

All image files were imported to the 3-D workstation. The 3-D workstation houses the *GammaSoft*TM software, the *3-D processing* software, the AUTOCAD software and the *GammaCad*TM software. The *GammaSoft*TM is same as that on the system PC. The *3-D processing* software is used to locate the sensor head positions, deconvolve extended 2-D radiation sources into a series of point sources, and calculate the 3-D positions of the radiation sources. The AUTOCAD software is used to generate 3-D representations of the visual objects. The *GammaCad*TM software is used to merge the radiation source data with the 3-D AUTOCAD drawing of the visual objects.

For those objects that had no detectable radiation, *GammaSoft*TM is used to complete the analysis and evaluated the upper limit for any potential gamma radiation. *GammaSoft*TM can generate images in any standard graphic format for export to another program if desired.

For those objects with detectable radiation, *GammaSoft*TM is used to export two text files, a marker file and a gamma ray image file, that are used by the *3-D processing* software. The marker text file contains an ordered list of the range and direction to each reference point for a given sensor head location. Using all the marker files, the relative positions of the sensor head locations can be determined. From the gamma radiation image data, location in the image corresponds to a direction from the gamma detector axis. For extended sources, line sources, etc., the 2-D image can be deconvolved into a series of point sources using our knowledge of the point-spread function for the detector. The locations in the image of the resulting point sources are the directions to the true locations for the sources. The deconvolution analysis also provides the intensity of the source at the sensor head. This intensity can be converted to a dose at the sensor head for the source. Similar to the reference points the sources seen in a 2-D view must be cross-referenced to the sources seen in another 2-D view. By knowing the sensor head positions, the pointing directions for the sensor head, the directions of the radiation sources for each view, and the cross-referencing of the sources, the 3-D location of the sources can be calculated along with their source strengths. The source strengths are calculated from each image in which the source is detected. If there is no differential attenuation between the views, then the calculated source strengths agree. If there is a difference, then the largest value for the source strength is reported. The results are stored to a file that can be used by *GammaCad*TM to merge these results with the visual representations in AUTOCAD.

The 3-D source file can be used with a "dose" program that allows the dose to be calculated at any point in the coordinate system of the object. If the absolute coordinates of the objects are established, then the multiple 3-D source files can be combined to calculate the overall radiation field resulting from the objects being characterized. This capability can be used in the future as the remaining objects are surveyed to create a map of the radiation environment relative to the contaminated equipment. This capability will be very usefully in supporting the CDI objectives.

In the detailed analysis after the demonstration, it was noted that additional corrections were required in the 3-D analysis to correctly locate the position the sources. First the sensor head was not mounted truly level on the crane hook, resulting in the sensor head not rotating around the vertical axis while being

panned. Secondly, the tilting of the 55 pound sensor head caused a compensating motion of the crane hook and this effect must be taken into account. With known dimensions such as cell sizes etc., the magnitude of the corrections were determined and incorporated into the *3-D processing* software.

In the future, additional changes could be made to the hardware design to eliminate these effects. First, leveling adjustments could be added to the mounting interface (the crane hook interface) to level the base of the pan and tilt assembly. Second, a different pan and tilt assembly could be designed that would pivot the sensor head through its center of gravity (this would not cause a compensating moment of the crane hook).

SECTION 3 PERFORMANCE

Demonstration Plan

The demonstration of the AIL 3-D GammaModeler™ visual and gamma-ray imaging system was completed at the DOE Hanford site, 221-U facility as a part of the Canyon Disposition Initiative Project. The system was used to provide images and radiation measurements of equipment, tanks, etc., on the canyon deck and in the processing cells.

The canyon portion of the building is approximately 800 feet long, 36 feet wide and is divided into twenty sections. Each section is approximately 40 feet long and contains two process cells. The cells contain process equipment, such as vessels, centrifuges, piping etc. The cells measure approximately 13 by 18 feet and are 28 feet deep from the top of the concrete cell covers to the bottom of the cell. Cell 10 is designed to accumulate water in the canyon and is 47 feet deep. A diagram of the facility cross section is shown in figure 4.

The 221-U facility was not used for any “true” processing activities. However, the cells and the canyon deck are being used for storage of contaminated equipment. Figure 5 shows some of the equipment stored on the canyon deck.

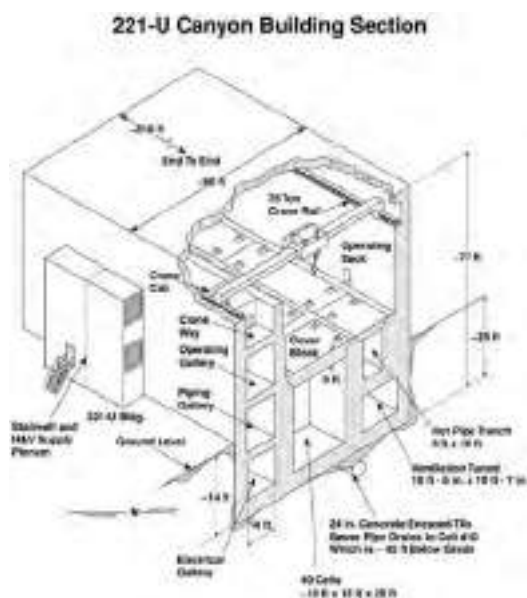


Figure 4 Cross Section of the 221-U facility.



Figure 5 221-U facility (canyon) deck.

The CDI personnel provided a list of objects they desired to have surveyed and imaged. The list included equipment of most interest located on the deck. During the demonstration, several open cells were also surveyed.

The primary objectives of this demonstration were to evaluate the capability of the imaging system for surveying objects for radiological contamination to yield high-quality, usable characterization information to meet CDI project requirements, to support the Performance Assessment, and to compare the 3-D system to the 2-D baseline system.

Results

A total of 20 objects were imaged during the demonstration period at the 221-U Facility. With the narrow FOV, multiple images had to be taken to completely survey large objects. Seven of these objects had observable gamma radiation and measurements were taken at several viewing angles to support the 3-D rendering of the objects. The objects in *italic* were added to the original list provided by BHI.

The objects with detected radiation are the following:

- A high rad tank on Cell 35
- A High Rad equipment and PUREX Centrifuge on Cell 6
- *The interior of Cell 10*
- *Equipment in Cell 25*
- Centrifuge parts on the canyon deck
- *Pump equipment in Cell 7*
- Fuel Carrier on the canyon deck

Examples of objects with no detected radiation are the following:

- Shipping casks (multiple views)
- Another fuel carrier on the canyon deck
- The thimble (multiple views)
- Heat exchanger (multiple views)
- Dissolver tank
- Ventilator (multiple views)
- Cell 39 (multiple views)

The High Rad tank on cell 35 was the first to be imaged and analyzed. Four gamma images were obtained. One image was shown previously as figure 3. Figures 6,7 and 8 are the other viewing angles. In the views from the front (fig 6) and the back (figs. 3, and 8), the source is observed to be an elongated source rather than a point source. The view from the side does not show the source strongly. This is probably due to some internal structure that attenuates the gamma radiation. The source seen in fig. 7 is treated as an ambiguous source that cannot be triangulated with other views. For sensor head position 1, the source appears to be near the bottom of the object. However, for sensor positions 3 and 4, the source is not near the bottom but appears to be in other locations. 3-D analysis shows that the source position seen by sensor position 1 is very close to the position seen in the gamma image.



Figure 6 Sensor Position 1



Figure 7 Sensor Position 2



Figure 8 Sensor Position 3

The “marker” reference points were cell seams on the canyon deck, the bail hooks on the cell 35 cover blocks, and points on the object itself. These reference points were seen in two or more sensor head locations and allowed the relative positions of the sensor head to be calculated. The relative positions of the sensor head could be further adjusted to allow the bottom center of the tank to be defined as $x=0$, $y=0$, and $z=0$. Since this tank is located on the cell 35 cover of the canyon, the absolute canyon location for this location is approximately $x = 18$, $y = 700$, and $z = 0$. For this demonstration, the 3-D localization and rendering is done in the coordinate system of the object.

In the coordinate system of the object, the y direction is along the canyon length, and the x direction is across the canyon. In figure 6 (sensor head position 1), the sensor is located in the positive y direction and in the negative x direction relative to the tank. Sensor positions 3 and 4 are behind the tank in the negative y direction. Sensor position 4 was taken from a higher elevation than sensor position 3 with the sensor head tilted down more to keep the tank in the FOV.

For each 2-D image, the extended source was deconvolved into five point sources. The direction from the

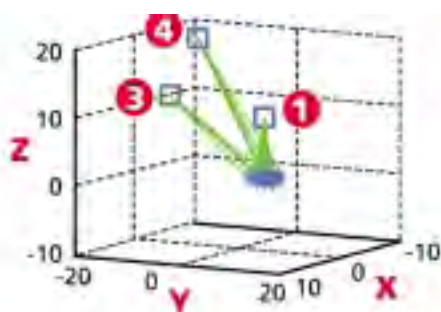


Figure 9 Calculated sensor Positions, Source Positions

sensor head to the source locations was determined and the intensity at the sensor head. Knowing the sensor head locations and the directions to the sources, the source positions are determined by the positions of closest approach for the source ray traces. Figure 9 shows a 3-D plot locating the sensor head locations (small labeled boxes), the direction ray traces from the sensor locations, the locations of closest approach, and the source position for each pair of ray traces. In this figure, the sensor head locations have been adjusted so that the coordinate $(0,0,0)$ corresponds to the bottom center of the tank. The same program that generates this plot generates the file, which contains the source locations and the 30-cm dose values.

A 3-D representation of the object was generated using AUTOCAD. From the marker image data, it was determined that the tank diameter was 10 feet. The tank's center was positioned at $x=0$ and $y=0$. There the visual representation coordinate system is the same as that for the gamma radiation analysis. The tank was made transparent so that the sources located interior to the tank can be seen in the merged drawing.

GammaCad™ is used to merge the gamma radiation data with the visual representation. *GammaCad™* opens the AUTOCAD drawing of the visual object and the file containing the gamma radiation source information. The data for the sources are the following:

Source	X	Y	Z	30 cm dose
1	-0.6	4.6	0.8	678 mR/hr
2	-1.2	4.6	0.6	350 mR/hr
3	-1.8	4.6	0.7	253 mR/hr
4	0.1	4.6	0.9	440 mR/hr
5	0.5	4.2	0.6	343 mR/hr
Ambiguous Source				
1	3.6	1.8	4.5	25 mR/hr

The *GammaCad™* creates color spheres for each of the point sources. The color of the spheres is related to the strength of the source. Red corresponds to those sources in the highest 1/3 intensity. Green corresponds to the middle third. Blue corresponds to the lowest third.

Figures 10 and 11 show the merged 3-D visual and gamma radiation results as an AUTOCAD representation.

AUTOCAD allows the object to be viewed from any direction. The two figures represent different rotations of the same object. Five colored spheres represent the extended source; their color relates to the 30-cm dose

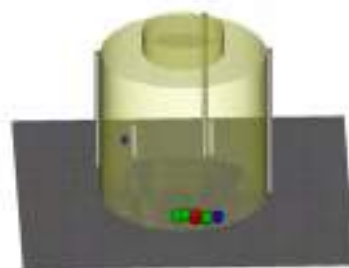


Figure 10 3-D Rendering of High Rad Tank

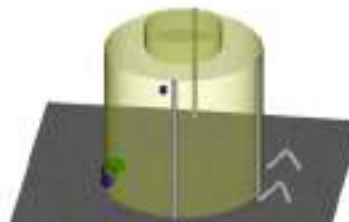


Figure 11 Rotated 3-D Rendering of High Rad Tank

strength. The center sphere is red and corresponds to 678 mR/hr (the most intense source). In figure 10, the sphere on the right is blue representing 253mR/hr (within the lowest third strength). The other spheres are green and have values between 243 and 461 mR/hr.

The cube in the figures 10 and 11 is the ambiguous source seen in the 2-D image from sensor position 2. The source location is positioned near the surface of the tank at the location observed from the sensor head. Extrapolating the direction rays for this source would place the ambiguous source near the edge of the five located sources. The cube is blue because it is estimated to have a strength of less than 25 mR/hr at position indicated.

This object was rendered during the demonstration and was shown at the presentation on the last day of the demonstration. The initial 3-D analysis and rendering required a little over 3 hours of analysis time. During the detailed post demonstration analyses, additional corrections were identified and improvements to the analysis software were made. However, the results presented in this report are essentially the same results presented in near real time.

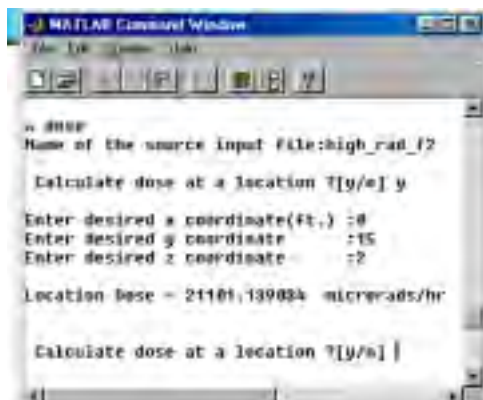


Figure 12 Typical dose calculation

The radiation source file can be accessed by a program called *dose* that calculates the dose at any position in the coordinate system. Figure 12 shows a screen capture of a dose calculation for the same high rad tank. The program requests the file name and then the coordinates for the point where the dose is desired. The coordinates correspond to a location near the edge of the radiation exclusion zone. The calculated dose is 21 mR/hr. The calculation can be repeated for another location.

The 3-D capability of the GammaModeler™ system allows the sources locations to be easily seen, and the relative and absolute intensities to be known. For sources that are internal to objects, the locations are easily identified and characterized.

Additional 3-D rendering results are presented in Appendix C.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

The baseline technology with which the GammaModeler™ system competes is the GammaCam™ system. The GammaModeler™ system represents an advancement of the GammaCam™ with additional features such as the laser range finder, pan and tilt assembly, and upgraded software that provides a capability for 3-D rendering of gamma radiation sources and visual objects.

Similar, but not identical competing technologies include:

- In Situ Gamma Spectroscopy with ISOCS (an In Situ Object Counting System) developed by Canberra Industries, Inc.
The ISOCS is a Germanium based gamma-ray spectroscopy system that identifies radioactive isotopes and provides real time quantitatively assays the radioactive contents of containers, surfaces, and samples. The entire system is mounted on a portable cart, which allows rotation of the detector about a horizontal axis. The ISOCS does not produce an image but different collimators can be placed in front of the detector for defining a 30, 90, or 180 degree field of view.
- RadScan 600 developed by BNFL Instruments, Ltd.
BNFL's RadScan imaging system is a shielded collimated detector. The collimators can have a 2, 4, or 9 degree field of view. An image is produced by raster scanning the sensor head and recreating the gamma image by overlapping the results of each measurement. Because of the shielding requirement associated with this detector, the inspection head weighs approximately 105 kg (230 lbs). This system does provide some spectroscopic information for isotope identification.
- Cartogram developed by Eurisys Mesures.
The CARTOGAM gamma camera has been developed with the aim of providing a very compact and portable device. The detection head is contained in a stainless steel cylinder. Its external diameter is 8 cm for a length of 40 cm. The shield is tungsten ranging from 16 mm to several centimeters. The collimator has a double-cone opening, of either 30 or 50 degrees. The gamma image is formed directly on the scintillator. The minimum detectable dose with this system is higher than that for the GammaCam™. This system does provide some spectroscopic information for isotope identification.

Technology Applicability

The applicability and benefits of AIL's 3-D GammaModeler™ Gamma Ray Imaging technology at the 221-U facility includes:

- Characterization with minimum exposure to personnel
- Rapid characterization via imaging of large areas from a safe standoff distance
- Characterization in a high radiation environment
- Characterization of radiation environment internal to the equipment
- Characterization that provides a visual electronic records
- 3-D localization of sources provides better estimates of radiation intensities, which leads to cost effective D&D planning and operation.
- Pan and Tilt capability allows measurements from new directions previously not available.

Patents/Commercialization/Sponsor

- Patents have been granted to AIL Systems Inc for this coded aperture technology.
- The system is commercially available for gamma surveys at radiological contaminated sites. The technology can be applied to those sites where characterization, remediation, and D&D activities are planned.

SECTION 5 COST

Methodology

This cost analysis compares the innovative technology, the GammaModeler™, against the baseline GammaCam™ technology. The selected basic activities being analyzed originate from the Hazardous, Toxic, and Radioactive Waste Remedial Action Work Breakdown Structure (HTRW RA WBS) and Data Dictionary, USACE, 1996.

Some costs are omitted from the analysis to facilitate understanding and comparison with costs for the individual site. The Hanford indirect expense rates for common support and materials are omitted from this analysis. Overhead and general and administrative (G&A) rates for each DOE site vary in magnitude and the way they are applied. The impact resulting from the omission is judged to be minor because overhead is applied to both the innovative and baseline technology costs. Engineering, quality assurance, administrative costs, and taxes on services and material are also omitted from the analysis for the same reasons indicated for the overhead rates.

An average labor rate (\$60.00) is used in this analysis for the portion of the work performed by local crafts. Additionally, the analysis uses a 10-hour workday with a 4-day week. Operations in the canyon area is usually limited to 4 hours. During the demonstration period, two 3-hour operations were achieved in a single day. The production rates and the observed duration used in the cost analysis do not include “nonproductive” items such work breaks, loss of dexterity [due to cumbersome personnel protective equipment (PPE)], and heat stress. A Productivity Loss Factor (PLF) is a historically based estimate of the fraction of the workday that the worker spends in nonproductive activities and is not included in the analysis. The PLF is the same for the GammaModeler™ and the GammaCam™ since they are similar technologies.

Cost Analysis

The prices shown in Table 1 are based on recent quotes from AIL System Inc. The equipment costs used in the analysis are based on the one-month lease costs for each instrument. Equipment purchase and leases includes AIL Systems provided instruction.

Table 1. Technology acquisition costs

ACQUISITION OPTION	GammaModeler™	GammaCam™
Purchase	\$260,000	\$230,00
One month lease	\$25,000	\$20,000

The DOE complex presents a wide range of D&D work conditions because of the variety of functions and facilities. The working conditions for an individual job directly affect the manner in which the D&D work is performed and, as a result, the costs for an individual job are unique. The innovative and baseline technology estimates presented in this analysis are based upon a specific set of conditions or work practices found at the 221-U facility.

Cost Conclusions

The cost elements for the GammaModeler™ and GammaCam™ are shown in figure 13. The percentage of objects with radiation compared to those with no detectable radiation will substantially affect the costs because of the additional effort to acquire data from multiple views and the effort to complete a 3-D rendering. Based on the demonstration, the assumed ratio of objects with radiation to those with no detectable radiation is 1:3. The analysis performed shows that use of a GammaModeler™ system will result in less than a ten percent increase in cost. Another factor that can influence the costs is the time to take the image. The sources are assumed to have greater than tens of mR/hr source strength. It is possible to image much weaker sources with accumulation times being an hour or greater.

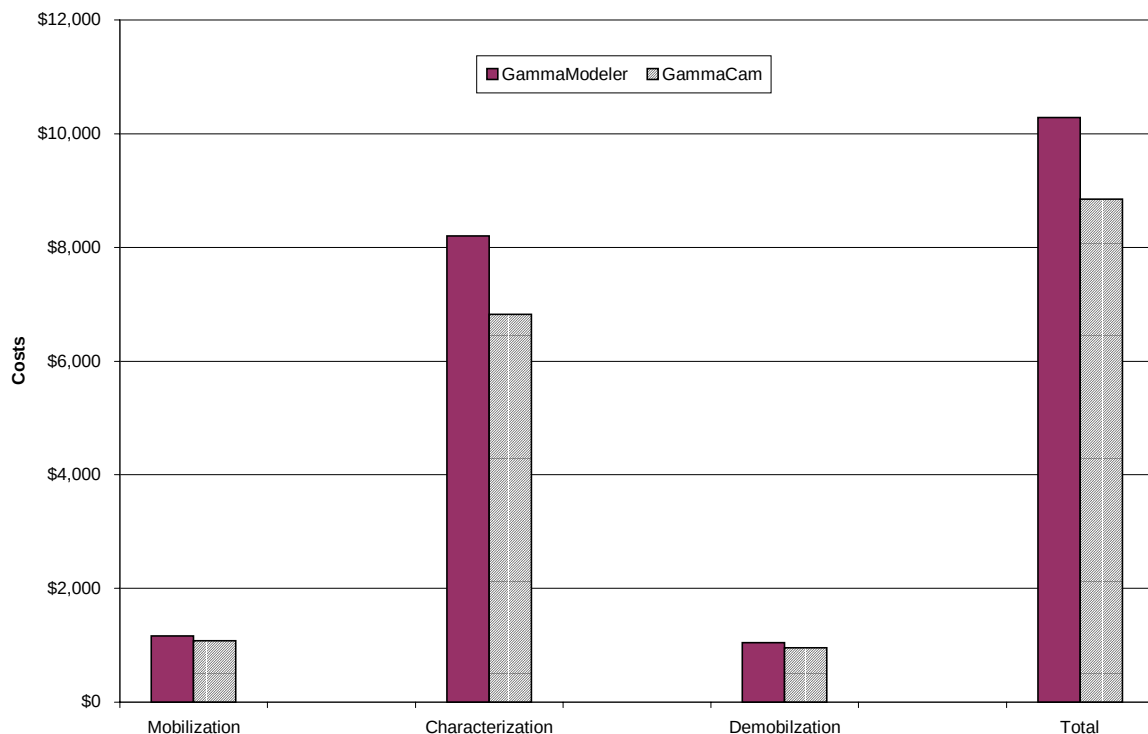


Figure 13 Technology Cost Comparison

It is important to note that the GammaModeler™ technology acquires and produces additional data that cannot be acquired by the baseline technology. The GammaModeler™ system collects sensor head angle information and range data that are required for 3-D processing. 3-D processing is not possible from multiple 2-D images acquired with the GammaCam™. These data allows better understanding of the source locations (even internal to the visual objects). With source locations known, estimates of the dose in the vicinity of an object can be determined. The pan and tilt capability allows the gamma camera to examine the objects from directions different than the single view provided by the baseline technology. This additional information can be very important in any characterization effort - in this case, in support of the CDI.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

- The GammaModeler™ system is designed as a survey tool for inspecting and measuring contaminated objects. There are no special regulatory permits required for use of this technology.
- Although the demonstration took place at a Comprehensive Environmental Response, Compensation, and Liability Act (CERLA) site, no CERLA requirements apply to the surveys conducted. However, some evaluation criteria required by CERLA, such as protection of human health and community acceptance, are briefly discussed below.

Safety, Risks, Benefits, and Community Reaction

The purpose of the GammaModeler™ technology is to provide data needed for cleanup, D&D characterization, radiation source localization and determination, and planning. The safety issues with the GammaModeler™ system are limited to those routinely encountered in an industrial environment.

This technology can be utilized in high radiation areas with the operator located in a low radiation area reducing radiation exposure.

A benefit of GammaModeler™ is that the superimposed radiation and visual images and representations can provide the public and regulators with an improved understanding and confidence in the measured data.

Implementation of this technology has no adverse impacts on community safety.

SECTION 7 LESSONS LEARNED

Implementation Considerations

The demonstration at the 221-U Facility has resulted in the following recommendations for future measurement operations.

- The GammaModeler™ system, as demonstrated, only had a narrow FOV (25°) capability because of the placement of the laser range finder. Restoring the wide FOV (50°) would allow greater portions of the objects to be imaged with a single image. This could lead to a reduction in images and time to complete an object inspection.
- Improve the cable management. After the attachment of the sensor head to the crane hook while at the canyon deck level, the extra lengths of the two system cables that went from the crane cab to the sensor head and pan and tilt assembly were looped and tied to the crane hook. This action prevented the sensor head from being lowered below the deck level and into the cells. Likewise, for some positions of the sensor head, the pull of taut cables can cause an unknown amount of rotation of the sensor head.
- The base of the pan and tilt assembly was not mounted level on the crane hook. This caused some initial difficulty in the post-demonstration 3-D analysis to identify the problem and its magnitude. Changes were made to the analysis software to incorporate correction terms for this effect. Future measurements should image an object with known dimensions in order to rapidly assess any tilting and allow correction to be made for this effect.
- Reverse mounting of the sensor head for inverted operation. The demonstration utilizes the sensor head in an inverted position. This position causes the video and gamma images to be inverted also. For ease in recognizing the objects in the images it would be beneficial to reverse the mounting of the sensor head in order to have the images right side up.
- Finer control for the pan and tilt would allow the operator to quickly position the laser range finder for the marker images.
- Availability of existing drawings of the objects to be 3-D rendered would allow quicker generation of the AUTOCAD visual representations of the objects and would reduced the time and effort to crate these rendering.

Technology Limitations and Needs for Future Development

- There are limitations associated with the use of a coded aperture system that can influence a radiation survey. The first is that a uniform radiation field cannot be detected. This can be overcome by making sure that the FOV includes a non-uniform region. The coded aperture also has some limitations in terms of the maximum-to-minimum signal that can be detected in the FOV. The image threshold is related to the total radiation in the FOV. If there are many sources in the FOV, the threshold increases leading to limitation on the ratio of the maximum-to-minimum signal detected.
- The deployment platform for the GammaModeler™ system must be robust and level. It can be moved but should not rotate or tilt during the measurement. Additional uncertainties caused by platform rotation or tilting could prevent 3-D rendering of the radioactive sources.
- The dose estimates are based on calibrations of the instrument using isotopic sources. For a given dose estimate, knowledge of the isotope is assumed. However spectral modification often occurs due to intervening material and the calibration values do not account for these changes in the source spectrum. Future developments to provide a measure of this spectral modification can lead to better dose estimates.

Technology Selection Considerations

- Any nuclear site can use this technology. In particular, the 3-D capability of the GammaModeler™ allows the radiation environment interior to an object to be determined. This information is obtained remotely without the need of exposing workers to the radiation source. The remote pan and tilt capability of the system allows the operator ease in locating radiation sources
- The visual and gamma radiation results are saved in digital format and can be easily archived for a permanent record of the measurement survey.

APPENDIX A REFERENCES

GammaCam™ Radiation Imaging System, 1998, Innovative Technology Summary Report, U.S. Department of Energy, Office of Environmental Management, DOE/EM-0345.

Hazardous, Toxic, and Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary. 1996, Head quarters United States Army Corps of Engineers, 20 Massachusetts Avenue, NW, Washington, D.C., 20314-1000.

Management/Test/Work Plan for Demonstration of 3-D Gamma-Ray Imaging Technology at the U-Facility Canyon Using AIL System's 3-D GammaModeler™, prepared for FETC contract DE-AC26-99FT40555.

Migliaccio, R. and Petito D. (AIL Systems Inc.) and Nutter, V. and Smith, D. (Consolidated Edison of New York), 1996 "Gamma Ray Imaging in Nuclear Power Plants," *Nuclear Plant Journal* March-April.

APPENDIX B

TECHNOLOGY COST COMPARISONS

This appendix contains definitions of cost elements, descriptions of assumptions, and computation of unit costs that are used in the cost analysis. An assumption in the technology cost comparison is that the GammaModeler™ and the GammaCam™ systems are available on-site. System unit costs are based on the one-month lease rates for each system.

Innovative Technology – 3-D GAMMAMODELER™

Mobilization (WBS 331.01)

Transport Equipment to Work Area

Definition: The GammaModeler™ is transported from the on-site storage location to the work area.

Duration is ¾ hour for D&D worker.

Functional Tests of Equipment

Definition: The GammaModeler™ equipment is turned on to assure that video and gamma images can be obtained.

Duration is ½ hour. This includes cooldown time for the sensor head.

Prepare Equipment for Use

Definition: The equipment is prepared for use in canyon area (includes wrapping cables and sensor head with plastic to minimize potential contamination).

Crew consists of one radiological control technician (RCT) for one hour (based on experience during the demonstration).

Install Equipment in Canyon on Crane

Definition: The equipment is moved into the canyon area for installation on the crane hook. The system computer and pan and tilt controller are installed in the crane cab. System cables are connected. The system is turned on and tested for functionality before personnel in canyon are released.

System cables are already installed in canyon. Two RCTs and one D&D worker are required for canyon entry for installation of equipment on crane hook. System operator and crane operator are in the crane cab. The RCTs and D&D workers require PPE for canyon entry. The system operator and the crane operator do not require personnel protective gear. This activity requires 1 hour.

Personnel Protection Equipment

Canyon entry requires the personnel to use personnel protection equipment. The donning and doffing of the equipment takes 1 hour per person. The equipment is single use only.

Characterization (WBS 331.17)

Set Up and Move Equipment

Definition: The time required for moving from one survey area to the next.

The duration is 1/6 hour and the crew is the crane operator.

Surveys

Definition: The time required to acquire a gamma image. If radiation is detected, additional marker images and other views with marker images are taken. Based on the 221-U Facility demonstration, one of three objects have radiation and required the additional data.

The time to acquire a survey for an object without any detectable radiation is $\frac{1}{4}$ hour. The acquisition of the complete data set for 3-D rendering is 0.75 hours.

Transfer 2-D Data to Workstation

Definition: The data files are transferred out of the canyon area for processing. The data disks are surveyed for contamination prior to release.

This task requires one RCT for one hour.

Process 2-D Data

Definition: This activity includes processing the 2-D data from the measurement using the GammaSoft software, generate report for images with upper limits and generating files required for 3-D processing.

This task requires one RCT for 0.5 hours per image.

3-D Rendering

Definition: This activity includes determining the locations of the sensor head for each view, locating sources and cross referencing them between views, calculating the locations and intensities of each source, generating 3-D representation of visual objects in AUTOCAD format, merge gamma radiation data with visual representation, and generate report.

Daily Meetings

Definition: This cost element provides for safety/ project-planning meetings during the work.

The estimate assumes one 15 min safety meeting per day. One RCT, one D&D and one crane operator are in attendance.

Demobilization (WBS 331.21)

Remove Equipment from Canyon

Definition: The equipment is de-mounted from crane hook, removed from canyon area, and the plastic wrap removed from sensor head.

Requires 3 workers-one hour.

Survey and Decontaminate Equipment

Definition: Equipment is surveyed for contamination. Decontamination is performed as needed for free release.

This task requires one RCT for two hours.

Transport Equipment to Storage

Definition: The equipment is transported to an on-site storage area.

The effort is assumed to be $\frac{3}{4}$ hour for one D&D worker.

Personnel Protection Equipment

Canyon entry requires the personnel to use personnel protection equipment. The donning and doffing of the equipment takes 1 hour per person. The equipment is single use only.

The activities, quantities, and costs utilized in the innovative technology are shown in Table B-1: Innovative Technology Cost Summary.

Table B-1. Innovative Technology Cost Summary – 3-D GAMMAMODELER™

Task	Unit Cost (UC)					Total Quantity (TQ)	Unit Of Measure	Total Cost (TC)	Comments	
	Labor		Equipment		Other					Total UC
	Hour	Cost	Hour	Cost						
Mobilization							Subtotal	\$1272		
Transport Equipment to Work Area	0.75	\$60.00	0.75	\$156.00	\$0	\$162	1	Each	\$162	1 D&D worker
Functional Test of Equip.	0.50	\$60.00	0.50	\$156.00	\$0	\$108	1	Each	\$108	1 RCT & Equipment
Prepare Equipment for Use	1.00	\$60.00	1.00	\$156.00	\$0	\$216	1	Each	\$216	1 D&D worker
Install Equipment in Canyon	5.0	\$60.00	1.00	\$156.00	\$0	\$456	1	Each	\$456	2 D&D + 1 RCT + crane operator +1Elec.(1 hour)
Personal Protection Equipment	1.0	\$60.00			\$50	\$110	3	Person	\$330	3 workers(1.0 hour)
Characterization							Subtotal	\$7927		
Set Up and Move Equipment	0.32	\$60.00	0.16	\$156.00	\$0	\$44	35	Object	\$1540	1 D&D worker 1 crane operator (0.16 hour)
Surveys(no radiation detected)	0.50	\$60.00	0.25	\$156.00	\$0	\$69	14	Object	\$ 966	Total of 21 objects being surveyed
(radiation detected)	1.50	\$60.00	0.75	\$156.00		\$207	7	Object	\$1449	
Transfer Data to Workstation	1.00	\$60.00	1.00	\$156.00	\$0	\$216	4	Each	\$864	4days of imaging
Process 2-D Data/Report	0.5	\$60.00	0.5	\$156.00	\$0	\$108	14	Object	\$1512	14 objects without detectable radiation
3-D Rendering/Report	3.0	\$60.00			\$0	\$180	7	Object	\$1260	3-D rendering performed @ AIL Systems

Daily Meetings	0.75	\$60.00	0.25	\$156.00	\$0	\$84	4	Day	\$336	1 D&D + 1 RCT + crane operator (0.25 hour)
Demobilization								Subtotal	\$1044	
Remove Equipment from Canyon	3.0	\$60.00	1.0	\$156.00	\$0	\$336	1	Each	\$ 336	1 D&D + 2 RCT (1 hour)
Survey and Decontaminate Equipment	1.0	\$60.00	1.0	\$156.00	\$0	\$216	1	Each	\$ 216	1 RCT
Transport to Storage	0.75	\$60.00	0.75	\$156.00	\$0	\$162	1	Each	\$162	1 D&D worker
Personal Protection Equipment	1.0	\$60.00			\$50	\$110	3	Person	\$330	3 workers

BASELINE TECHNOLOGY -- 2-D GAMMACAM™

Mobilization (WBS 331.01)

Transport Equipment to Work Area

Definition: The GammaCam™ is transported from the on-site storage location to the work area.

The duration is ¾ hour for D&D worker.

Functional Tests of Equipment

Definition: The GammaCam™ equipment is turned on to assure that video and gamma images can be obtained.

The duration is ½ hour. This includes cooldown time for the sensor head.

Prepare Equipment for Use

Definition: The equipment is prepared for use in canyon area (includes wrapping cables and sensor head with plastic to minimize potential contamination).

Crew consists of one radiological control technician (RCT) for one hour (based on experience during the demonstration).

Install Equipment in Canyon on Crane

Definition: The equipment is moved into the canyon area for installation on the crane hook. The system computer and pan and tilt controller are installed in the crane cab. System cables are connected. The system is turned on and tested for functionality before personnel in canyon are released.

System cables are already installed in canyon. Two RCTs and one D&D are required for canyon entry for installation of equipment on crane hook. System operator and crane operator are in the crane cab. The RCTs and D&D workers require PPE for canyon entry. The system operator and the crane operator do not require PPE. This activity requires 1 hour.

Personnel Protection Equipment

Canyon entry requires the personnel to use personnel protection equipment. The donning and doffing of the equipment takes 1 hour per person. The equipment is single use only.

Characterization (WBS 331.17)

Set Up and Move Equipment

Definition: The time required for moving from one survey area to the next.

The duration is 1/6 hour and the crew is the crane operator and D&D worker.

Surveys

Definition: The time required to acquire a gamma image. If radiation is detected, additional marker images and other views with marker images are taken. Based on the 221-U Facility demonstration, one of three objects have radiation and required the additional data.

The time to acquire a survey for an object without any detectable radiation is ¼ hour. The acquisition of multiple 2-D images 0.75 hours. Crane operator and D&D worker required.

Transfer 2-D Data to Workstation

Definition: The data files are transferred out of the canyon area for processing. The data disks are surveyed for contamination prior to release.

This task requires one RCT for one hour.

Process 2-D Data

Definition: This activity includes processing the 2-D data. For images with no detected radiation upper limits are established. For multiple images with detected radiation dose values are estimated and locations are inferred.

This requires one RCT for 0.5 hour (no radiation) ,1.5 hour per object (radiation detected).

Daily Meetings

Definition: This cost element provides for safety/ project-planning meetings during the work.

The estimate assumes one 15 min. safety meeting per day. One RCT, one D&D and crane operator in attendance.

Demobilization (WBS 331.21)

Remove Equipment from Canyon

Definition: The equipment is de-mounted from crane hook, removed from canyon area, and the plastic wrap removed from sensor head.

Requires 3 workers one hour.

Survey and Decontaminate Equipment

Definition: Equipment is surveyed for contamination. Decontamination is performed as needed for free release.

This task requires one RCT for one hour.

Transport Equipment to Storage

Definition: The GammaCam™ equipment is transported to an on-site storage area.

The effort is assumed to be ¾ hour for one D&D worker.

Personnel Protection Equipment

Canyon entry requires the personnel to use personnel protection equipment. The donning and doffing of the equipment takes 1 hour per person. The equipment is single use only.

The activities, quantities, and costs utilized in the baseline technology are shown in Table B-2: Baseline Technology Cost Summary.

Table B-2. Baseline Technology Cost Summary – 2-D GAMMACAM™

Task	Unit Cost (UC)					Total Quantity (TQ)	Unit Of Measure	Total Cost (TC)	Comments	
	Labor		Equipment		Other					Total UC
	Hour	Cost	Hour	Cost						
Mobilization							Subtotal	\$1172		
Transport Equipment to Work Area	0.75	\$60.00	0.75	\$125.00	\$0	\$139	1	Each	\$139	1 D&D worker
Functional Test of Equip.	0.50	\$60.00	0.50	\$125.00	\$0	\$93	1	Each	\$93	1 RCT & equipment
Prepare Equipment for Use	1.00	\$60.00	1.0	\$125.00	\$0	\$185	1	Each	\$185	1 D&D worker
Install Equipment in Canyon	5.0	\$60.00	1.0	\$125.00	\$0	\$425	1	Each	\$425	2 D&D + 1 RCT + crane operator + elec. (1 hour)
Personal Protection Equipment	1.0	\$60.00			\$50	\$110	3	Person	\$330	3 workers
Characterization							Subtotal	\$7253		
Set Up and Move Equipment	0.32	\$60.00	0.16	\$125.00	\$0	\$39	21	Each	\$819	1 D&D + crane operator (0.16 hour)
Surveys no radiation	0.50	\$60.00	0.25	\$125.00	\$0	\$61	14	Object	\$854	1 D&D
radiation	1.50	\$60.00	0.75	\$125.0		\$184	7		\$1288	+ crane operator
Transfer Data to Workstation	1.00	\$60.00	1.00	\$125.00	\$0	\$185	4	Each	\$740	1 RCT
Process 2-D Data/Report	0.5	\$60.00	0.5	\$125.00	\$0	\$93	14	Object	\$1302	1 RCT worker
Radiation detected	1.5	\$60.00	1.5	\$125.00		\$278	7		\$1946	

Daily Meetings	0.75	\$60.00	0.25	\$125.00	\$0	\$76	4	Day	\$304	1 RCT + 1D&D + crane operator (0.25 hour)
Demobilization								Subtotal	\$959	
Remove Equipment from Canyon	3.0	\$60.00	1.0	\$125.00	\$0	\$305	1	Each	\$305	1 D&D +2 RCT
Survey and Decontaminate Equipment	1.0	\$60.00	1.0	\$125.00	\$0	\$185	1	Each	\$185	1 D&D worker
Transport to Storage	0.75	\$60.00	0.75	\$125.00	\$0	\$139	1	Each	\$139	1 D&D worker
Personal Protection Equipment	1.0	\$60.00			\$50	\$110	3	Person	\$ 330	3 workers

APPENDIX C

ADDITIONAL 3-D RENDERING RESULTS

Additional objects were 3-D rendered during this demonstration. The cell results presented in this appendix represent cases where it is not possible to obtain optimum viewing angles because all images were taken looking sharply down into the cell.

Cell 10

Multiple images of sources in the deep cell, cell 10, were obtained. 3-D rendering was accomplished during the demonstration. This cell had only one cover removed but the GammaModeler™ pan and tilt capability allowed images to be obtained for regions under the remaining cover. The baseline technology system, the GammaCam™, mounted pointing straight down on the crane hook could not obtain measurements for sources under the cell cover. Figure 14, shows a gamma image of cell 10 looking under the cell cover at a region of strong sources. Figure 15 imaged an area of the cell that was not under the cover but adjacent to the source seen in Figure 14. These images and others provide information on the entire cell so the source distribution and intensity can be displayed in a 3-D rendering. This deep cell is designed to accumulate water and had water a level covering the actual sources. Triangulation of regions where the images overlap showed the radiation to be coming from near the surface of the water. In the analysis for this case, not all the source positions are triangulated but are mapped to the constant level in the cell. The source distribution is represented by 15 point sources ranging from 1.2 R/hr to 9.2 R/hr. While the sources are in the range of several R/hr, the dose at the canyon deck level is at the mR/hr level when calculated using the *dose* program.

For all cell renderings, the up-canyon corner of the cell at the deck level is the origin of the coordinate system. For cell 10, the absolute canyon coordinates for this corner are $x = 19$, $y = 53$, and $z = 0$. The rendering for cell 10 is shown in Figure 16 (presented on next page). The remaining shield cover is rendered opaque whereas the cell is made transparent in order to observe the source locations. If the rendering is rotated to correspond to viewing with the downward looking baseline GammaCam™, all the sources located under the shield would not be observed. The sources under the shield account for greater than 70 percent of the radioactive inventory for this cell.



Figure 14 Image of Sources under Shield Cover



Figure 15 Images of Sources in Open Part of Cell

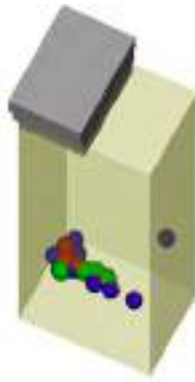


Figure 16 3-D rendering of Cell 10

Cell 25

Another cell that was surveyed during the demonstration was cell 25. Cell 25 has processing equipment stored deep in the cell and pumps stored on racks at the top of the cell. Four images of this cell were taken. Again looking down into the cell restricts the viewing angles for the 3-D rendering. Even with restrictive viewing the source locations could be calculated and a visual representation of the cell contents could be created. The coordinate origin for this representation was the up-canyon corner at the deck level. Figures 17 and 18 show two of the 2-D images taken for cell 25.

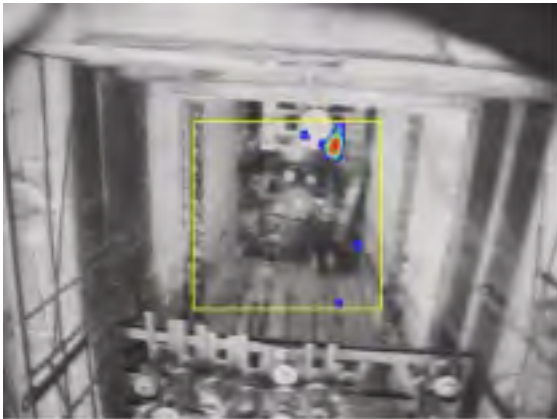


Figure 17 Cell 25 Image



Figure 18 Cell 25 Image (Another View)



Figure 19 3-D Rendering of Cell 25

Figure 19 uses source data from four images to create the radiation source location for the rendering. The sources are primarily located in the tank portion of only one object located in the cell. Another isolated source is located on the floor under the pumps near the back edge of the cell. The pumps were not gamma imaged so it is not known if they contain any radioactive contamination. The 3-D rendering view is from the side of the cell, allowing the location of the sources to be easily seen. For this rendering the cell, both the cell walls and the objects are transparent so the source location can be seen.

APPENDIX D

ACRONYMS AND ABBREVIATIONS

2-D	Two Dimension
3-D	Three Dimension
AIL	AIL Systems Inc.
ALARA	As Low As Reasonably Achievable
AUTOCAD	Computer Aided Drafting Software Package
BHI	Bechtel Hanford, Inc.
CCD	Charge Coupled Device
CDI	Canyon Disposition Initiative
CELCLA	Comprehensive Environmental Response, Compensation, and Liability Act
D&D	Decontamination and Decommissioning
DOE	U. S. Department of Energy
<i>dose</i>	Software to Calculate Dose Using Gamma Source File
FETC	Federal Energy Technology Center
FOV	Field of View
GAMMACAD	Software to Merge Gamma Source File Data with AUTOCAD drawing
GAMMASOFT	Operating software of GammaModeler™ system
G&A	General and Administrative
keV	Thousand electron Volts (Unit of Energy)
MeV	Million electron Volts (Unit of Energy)
mR/HR	milliRad/ Hour (Unit of Dose Rate)
NETL	National Energy Technology Laboratory
PA	Performance Assessment
PC	Personal Computer
PLF	Productivity Loss Factor
PPE	Personnel Protective Equipment
R	Rad (Unit of Dose)
R/HR	Rad/Hour (Unit of Dose Rate)
RCT	Radiological Control Technician
RL	U. S. Department of Energy, Richland Operation Office
ROD	Record of Decision
USACE	U. S. Army Corps of Engineers
WBS	Work Breakdown Structure

INNOVATIVE TECHNOLOGY

Summary Report

DOE/EM-0390

Gamma-Ray Imaging System

**Deactivation and Decommissioning
Focus Area**



Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

November 1998



Gamma-Ray Imaging System

OST Reference #1793

**Deactivation and Decommissioning
Focus Area**



Demonstrated at
Hanford Site
Richland, Washington



Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at <http://OST.em.doe.gov> under "Publications."

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SECTION 1

EXECUTIVE SUMMARY

The RadScan 600 gamma-ray imaging system is designed to survey large surface areas for radiological contamination with accuracy and efficiency. The resulting survey data are clear, concise, and precise in describing how much contamination is present at exact locations. Data can be permanently stored electronically and on video tape, making storage and retrieval economical and efficient. This technology can perform accurate measurements in high radiation contamination areas while minimizing worker exposure. The RadScan 600 system is a safe and effective alternative to hand-held radiation detection devices. Performance data of the demonstrated survey area of the RadScan 600 system versus the baseline, which is the hand-held radiation detection devices (RO-2 & RO-7) for a given survey, production rate is 72% of the baseline. It should be noted that the innovative technology provides 100% coverage at a unit cost of \$8.64/m² versus a static measurement of a unit cost of \$1.61/m² for the baseline.

Technology Summary

The RadScan 600 gamma-ray imaging system, developed by British Nuclear Fuels Ltd. (BNFL) and Pajarito Scientific Co. (PSC)/BNFL Instruments. The RadScan system characterizes contaminated sites containing high levels of surface radiation (contact dose rate of 5×10^{-5} Gy/hr (5 mR/hr) at 30 cm (12 in.) distance). This system provides real-time data on the location and concentration levels of gamma radioactive material. Since the inspection head is operated remotely, worker exposure and access constraints typically associated with traditional hand-held survey instrumentation are minimized. The RadScan 600 employs spectroscopy to identify isotopes on any hot spots automatically identified by the system. Computer-based data files and video imaging provide efficient data storage and retrieval features. Surveys of contaminated surfaces and reporting times are improved while the volume and quality of data generated are enhanced.



RadScan 600 inspection head.

Problem Addressed

At the Hanford Site, decontamination and decommissioning (D&D) planning and operational activities require characterization of radiation fields, for both inside and outside of facilities, often in high-exposure areas. Commonly used technology employs hand-held survey instrumentation that is operated in the radiological zone by radiological control technicians (RCTs) wearing anti-contamination coveralls with hoods and, often, respirators. This method is sometimes hampered by worker exposure concerns and limited access to confined areas. The data generated by such surveys are minimal, and the precision and accuracy level are barely adequate. The time required to conduct a survey and to produce a report is lengthy. In summary, measurement difficulties, worker exposure, and physical access constraints have limited the effectiveness of hand-held survey technology. The traditional (baseline) approach requires sample acquisition and analysis to obtain isotopic identification.

There is a need for flexible survey instrumentation that provides real-time data that can be operated remotely, outside of contaminated areas, both to limit worker exposure and to reduce fatigue caused by operation of hand-held instrumentation. The need for precise reporting of survey data including isotopic information also exists. The remotely controlled RadScan 600 gamma-ray imaging system is an attractive alternative to traditional surveying methodologies that satisfies these needs.

EXECUTIVE SUMMARY continued***Features and Configuration***

Major Features:

- Controlled remotely to minimize worker exposure
- Survey data are available immediately
- Data are stored in both electronic and video media
- Electronic data are supplemented by graphics in the form of contour/surface maps
- Spectroscopy is used to obtain isotopic information.

Components:

Inspection Head

- Thallium-doped cesium iodide and silicon photo diode scintillation detector (20-mm by 25-mm)
- Truncated cone shield/collimator combination made of tungsten (with 2, 4, and 9 degree view angles)
- Laser range finder (± 15 cm at 1 to 30 m from surfaces)
- High-resolution video camera with a zoom lens and a 500-W floodlight

Remote Workstation

- Personal computer (PC) (controller) with Microsoft Windows™ 3.1-based software for controlling the equipment and collecting data
- PC-based multichannel analyzer card
- Super video graphic architecture (SVGA) display screen.

Potential Markets

Marketplace opportunities for the RadScan 600 are at radiologically contaminated sites containing high surface radiological contamination. The technology can be applied to those sites where characterization, remediation, and D&D activities are planned, such as at U.S. Department of Energy (DOE), U.S. Environmental Protection Agency, and U.S. Nuclear Regulatory Commission sites.

Advantages of the Innovative Technology

The following table summarizes RadScan survey technology and compares the baseline technology areas:

Category	Comments
Cost	Higher than the baseline (unit cost of \$8.64/m ² verses \$1.61/m ² for the baseline), but more continuous data and includes isotopic information
Performance	Performs better than the baseline technology for reliability and completeness of data
Implementation	No special site services required for implementation
Secondary waste generation	Does not generate secondary waste
ALARA/Safety	Use of this tool improves ALARA practice and safety compared to baseline
Ease of use	Easy to operate, but much heavier 105 kg (231 lbs) than the baseline instruments

Shortfalls/Operator Concerns

Due to the physical size and geometry of the RadScan technology, there is some difficulty maneuvering the unit in congested areas, and it is also somewhat difficult to obtain near-corner and wall measurements.

™Microsoft Windows 3.1 is a registered product of the Microsoft Corporation, Bellevue, Washington.



EXECUTIVE SUMMARY

continued

Skills/Training

This system does not require a skilled operator, and an RCT familiar with computer operation can learn to operate the system in a very short time (<4 hr).

Demonstration Summary

This report covers the March 1997 period when the RadScan 600 gamma-ray imaging system was demonstrated on asphalt-coated concrete floors, walls, columns and curbs surfaces in the southeast corner of the C Reactor Fuel Storage Basin.

Demonstration Site Description

At its former weapons production sites, the DOE is conducting an evaluation of innovative technologies that might prove valuable for facility D&D. As part of the Hanford Site Large-Scale Technology Demonstration (LSTD) at the C Reactor Interim Safe Storage Project, at least 20 technologies will be tested and assessed against baseline technologies currently in use. DOE's Office of Science & Technology/Deactivation and Decommissioning Focus Area, in collaboration with the Environmental Restoration Program, is undertaking a major effort of demonstrating improved and innovative technologies at its sites nationwide. If successfully demonstrated at the Hanford Site, these innovative technologies could be implemented at other DOE sites and similar government or commercial facilities.

Applicability

The DOE's Richland Operations Office (DOE's Hanford Site) has successfully completed a demonstration to verify the capabilities of the RadScan 600 gamma-ray imaging system. This system represents an innovative technology that can be used where there is a need for characterizing contaminated surfaces with high levels of radiation in support of D&D or remedial design projects. The technology is currently commercially available for floors and walls.

Key Demonstration Results

- The RadScan 600 gamma-ray imaging system was capable of accurately correlating radiation levels to specific locations (± 2 cm at approximately 2 meters from surfaces). The dynamic range of the detector is approximately from 10 μ Ci to < 0.2 Ci for Cs-137 in field of view of detector at 1 meter. The detector should be repositioned as needed to view surfaces that are otherwise behind objects.
- The system produced useful radiological data that were conveniently stored in database format and were easily retrievable.
- The data were supplemented by clear, concise graphical representation of survey data in the form of contour/surface maps.
- A video tape documented the location of measurements.
- The system works best in areas with higher radiation contamination levels due to its high minimum detection level.
- The monetary costs of implementing the RadScan 600 gamma-ray imaging system were higher than the baseline (hand-held survey instrumentation, i.e., Eberline RO-2 and RO-7 probes) and it took somewhat longer than the baseline to set up for project application. However, there were benefits that were not available with the baseline technology. For example, with the new technology, worker exposure in radiation areas is reduced, spectroscopy information is available, and precision and comprehensiveness of data is much greater.



EXECUTIVE SUMMARY

continued

- Since the RadScan 600 can do in situ gamma spectroscopy, isotopic analysis can be done with some measurements, thus, eliminating the need for ex situ sample analysis. Core samples to determine depth of contaminant penetration can also be eliminated if at least two gamma analyses are available to perform peak ratio/shield theory analysis. These advantages of the innovative technology reduce characterization cost compared to baseline characterization methods.

Regulator Issues

The RadScan 600 is an investigation tool for characterizing contaminated surfaces. Therefore, there are no special regulatory permits required for the use of this technology. This system is not designed to meet the intent of 10 *Code of Federal Regulations* Parts 20, 835, or Proposed 834.

Technology Availability

This technology is commercially available for gamma surveys of floors and walls. Patents have been granted to BNFL/PSC for this technology.

Technology Limitations/Needs for Future Development

The major concern encountered during the demonstration was maneuvering the unit in congested areas. Also, due to physical size and geometry of the RadScan 600 and measurement location geometry, near-corner and wall measurements could not be easily obtained. The demonstrated innovative system is not suitable for surveying areas with low levels of radiation, such as for release surveys. However, there is currently no need to modify the system demonstrated at the Hanford Site's C Reactor.

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Other

All published Innovative Technology Summary Reports are available at <http://em-50.em.doe.gov>. The Technology Management System, also available through the EM-50 web site, provides information about OST programs, technologies, and problems. The OST reference # for the Gamma Ray Imaging System (PSC/BNFL RADSCAN 600) is 1793.



SECTION 2

TECHNOLOGY DESCRIPTION

■ Overall Process/Technology Description

DOE's nuclear facility decommissioning program requires the characterization of radiation fields, inside and outside of facilities, as part of D&D planning and activities, especially in higher exposure areas. Historically, this has been attempted using hand-held survey instrumentation, surveying accessible areas as best achievable. Various measuring difficulties, worker exposure, and physical access constraints have limited the effectiveness of the traditional approach. The RadScan 600 provides a viable alternative to the current survey method. The system description presented here follows PSC documentation (Reference 2 in Appendix A) on this technology.

Inspection Head and Video System

The inspection head (Figure 1) incorporates the following components:

- Gamma detector - The detector is a thallium-doped cesium iodide scintillation crystal with a silicon photo diode. The crystal is 20 mm diameter by 25 mm long. A main amplifier incorporated within the detector allows the output signal to be connected directly to a multichannel analyzer system.
- Collimator - One of three tungsten collimators with angles of 2, 4, and 9 degrees can be fitted to the inspection head.
- Laser-based range finder - The head assembly has motorized pan and tilt capabilities, allowing large angles (340 degrees laterally for panning and 130 degrees vertically for tilting) to be scanned both manually and automatically using the remote workstation. The range finder allows the system to automatically record its distance from the surface. The tolerance is ± 15 cm at 1 to 30 m.
- Video Camera - This is a high-resolution color charge collective device with a zoom lens. The lens for the camera is focused remotely from the workstation keyboard and has a motorized zoom that is also remotely controlled. A 500-W floodlight has been added to the basic system.
- Telemetry Unit - Inspection head movement is controlled by a telemetry unit that communicates with the remote workstation.

Workstation

The remote workstation (Figure 2) houses all the processing electronics and with the standard system cable can be located up to 40 m (~131 ft) from the inspection head, preferably in a clean environment where it will not become contaminated. (Longer cables can be deployed.) Full control of all scanning and data acquisition facilities, including the analysis of results, is provided by the workstation, which contains the following components:

- Computer - The onboard computer is mounted in an industrial chassis.
- SVGA Monitor - The SVGA picture signal is input to a video recorder. The monitor and associated software allow video to be displayed from a composite or S-video source [e.g., camera or video cassette recorder (VCR)]. The video appears in a window on the display screen.
- Software - The video signal is displayed on an SVGA monitor in real-time using the Microsoft Windows™ software environment. The RadScan 600 software provides a video replay facility where all the VCR control push buttons are duplicated on the computer monitor.
- Video Cassette Recorder - Video information is recorded on a high-fidelity VCR controlled by the computer. The operator can select a particular control function (e.g., play, pause, forward) by clicking the appropriate button, allowing inspection data to be easily replayed.



TECHNOLOGY DESCRIPTION	continued



Figure 1. RadScan 600 inspection head.



Figure 2. RadScan 600 workstation.

Software

The RadScan 600 runs Microsoft Windows 3.1™ under the MS-DOS operating system. The user interacts with the system through a number of window displays. The software allows the real-time count rate information to be displayed in one of three ways:

- Count mode - Displays the count rate(s), corrected for dead time, at the detector from objects within the current viewing zone with no correction for distance. The count mode can be set for up to three user-defined regions of interest.
- Range corrected mode - Allows the operator to correct the real-time count rate(s) to the rate(s) that would appear if the object were at a user-specified distance.
- Normalization mode - Allows the operator to correct the real-time count rate(s) to the count rate from a user-specified object and to correct for range. The corrected rate enables the operator to estimate whether a zone contains more or less activity relative to the normalization zone.

Surveys can be performed manually or automatically in any one of the three system output modes described above. When operated manually, the operator controls the movement of the inspection head from the PC keyboard and uses the viewing zone circle that is overlaid on top of the video image to identify the origin of the gamma radiation. Alternatively, scanning can be carried out by manually setting the extreme scan limits initially and allowing the RadScan 600 software to automatically scan the area of interest in a raster pattern, recording all important information at incremental positions.

■ System Operation

The remote workstation houses all of the processing electronics and is mounted on wheels. Ideally, the workstation will be located in a clean environment (as was done for this demonstration) to prevent and control equipment contamination. Full control of all scanning and data acquisition facilities, including the analysis of results, is provided by the computer workstation.

Set Up Procedure

The operator starts the RadScan 600 software and enters the following survey parameters:

- survey name (file name)
- explanation of the survey being performed
- the solid angle of the collimator (collimator selection)
- the inspection head stand height
- the field-of-view overlap confidence level
- the region of interest
- the date, time, and count time at each solid angle.

Surface Scanning

The scanning system is then activated and begins measurements, recording the results at each solid angle for the preset amount of time. The survey continues through a series of solid angles (by automatically changing the pan and tilt angles of the inspection head) until the entire selected area is surveyed. The system automatically records the distance from the surfaces using the onboard laser range finder, along with the radiological information associated with each solid angle. Any time the system identifies a hot spot, a radiometric measurement of the hot spot for a preset amount of time is conducted based on user-defined regions of interest. A spectroscopic analysis is made at the user's option. All data collected are saved to a hard-disk drive. A video of the area under investigation is simultaneously recorded for data and physical location association. All information stored in the system is analyzed by the onboard computer to produce the final results. Final data can be presented in units of counts per second (cps) for specific tilt and pan angles. Also, data can be presented in the form of cps contours for pan and tilt angles.

This system does not require a skilled operator, and an RCT familiar with computer operation can learn to operate the system in a very short time (<4 hr).



SECTION 3

PERFORMANCE

■ Demonstration Plan

The demonstration of the RadScan 600 gamma-ray imaging system was completed at the DOE's Hanford Site C Reactor as an integral part of the Interim Safe Storage Project. Specifically, surveys intended to detect gamma radiological contamination on surfaces, such as walls, ceilings, and floors (interior or exterior), were conducted in the Fuel Storage Basin. The basin no longer contains water and was dry during the demonstration. The purpose of the characterization surveys is to support assessments and decisions regarding decontaminating and decommissioning alternatives.

The surface area surveyed totaled approximately 47 m². The surfaces scanned are concrete, covered with asphalt emulsion up to 3 m (10 ft) high. Walls and column surfaces were scanned to a height of 4.5 m (15 ft). The specifications of the surfaces surveyed for the purpose of the demonstration included:

- 41.8 m² (450 ft²) of wall area at a corner of the Fuel Storage Basin, with approximately 4.6 m (15 ft) vertical distance and 6.1 m (20 ft) horizontal distance from the corner of the wall, as well as 3.1 m (10 ft) horizontal distance on the adjacent wall
- Two faces on each of two columns, with a 4.6 m (15 ft) vertical distance
- 2.8 m² (30 ft²) of a divider wall (curb surface).

All surveys were conducted inside of the Fuel Storage Basin below the upper wooden deck. This area was selected because it has more high-radiation surfaces than other reactor areas.

Performance Objectives

The primary objective of this demonstration was to evaluate the capability, and its application at full scale, and to assess its performance and cost versus the baseline, for surveying radiologically contaminated surfaces from a remotely controlled workstation and of differentiating among radionuclides. The purpose of having the workstation located away from the area of contamination is to limit worker exposure and minimize access restriction impacts. The demonstrated technology was to produce both paper-copy and electronic data for analysis. The vendor was tasked to furnish and operate an appropriate gamma radiation-sensing device and transmitting equipment with the following specifications and capabilities:

- A. A 9.1-m (30-ft) minimum-length communications system.
- B. Gamma-energy levels and locations recorded electronically at the workstation, including displays of data overlaid on a physical image (developed by the system) of the basin wall, columns, and divider wall (curb), preferably using a real-time video camera and remote video monitor.
- C. Production of both electronic and hard copy products.
- D. Ability to store and display count rates.
- E. The composite electronic file must be downloadable to a commercially available PC system. The computer, software, and software license must be supplied with the unit.
- F. Capability to operate in a radiologically contaminated zone and ability to perform the demonstration avoiding contamination (e.g., the system could be wrapped in plastic). Capability to differentiate among radionuclides (e.g., Cs-137) and scan a predefined region of interest.
- G. Perform in an energy range of 100 keV to 2 MeV. An extended energy range down to 50 keV is desirable.



PERFORMANCE

continued

- H. As a minimum, the ability to read/detect a contact dose rate of 5×10^{-5} Gy/hr (5 mR/hr) at 30 cm (12 in.) distance with an accuracy of plus or minus 25 percent is desired. The instrument should be capable of the desired sensitivity in a background field ranging from 5×10^{-5} Sv/hr (5 mrem/hr) to 1×10^{-3} Sv/hr (100 mrem/hr).
- I. Preselectable/designated scanning patterns from which the operator can choose are preferred. A scanning-mode selection feature is required that has the ability to set up and scan without user input after the scan pattern is selected.

Major Demonstration Elements

In order to meet the demonstration objectives, PSC developed and submitted a procedure for the completion of surveys of the specified C Reactor Fuel Storage Basin surfaces. The procedure consisted of three primary elements:

- A system pretest to ensure functionality and to check calibration
- The series of gamma surveys
- A post-test to verify that the system remained in calibration and functioned properly.

A technician first made a crude sketch of the area and indicated the location of the RadScan 600 and the surface area that the system was planned to survey. The scanning system was then activated and took measurements, recording the results at each solid angle for the preset amount of the time.

The display provided information during the survey process, including the survey name, average surface gamma activity (cps), pan and tilt angle, and range (system distance from surfaces), as well as a video image of the measurement area.

Demonstration Chronology

The chronology for the demonstration's performance is described below:

All operations vital to the correct operation of the RadScan 600 were verified, including calibration of the cesium iodide detector, by using known calibration sources of Cs-137 and Co-60. Both sources were mounted to the front of the 4-degree tungsten collimator, and a spectroscopic analysis was performed on each source. The variation in channel numbers between the original calibration at PSC and the source-check verification at 100-N was within the limit of expected variation of the system (within two channels).

The RadScan 600 was transferred on March 18, 1997, from the 100-N Warehouse to the C Reactor building area. The RadScan 600 was then moved to the south side of the C Reactor complex. The system was again unpacked and assembled. The support stand, pan and tilt motor assembly, and inspection head were wrapped in 6-mil plastic to prevent possible contamination (Figure 3). After the equipment was thoroughly protected, it was transferred to the platform area (Figure 4) within the fuel basin building to prepare for lowering the system into the Fuel Storage Basin. A ¼-ton hoist was suspended from the overhead gantry rail and positioned over the access opening in the platform. The inspection head (105 kg [231 lb] plus the weight of the support stand) was attached to the hoist and manually positioned by moving the hoist and detector assembly along the gantry rail.



PERFORMANCE

continued



Figure 3. Plastic wrapping of RadScan 600.



Figure 4. Platform area.

The unit was lowered further into the Fuel Storage Basin (Figure 5) and oriented after the support stand made contact with the bottom of the basin. The approximate areas that were scanned in the deep basin included (1) a 6-m (20-ft) by 4.5-m (15-ft) high section of the east wall; (2) a 3-m (10-ft) by 4.5-m (15-ft) high section of the south wall, including a gate to a fuel transfer pit; (3) a 3-m (10-ft) by 0.75-m (2.5-ft) section of a 0.75-m (2.5-ft) high divider wall; and (4) two 0.3-m (12-in.) wide column faces, 90 degrees apart, on each of two vertical columns. These surfaces were constructed of concrete that had been coated with asphalt emulsion up to a height of 3 m (10 ft). The unit was positioned in the southeast corner of the Fuel Basin in Row 2, Position 1 (Figure 6). Further scans were performed during March 19-20 at positions 2 through 7.



Figure 5. Fuel Basin floor, divider walls (curbs), and columns.

PERFORMANCE

continued

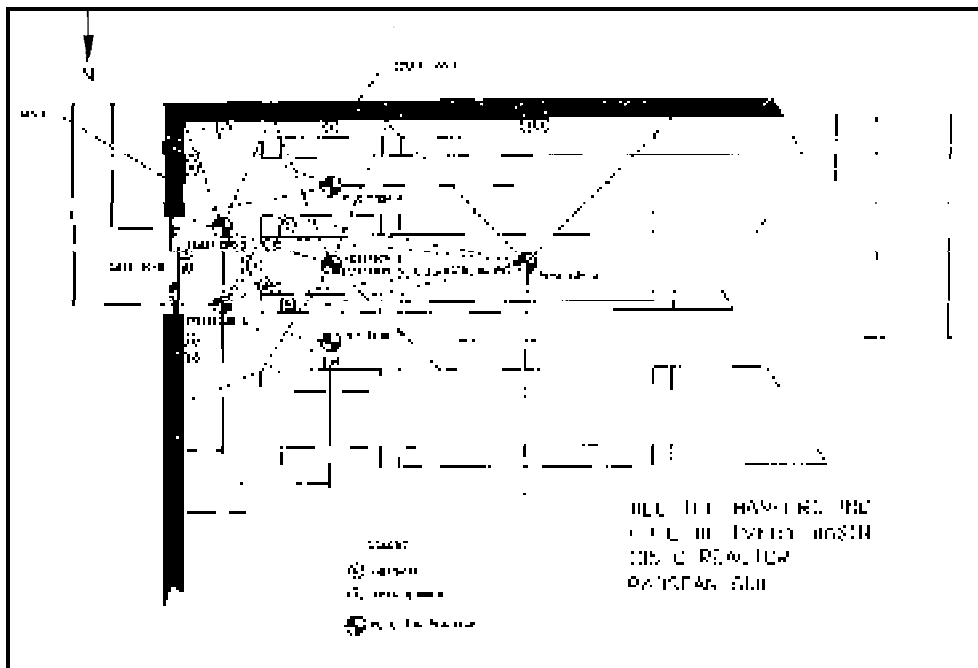


Figure 6. RadScan 600 positions in the Fuel Storage Basin.

When scanning had been completed, the unit was moved back to the access opening in the platform and the unit was lifted out of the fuel basin. The assembly was surveyed by two RCTs and was released to PSC personnel for unwrapping and disassembly. The RadScan 600 was then transferred to the 100-N Warehouse for the post-test source check.

The post-test source check was performed by again verifying the cesium iodide detector's calibration, using known calibration sources of Cs-137 and Co-60. Both sources were mounted to the front of the 4-degree tungsten collimator, and a spectroscopic analysis was performed on each source. The channel numbers at which these energy peaks were recorded were then compared to the calibration performed at PSC/BNFL Instruments in Los Alamos, New Mexico. Source checks indicated that the instruments were functional and were within 10% of the calibration results obtained in the PSC/BNFL Instruments facility.

■ Technology Demonstration Results

To estimate the system response in units of mR/hr, a 7.8-mCi Cs-137 point source was located in front of the inspection head at a distance of 2 m from the detector. The detector response to this source was 580 cps. The radiation field due to this source was measured 0.75 mR/h using a dose rate-probe. These measurements were performed by BNFL at its facility.

The RadScan 600 configuration that was used for this demonstration is as follows:

1. Collimator: 4 degrees
2. Stand height: 0.9 m (35.25 in.)
3. 500-W halogen lamp attached to inspection head
4. 36.4 m (120 ft) umbilical cord
5. System weight = 125 kg (275 lbs), including 105 kg (231 lbs) for the inspection head
6. Operators console outside the radiation buffer area.

PERFORMANCE

continued

A summary of the results from two of the scans where hot spots were noted is outlined as follows:

Scan Number 2 (east wall - Gate 10-B scan to floor)

- Distance from detector to wall = 2.68 m (8.85 ft)
- Total area scanned = 5.73 m² (62.45 ft²)
- Vertical distance = 5.25 m (17.34 ft)
- Horizontal distance = 1.09 m (3.60 ft)
- Field of view overlap confidence level = 50%
- Scan duration = 14.4 minutes
- Scan time per point = 8 seconds
- Highest data point = 964 cps.

Conclusions: Hot spots exist at the bottom of the gate and at the top of the transfer pit gate. Spectroscopy revealed the presence of Cs-137 and Co-60 isotopes (Figure 7, scan 2).

Scan Number 9 (east wall - south corner to floor)

- Distance from detector to wall = 1.89 m (6.23 ft)
- Total area scanned = 6.64 m² (72.32 ft²)
- Vertical distance = 3.11 m (10.25 ft)
- Horizontal distance = 1.60 m (5.29 ft)
- Field of view overlap confidence level = 50%
- Scan duration = 36.6 minutes
- Scan time per point = 10 seconds
- Highest data point = 277 cps.

Conclusions: A hot spot was found on the lower portion of the wall near the floor. Spectroscopy revealed the presence of Cs-137 and Co-60 isotopes (Figure 8, scan 9).

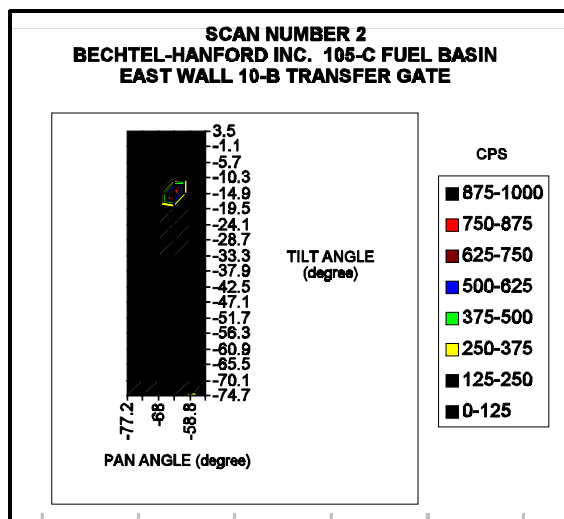


Figure 7. Results of scan number 2.

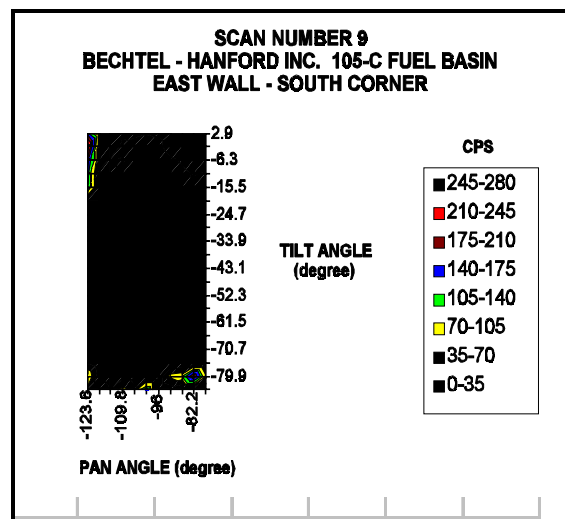


Figure 8. Results of scan number 9.

PERFORMANCE

continued

Monitoring Performance**System Pre/Post-Demonstration Source Check Functionality**

The system was source-checked before and after the demonstration. The system was also checked for mechanical functionality before and after the technology demonstration.

Meeting Demonstration Objectives

The demonstration objectives listed in the Demonstration Plan section were met, except for item G. Item G (energy range) could be met as required, but the lower energy range desired, down to 50 keV, could not be met with the model demonstrated. The lower energy range for the system used at the 105-C Reactor was set at 100 keV, well below the gamma energies of the two radionuclides of interest, Cs-137 (662 keV) and Co-60 (1173 and 1333 keV). The system can meet the requirement of 2 MeV for the highest energy level, but was preset by BNFL Instruments at 1.5 MeV in order to maximize crystal sensitivity and collimator effectiveness. The gain of the system can be factory set to measure 2 MeV or higher

Baseline Survey

The standard methodology for determining the extent of contact and general area radiation fields consists of an RCT manually passing a gamma-sensitive detector (typically a RO-2 or RO-7 probe) near the surfaces [contact, approximately 1 cm (0.4 in.) from surfaces] or a set distance [approximately 30 or 100 cm (12 or 39 in.)] away from the surface of the area being surveyed.

Two RCTs performed a pre-job survey of a portion of the interior of the basin, including 5.5 m² (60 ft²) of the south wall (at the east end of the wall) using the traditional instrumentation. Readings were collected with an RO-7 probe positioned approximately 50 cm (20 in.) from the wall. A plastic-wrapped flashlight was taped to the probe, which was suspended from an L-shaped holder approximately 4 m (13.2 ft.) total length to reach near the south wall. The probe with the flashlight was lowered into the basin, with the RCTs stationed above the basin on the wooden decking. The probe was connected to an above-deck portable indicator via an unwrapped cable 15 m (49.5 ft) long. One RCT maintained control of the instrument probe placement at all times, while the other observed the detection instrument response and documented all gamma radiation fields that were observed. Measurements were static-type measurements.

A typical radiological survey report (Figure 9) was prepared that contained relevant information regarding the conduct of the survey (e.g., date, time, instruments used, location) and the survey results. This report included a hand-drawn sketch of the surveyed areas with associated radiation levels. Measurement locations indicated on the survey map were approximate and were not drawn to scale.



PERFORMANCE

continued

Comparison Of Innovative Technology to Baseline

The performance and operation of the innovative technology system compared to baseline technology are tabulated below:

Activity	Innovative Technology	Baseline
Source and system check	1 hour ^a	3 minutes
Survey speed	6-10 seconds @ each angle	Static 4 to 5 seconds at 0.6 to 0.9 m (2 to 3 ft)
Survey time	Approx. 4 hours	3 hours
Survey area	Approx. 182 m ² (600 ft ²)	18.2 m ² (60 ft ²) ^b
Survey area coverage	Approx. 100%	Note c
Survey Report	3 minutes	30 minutes
Sensitivity	Poor for release level; good for higher radiation areas	Note c
Flexibility	Low for sensitivity, but flexible for degrees of collimation, speed of data acquisition and size of automatic scans	Low
Precision, accuracy, representativeness and completeness	Better than baseline	Minimally acceptable
Safety	Good, but heavy weight and higher voltage	Good
Durability	Complex system to maintain	Good
Data interpretation	More and better data generated	Minimal data generated
Ease of operation	Note d	Note d
Waste generation	Minimal, but more plastic wrap	Minimal
Utility requirements	115 VAC	Battery

^a Special pretest and post-test source checks were performed as part of the demonstration to check for gamma-detection system drift and to confirm calibration. Normal use of the system does not require a source check, and a system check can be done in approximately 5 minutes. Also, the survey speed can often be done at 5 seconds at each angle.

^b More areas in the Fuel Storage Basin were surveyed using the baseline method; these areas were floor, curb walls, and some columns.

^c The baseline probe has no collimator and is an omnidirectional detector.

^d The innovative technology requires more training because it uses a computerized system.

VAC = volts alternating current



PERFORMANCE

continued

ERC Radiological Survey Record - DOSE RATE -						Page 1 of 2															
Type of Survey (check one only) ☐ Release ☐ Routine ☒ Work Progress ☐ Shipment						Survey # RSR-1056-97-246															
RWP # / Rev. # PS-1056-34/0		Date 5-20-97		Time 0900		Location FSB															
Comparison Survey for Toxic Dose Transfer Pipe Case <table border="1"> <tr><td>4</td><td>5</td></tr> <tr><td>5</td><td>7</td></tr> <tr><td>8</td><td>6</td></tr> <tr><td>9</td><td>8</td></tr> <tr><td>12</td><td>10</td></tr> <tr><td>13</td><td>13</td></tr> <tr><td>12</td><td>10</td></tr> </table> Note: Survey is for information only. Readings are not to be used to set dose max. RO-7 was used with low range probe calibrated to a different RO-7 body. South East Corner of Fuel Storage Basin Readings are Gamma, ground level, taken from 5" to 18" away from wall.								4	5	5	7	8	6	9	8	12	10	13	13	12	10
4	5																				
5	7																				
8	6																				
9	8																				
12	10																				
13	13																				
12	10																				
-C- Contamination Area	-H- High Contamination Area	-D- Radiological Buffer Area	-R- Radiological Exclusion Area	-RM- Radiological Material Area	-R- Radiation Area	-HR- High Radiation Area															
-A- Access Restricted Area	-M- Maximum Contamination Level	-S- Safety Area	-S- Safety Area	-SCA- Safety Contamination Area		-V- Very High Radiation Area															
Instruments																					
Model	Serial #	Source of Initials	Cal Due Date	Model	Serial #	Source of Initials	Cal Due Date														
RO-7	0026	NA	3/2/98	NA	NA	NA	NA														
DTESL	0039	NA	12/19/97	NA	NA	NA	NA														
RCT Name/Signature/Date: Denny Taylor / <i>[Signature]</i> / 5-20-97				RCT Signature/Name/Signature/Date: S. R. BEED / <i>[Signature]</i> / 05/20/97																	
Batt TAI RCD-01.3.01		RSP completed in accordance with SH-SH-03, Procedure 1.1				Form															

Figure 9. Environmental Restoration Contractor Radiological Survey Record.



PERFORMANCE

continued

Expected Performance Under Variable Conditions

The DOE complex presents a wide range of D&D work conditions because of the variety of functions and facilities. The working conditions for an individual job directly affect the manner in which D&D work is performed. As a result, each individual job is unique. The innovative and baseline technology comparison presented in this analysis is based upon the specific set of conditions or work practices at RL. These conditions are presented in Table 3-1, which is intended to help the technology user identify unique work conditions that could result in cost differences.

Table 1. Summary of variable conditions

Variable	RadScan 600 Gamma-Ray Imaging	Baseline Survey
Scope of Work		
Quantity and Type	128 preliminary scans with 25% overlap* confidence level to cover 3,357 m ² (36,100 ft ²) and 7 detailed scans to delineate hot spots, with 75% overlap* confidence level to cover 1.21 m ² (13 ft ²)	Extrapolated to 3,357 m ² (36,100 ft ²) based on typical production rates observed in the demonstration.
Location	Fuel Storage Basin (no water in basin).	Fuel Storage Basin (no water in basin).
Nature of Work	Columns are present that can obscure areas from being scanned (more setups required); a hoist required to move from one position to the next. The surveying was performed along a grid pattern that follows the spaces between boards in the decking that covers the basin, and duration of individual scan increment is 8 seconds.	Surveying along a grid pattern that follows the spaces between boards in the decking covering the basin.
Work Environment		
Worker Protection	Anti-contamination coveralls with hood, but no respirator.	Anti-contamination coveralls with hood, and respirator.
Level of Contamination	Classified as a contaminated area above the wood decking; at portions of the basin, it is a radiation area.	Classified as a radiation area (and temporarily as an asbestos area, which results in requirement for respirator at times).
Work Performance		
Acquisition Means	For the demonstration, equipment leased (30-day lease) and operation performed by vendor but estimated in this analysis as performed by site personnel with initial instruction in operation provided by vendor.	Site personnel with site-owned equipment.
Production Rates	Preliminary survey using 25% overlap confidence level has an assumed production rate of 0.4 m ² (4.45 ft ²) per minute [for a distance from the objective of 2.7 m (8.85 ft) the detailed survey rates varied from (0.62 to 2.4 ft ²) per minute to 0.06 to 0.22 m ²].	Baseline production rate is ~0.5 m ² (5.5 ft ²) per minute based on the average production observed [11 minutes to perform 5.5 m ² (60 ft ²) of surveys].
Equipment & Crew	One RCT and one D&D worker for the setup portion of the work, and two RCTs for halftime, and one D&D worker halftime for the scanning portion.	Two RCTs using one RO-7 probe.
Work Process Steps	1. Ship equipment to site 2. Transport from receiving area to work location 3. Provide instruction for operators (one time) 4. Set up equipment and wrap with plastic 5. Perform preliminary survey 6. Perform detailed surveys 7. Evaluate 8. Decontaminate and release 9. Transport to shipping area 10. Ship to Los Alamos	1. Prepare survey plans 2. Transport to work area 3. Set up 4. Conduct survey 5. Evaluate data and prepare reports 6. Decontaminate 7. Return transport
End Product	Characterization for planning work	Characterization for planning work

* This is based on the assumption that all of the Fuel Storage Basin surfaces have been scanned (preliminary type) with the innovative technology, plus seven detailed scans of hot spots. The number of hot spots is based on the historic findings of baseline surveys.

** This estimate is based on the demonstration performed and was pro-rated for the total area of the Fuel Storage Basin.



SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

■ Technology Applicability

- The RadScan 600 technology has the ability to survey large surface areas for gamma radiation with accuracy and a high degree of reproducibility.
- Compared to the baseline, RadScan 600 generates a more concise and understandable representation of the exact location and extent of contamination (radiation) present in an area (see Figures 7 and 8 for the innovative technology and Figure 9 for the baseline).
- Physical locations of readings are accurate to within 15 cm (6 in.) as measured by the range finder; the baseline technique is much less accurate.
- The readings and associated locations are recorded automatically in a computer file; baseline technology readings must be observed and recorded manually.
- The ability of the RadScan 600 to be operated remotely enables the measurement crew to stay in a very low exposure area and perform highly accurate measurements in higher contamination (radiation) areas, keeping exposure as low as reasonable achievable (ALARA).
- This technology can be used to provide well-documented surface radiation exposure and characterization surveys of contaminated or potentially contaminated floors, buildings, and structures prior to and during decommissioning and demolition.
- The RadScan 600 may be used on both interior and exterior surfaces.
- The survey documents provide easier review of characterization results than the survey report produced with the baseline technology, and with better precision and quality.
- The system can be configured with large detectors on mobile platforms, which allows large surface areas such as floors, ceilings, and walls to be surveyed.
- The system can provide relative isotopic information on surface contamination in the survey area, which is not available with the baseline technology.
- The system is applicable to high radiation areas and is useful for pre-job surveys. The RadScan 600 has the ability to map hot spot in high background or multiple hot spots areas. Using the omnidirectional baseline probe is much more subjective when characterizing an area (e.g., room, cubicle, hot cell).

■ Competing Technologies

- The RadScan 600 technology is more costly, but better in terms of worker exposure ALARA practice when compared with hand-held detectors used to characterize a high radiation area.
- An alternative to the RadScan 600 technology is the *Gamma Cam™ system (used at CP5 Technology Demonstration). However, the demonstrated system (RadScan) can automatically pan and tilt to cover wide areas and can perform spectral analysis, for aid in identifying isotopes, which the Gamma Cam system cannot.

*Gamma Cam is a registered trademark of AIL Systems (Deer Park, NY), a subsidiary of Eaton Corporation



■ Patents/Commercialization/Sponsors

- This technology is commercially available for gamma surveys of floors and walls.
- Patents have been granted to BNFL Instruments for this technology.
- Marketplace opportunities for the RadScan 600 are at radiologically contaminated sites containing high surface radiological contamination. The technology can be applied to those sites where characterization, remediation, and D&D activities are planned (e.g., DOE, U.S. Environmental Protection Agency, and U.S. Nuclear Regulatory Commission sites).



SECTION 5

COST

■ Methodology*Introduction*

This cost analysis compares the RadScan 600 gamma-ray imaging innovative technology to the baseline technology of conventional radiological surveying using hand-held instruments. The innovative technology was demonstrated using the vendor's personnel and equipment, and the baseline technology was performed using site labor and equipment. The production rates and durations from the demonstration were used to estimate the cost of characterizing all the surfaces of the Fuel Storage Basin. The estimated cost for characterization by conventional radiological survey methods is approximately 20% of the cost of performing characterization using RadScan 600 gamma-ray imaging technology. However, this cost study does not account for savings from improved ALARA practice that would be realized by using the innovative technology. Details of the cost comparison are covered in Appendix C of this report and summarized in Figure 10.

■ Cost Analysis

Costs for demonstration of the RadScan 600 technology are based on performing a preliminary survey of an area in the Fuel Storage Basin followed by more detailed surveys of hot spots identified by the preliminary survey. This scenario is intended to represent the cost for normal D&D work using the RadScan 600 gamma-ray imaging system (normal being defined by the vendor experience and judgment of the test engineer) and uses production rate data derived from the demonstration for estimating the cost of surveying the entire basin. One of the several scans performed at a significant distance from the objective was selected to represent the preliminary survey, and several of the close scans were used to represent detailed scans. Other adjustments of the observed data from the demonstration are as follows:

- It is assumed that the equipment is leased and operated by site workers (rather than purchased and operated by the vendor). This assumption was made because of the relatively large capital expense, the limited number of opportunities to use the equipment, costs for mobilizing vendor personnel, and the relative ease of learning to operate the equipment.
- RadScan 600 gamma-ray imaging equipment hourly rates were based on vendor quotes for a 30-day lease.
- 75% overlap confidence level of the scan increments is assumed typical of detailed scans, and 25% overlap confidence level is assumed typical of preliminary scans.
- The onsite calibration that was performed is for demonstration purposes only and would not be part of normal practice (the calibration performed by the vendor at the vendor's facility will be sufficient).
- During the demonstration, the vendor personnel as well as the RCT and D&D personnel were present throughout the demonstration; it is assumed this would not represent normal work (assume two RCTs one-half of the time and one D&D worker one-half of the time).

The activities, production rates, and unit costs observed during the demonstration are shown in Appendix C. The data contained in the innovative technology cost summary, Table C-1, can be used in developing a site-specific cost estimate.



COST

continued

RadScan Cost Data Compared with Baseline

The innovative technology is available from the vendor in the forms and at the rates indicated in Table 2:

Table 2. Innovative technology acquisition costs

Acquisition Option	Item	Cost
Equipment Purchase	Equipment & Software	\$180,000 - \$200,000
Rental or Lease	30 days	\$36,000 - \$40,000
	60 days	\$54,000 - \$60,000
	90 days	\$64,800 - \$72,000
Vendor-Provided Service	Crew & Equipment Daily Rate	\$1,200/day including subsistence

The rates and prices shown do not include shipping or mobilization costs. The prices will vary from those shown because of fluctuation in the exchange rate, shipping/mobilization distance, and circumstances of the individual job (such as period of work). The vendor will provide current prices upon request.

Observed unit costs and production rates for principal components of the demonstrations for both the innovative and baseline technologies are presented in Table 3:

Table 3. Summary of unit costs and production rates

INNOVATIVE TECHNOLOGY RadScan 600 Gamma-Ray Imaging		BASELINE TECHNOLOGY Conventional Radiological Surveys	
Unit Cost	Production Rate	Unit Cost	Production Rate
\$8.64/m ² (\$2.58/ft ²)	51.8 m ² /hr (170 ft ² /hr)	\$1.61/m ² (\$0.49/ft ²)	71.6 m ² /hr (235 ft ² /hr)

Note: The unit costs and production rates do not include training, mobilization, and demobilization costs.

The demonstration occurred under specific conditions that directly control cost. The most significant conditions affecting costs for this demonstration are:

- Number of obstructions (number of setups required) (for characterization of all basin surfaces, between 130 and 140 setups would be required)
- Radiologic conditions (classified as a contaminated area above the wood decking and as a radiation area at portions of the basin)
- Number of "hot spots" [detailed surveys required for seven areas for a total of 1.2 m² (13 ft²) of the basin surface]
- Period of lease (the rate used in this analysis was for 30 days).

For additional discussion of cost variable conditions that may occur when using the innovative technology and the potential effect these conditions may have on unit costs and production rates, refer to Section 3 of this report.



COST

continued

Cost Conclusions

The durations and production rates observed from the demonstration were used along with the surface area quantity for the Fuel Storage Basin to estimate the cost of scanning the entire surface of the Fuel Storage Basin. Some of the activities that are included in the cost estimate were not demonstrated (such as training for site operators and preliminary surveys to locate the "hot spots"). The durations and production rates for these two activities were developed from the vendor's experience and from the judgement of the test engineer based on observations made during the demonstration. The costs for the innovative technology and the three baseline technologies are shown in Figure 10. The costs are based on the following work activities:

- Ship equipment to site
- Transport from receiving to work area (C Reactor)
- Training for operators (one-time cost)
- Set up equipment and wrap with plastic
- Preliminary survey
- Detailed survey
- Data evaluation
- Decontaminate and release
- Transport to shipping
- Shipping to Los Alamos.

The costs shown in Figure 10 do not include overhead or general and administrative markup costs.

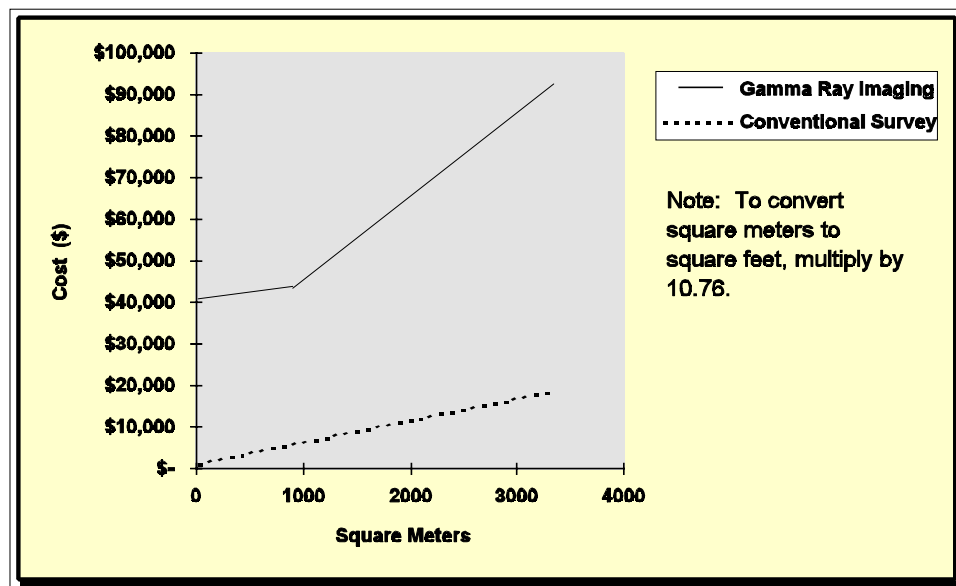


Figure 10.
d costs for innovative and baseline technologies for
Fuel Storage Basin.

Estimate

COST

continued

The estimate for characterizing the entire Fuel Storage Basin was based on 135 setups. The many columns and obstructions present in the Fuel Storage Basin require many setups and prevent efficient scanning of large areas. Other D&D sites may not be as severely obstructed as the C Reactor fuel storage basin, and the costs for gamma-ray imaging at other sites may be lower depending on the number of setups required. Productivity rates for scans at a distance of 1.7 m (5.58 ft) were 0.061 m²/min (0.66 ft²/min), while scans at distances of 4.2 m (13.78 ft) had productivity rates of 0.223 m²/min (2.4 ft²/min). Additionally, the production rates may vary for other situations due to the strength of the source and the resolution required (affects amount of required overlap for the individual scans and duration of each scan).

Since the RadScan 600 can do in situ gamma spectroscopy, isotopic analysis can be done with some measurements, thus, eliminating the need for ex situ sample analysis. Core samples to determine depth of contaminant penetration can also be eliminated if at least two gamma analyses are available to perform peak ratio/shield theory analysis. These advantages of the innovative technology reduce characterization cost compared to baseline characterization methods.



SECTION 6**REGULATORY AND POLICY
ISSUES****■ Regulatory Considerations**

- The RadScan 600 is an investigation tool for characterizing contaminated surfaces. Therefore, there are no special regulatory permits required for the use of this technology.
- This system is not designed to meet the intent of 10 *Code of Federal Regulations* Parts 20, 835, or Proposed 834.
- Although the demonstration took place at a Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) site, no CERCLA requirements apply to the surveys conducted.

■ Safety, Risk, Benefits, and Community Reaction**Worker Safety**

- Normal radiation protection worker safety procedures used at the facility would apply.
- Normal lifting and rigging precautions would apply.
- Technology users should implement contamination control practices.
- In high-radiation areas, this system provides ALARA exposures.

Community Safety

- The primary purpose of the RadScan 600 technology is to aid the decision process for cleanup, D&D characterization, radiation source term determination, and planning, as well as decontamination prioritization (especially in high radiation areas). Implementation of this technology would have no adverse impacts on community safety.

■ Environmental Impact

- Implementation of this technology would have no adverse impacts on the environment.

■ Socioeconomic Impact and Community Perception

- No socioeconomic impacts would be anticipated.



SECTION 7**LESSONS LEARNED****■ Implementation Considerations**

- To perform a survey effectively, obstructions (e.g., column, thick objects, walls) should not be present in the detector solid-angle view. The detector should be repositioned as needed to view surfaces that are otherwise behind objects.
- Planning for hoists or other rigging to maneuver the inspection head assembly should be considered due to the weight of the unit, which is 105 kg (231 lb) for the inspection head. The weight including the support stand is approximately 125 kg (275 lb).
- The RadScan 600 system demonstrated at the C Reactor is well suited for large open areas.
- The system is suitable for higher radiation areas, and discriminates well between the front and other directions (the detection system is directional). This results in the ability to locate hot spots more accurately than the baseline.
- The system can discriminate hot spot locations in areas with multiple hot spots.

■ Technology Limitations/Needs for Future Development

- The major concern encountered during the demonstration was maneuvering the unit in congested areas.
- Due to physical size and geometry of the RadScan 600 and measurement location geometry, near-corner and wall measurements could not be easily obtained.
- The demonstrated innovative system is not suitable for surveying areas with low levels of radiation, such as for release surveys.
- There is currently no need to modify the system demonstrated at the Hanford Site's C Reactor.
- A similar Gamma Ray Imaging System (Gamma Cam) has been purchased and is scheduled for deployment at Hanford's B Plant.

■ Technology Selection Consideration

- The technology is useful for site characterization in support of D&D engineering design and planning, particularly on floor and wall surfaces.
- This technology has the ability to capture both contamination and exposure level information, along with isotopic information for all surfaces surveyed, with a single detector.
- Reports can be generated automatically that provide a clear, concise, and understandable representation of the exact location and extent of contamination. The data can be used for job planning and decontamination activities, and for loading into dose assessment software packages with more accuracy, completeness, speed, and reproducibility than with the baseline technology.
- All information acquired with the system is scientifically derived and is not subject to subjective observations. The data are electronically logged and are not recorded manually, which enhances comprehensiveness and precision over the baseline technology.

APPENDIX A

COST**continued****REFERENCES**

10 CFR Part 835, *U.S. Code of Federal Regulations*, "Occupational Radiation Protection," *Code of Federal Regulations*, as amended..

Proposed 10 CFR Part 834, *U.S. Code of Federal Regulations*, "Environmental Radiation Protection," *Code of Federal Regulations*, as amended.

10 CFR Part 20, *U.S. Code of Federal Regulations*, "Occupational Radiation Protection," *Code of Federal Regulations*, as amended.

Ref. 1 *RadScan 600 Operator's Manual*, BNFL Instruments, Ltd., April 1996.

Ref. 2 *Gamma-Ray Demonstration Evaluation Report*, PSC, Los Alamos, NM, May 1997.

Ref. 3 *PSC Survey Protocols and Procedures*, PSC, Los Alamos, NM, May 1997.

Ref. 4 *Gamma-Ray Imaging Fact Sheet*, Hanford, WA, March 1997.

Ref. 5 AIF, 1986, *Guidelines for Producing Commercial Nuclear Power Plant Decommissioning Cost Estimates*, May 1986, National Environmental Studies Project of the Atomic Industrial Forum, Inc., Bethesda, Maryland.

Ref. 6 USACE, 1996, *Hazardous, Toxic, Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary*, U.S. Army Corps of Engineers Headquarters, Washington, D.C.



APPENDIX B**ACRONYMS AND ABBREVIATIONS**

Acronym/Abbreviation	Description
ALARA	as low as reasonably achievable
BHI	Bechtel Hanford, Inc.
BNFL	British Nuclear Fuels Ltd.
cps	counts per second
D&D	decontamination and decommissioning
DOE	U.S. Department of Energy
FETC	Federal Energy Technology Center
LSTD	Large-Scale Technology Demonstration (project)
PC	personal computer
PSC	Pajarito Scientific Co.
RCT	radiological control technician
RL	U.S. Department of Energy, Richland Operations Office
SVGA	super video graphic architecture
USACE	U.S. Army Corps of Engineers
VCR	video cassette recorder
WBS	work breakdown structure



APPENDIX C

TECHNOLOGY COST COMPARISON

The demonstration was conducted at the Hanford Site C Reactor under controlled conditions with onsite personnel operating the equipment for which timed, measured, and quantified activities were recorded.

The selected basic activities being analyzed come from the *Hazardous, Toxic, and Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary* (HTRW RA WBS), USACE, 1996. The HTRW RA WBS, developed by an interagency group, was used in this analysis to provide consistency with the established national standards.

Some costs are omitted from this analysis so that it is easier to understand and to facilitate comparison with costs for an individual site. The overhead and general and administrative (G&A) markup costs for the site contractor managing the demonstration are omitted from this analysis. Overhead and G&A rates for each DOE site vary in magnitude and in the way they are applied. Decision makers seeking site-specific costs can apply their site's rates to this analysis with out having to first back out the rates used at the Hanford Site. This omission does not sacrifice the cost savings accuracy, because overhead is applied to both the innovative and baseline technology costs. Engineering, quality assurance, administrative costs and taxes on services and materials are also omitted from this analysis for the same reasons indicated for the overhead rates.

This appendix contains cost data for the innovative technology and the baseline. These data are presented in a work breakdown structure for mobilization, characterization, and demobilization. The activities, production rates, and unit costs observed during the demonstration are shown in Table C-1, and can be used to develop site-specific cost estimates given the unique conditions present at the site. The subsequent table, Table C-2, shows cost data for the baseline technology and provides a basis for comparison with the innovative technology.



Table C-1. Cost summary - RadScan 600 gamma-ray imaging system

Work Breakdown Structure (WBS)	Unit Cost (UC)						Unit of Measure	Innovative Technology - Small Area Comments
	Labor		Equipment		Other	Total UC		
	HRS	Rate	HRS	Rate				
Mobilization (WBS 331.01)							Subtotal	
Ship Equipment	0.00	\$ -	32.00	\$250.00	\$500	\$8,500.00	Each	Shipping from Los Alamos, New Mexico to Central Warehouse (equipment lease period extended by shipping time of 4 days) lease rate in \$250/hour
Unload & Transport	2.00	\$36.35	2.00	\$259.52		\$591.74	Each	Teamster and truck to transport equipment from Central Warehouse to C Reactor and includes standby for RadScan 600 equipment
Unpack, Survey & Prepare	4.00	\$81.42	4.00	\$250.00		\$1,325.68	Each	One Radiological Control Technician (RCT) @ \$49.45/hr and one D&D worker at \$31.97/hr (includes wrapping instrument with plastic sheeting, instrument check out and initialization)
Instructions for Site Crew								One time cost for vendor to travel to RL to provide instruction on use of the equipment
Vendor to Site	8.00	\$57.13			\$693	\$1,149.54	Each	Includes vendor labor during flight from Los Alamos to Pasco (RL), per diem, and air fare
Site Training	8.00	\$57.13			\$74	\$531.04	Each	Site required training for entry to work area includes labor and per diem for one day
Conduct Instruction	8.00	\$57.13			\$74	\$531.04	Days	Training of the site workers for two days as the work proceeds (includes labor and per diem for vendor)
Vendor Return Home	8.00	\$57.13			\$618.5	\$1,075.54	Each	Includes vendor labor during return flight
Characterization (WBS 331.17)							Subtotal	
Set-Up & Move for Next Scan	0.17	\$81.42	0.17	\$250.00		\$55.06	Locations	Move equipment from preliminary scan location to the next detailed scan location (3 detailed scan locations) using a hoist, and prepare for next scan, crew is 1 RCT and 1 D&D worker
Preliminary Scan	0.004	\$65.44	0.004	\$250.00		\$1.17	Square Feet	Scan to identify location of hot spots using 25% overlap confidence level and minimum scan duration, crew includes 2 RCTs for ½ time and 1 D&D worker for ½ time
Detailed Scan	0.011	\$65.44	0.011	\$250.00		\$3.56	Square Feet	Detailed scan of identified hot spots, crew includes 2 RCTs for ½ time and 1 D&D worker for ½ time. Unit duration is an average based on total area for 5 surveys divided by total duration for 5 surveys
Evaluate Data & Final Report	1.00	\$98.90				\$98.90	Each	One RCT and the RCT supervisor
					\$22		Man Day	\$22/day per person for personal protective equipment (assumes 2 pair used per person per day)
Daily Meeting	0.50	\$81.42	0.50	\$250.00		\$165.71	Each	One safety meeting each morning prior to beginning work
Productivity Loss Factor	0.00	\$81.42	0.00	\$250.00		\$ -	Each	Productivity Loss Factor of 1.27 (adjusts for breaks and personal protective equipment changes by extending the work duration by 27%)
Demobilization (WBS 331.21)							Subtotal	
Decon and Survey Out	4.00	\$81.42	4.00	\$250.00	\$0.08	\$1,325.76	Each	Survey equipment for free release and remove protective plastic wrap, other costs include waste disposal of 5 lbs of low-level waste at \$60/ton
Load & Transport Equipment	2.00	\$36.35	2.00	\$259.52		\$591.74	Each	Transport to Central Warehouse for shipping
Shipping	0.00	\$ -	32.00	\$250.00	\$500	\$8,500.00	Each	Return shipping to Los Alamos, New Mexico from Central Warehouse (equipment rental period extended by shipping time of 4 days)

NOTE: TC = UC * TQ

TOTAL:



APPENDIX C

continued

Baseline Technology - Manual Survey

The cost of performing the work consists of conducting a manual survey of the Fuel Storage Basin surfaces and producing a survey report. The activities, production rates and unit costs utilized in the baseline are shown in Table C-2.

Table C-2. Baseline technology - manual survey

Work Breakdown Structure (WBS)	Unit Cost (UC)						Unit of Measure	Innovative Technology Small Area Comments
	Labor		Equipment		Other	Total UC		
	HRS	Rate	HRS	Rate				
Mobilization (WBS 331.01)								
Prepare Survey Plans	2	\$98.90	0	\$ -	\$ -	\$198	Each	Labor for two RCTs @ \$49.45/hr standard rate for BHI, RL
Transport Personnel & Equipment	1	\$98.90	1	\$1.25		\$100	Each	Includes \$0.50 for Eberline RO-7
Source Check Instrument	0.1666	\$49.45	0.1666	\$1.25		\$8	Each	One RCT with an Eberline RO-7
Characterization (WBS 331.17)								
Setup	1	\$98.90	1	\$1.25		\$100	Each	Crew of two RCTs and an Eberline RO-7 prepare for survey
Survey	0.00303	\$98.90	0.00303	\$1.25		\$0.30	Square Foot	Production rate of 5.5 ft²
Daily Meeting	0.5	\$98.90	0.5	\$1.25	0	\$50	Each	Daily meetings of ½ hour (typical of Hanford D&D work)
Personal Protection Equipment	0	\$ -	0	\$ -	\$22	\$22	Man Day	\$22/day per person for personal protective equipment (assumes 2 pair used per person per day)
Productivity Loss Factor	0	\$98.90	0	\$1.25		\$ -	Each	Productivity Loss Factor of 1.27 (adjusts for breaks and personal protective equipment changes by extending the work duration by 27%)
Data Evaluation and Report	10	\$49.45				\$495	Each	Includes preparation and review by RCT supervisor
Demobilization (WBS 331.21)								
Decon and Survey Out	0.1666	\$98.90	0.1666	\$1.25	\$0.03	\$17	Each	Labor plus equipment standby and 2 lbs of solid low-level waste generated
Transport for Return	1	\$98.90	1	\$1.25	\$ -	\$100	Each	Same as Mobilization cost element
TOTAL: NOTE: TC = UC * TQ								

NOTE: TC = UC * TQ



GammaCamTM Radiation Imaging System

Deactivation and
Decommissioning Focus Area



Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

February 1998

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GammaCamTM Radiation Imaging System

OST Reference # 1840

Deactivation and
Decommissioning Focus Area



Demonstrated at
Chicago Pile 5 (CP-5) Research Reactor
Large-Scale Demonstration Project
Argonne, Illinois



Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available online at <http://em-50.em.doe.gov>.



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SECTION 1

Technology Description

GammaCam™, a gamma-ray imaging system manufactured by AIL System, Inc., would benefit a site that needs to locate radiation sources. It is capable of producing a two-dimensional image of a radiation field superimposed on a black and white visual image. Because the system can be positioned outside the radiologically controlled area, the radiation exposure to personnel is significantly reduced and extensive shielding is not required.

How it Works

The GammaCam™ system is designed to provide two-dimensional information on the position and relative strengths of gamma-ray radiation fields located from a few feet to several hundred feet from the observer. The system consists of a portable sensor head that contains both gamma-ray and visual imaging systems and a portable computer for control. The sensor head is shown in Figure 1 mounted on a tripod. The data is collected and displayed by the computer that can be located several hundred feet from the sensor head. Figure 2 shows a sample output of the superimposed radiation and visual images for a cesium source located on a desk. Note: Actual output is in color, not black and white as shown.



Figure 1. GammaCam™ mounted on tripod.

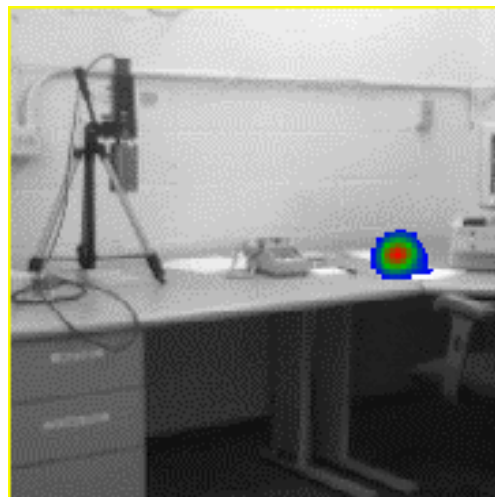


Figure 2. Image of a test source.

The gamma-ray imaging system uses a coded aperture for imaging of the radiation field. The gamma ray energy sensitivity of the system is approximately 0.1 to 2.0 Mega-electron Volts (MeV). The system is unable to distinguish between gamma rays of different energies and thus cannot be used to identify specific radioactive isotopes. The sensitivity of the system is approximately 1 micro-Rad (μR) dose at the sensor head for a 7:1 signal-to-noise ratio. The data acquisition time can be varied from 10 milliseconds to many hours. The field-of-view of the gamma-ray imaging system is either 25° (1.3° angular resolution) or 50° (2.6° angular resolution). Both the collection time and the field-of-view are controlled by a computer. The radiation and visual images are stored in a PCX format on disk.



Demonstration Summary

The demonstration of GammaCam™ in December 1996 was part of the Large-Scale Demonstration Project (LSDP) whose objective is to select and demonstrate potentially beneficial technologies at the Argonne National Laboratory-East (ANL) Chicago Pile-5 Research Reactor (CP-5). The purpose of the LSDP is to demonstrate that by using innovative and improved decontamination and decommissioning (D&D) technologies from various sources, significant benefits can be achieved when compared to baseline D&D technologies. This demonstration is sponsored by the U.S. Department of Energy (DOE), Office of Science and Technology, Deactivation and Decommissioning Focus Area (DDFA).

The purpose of these tests was to determine the capabilities, limitations, and suitable applications of the GammaCam™ system in the following three areas:

- surveying large floor or wall areas that may be contaminated due to spills,
- use of the system to identify the relative location and strength of different radioactive sources located in a large concrete vault through an opening in the shield wall, and
- demonstration of the usefulness of the composite two-dimensional radiation and visual images in determining shielding needs and in positioning subsequent shielding.

The baseline technology for comparison is a standard manual survey. Since the output from the GammaCam™ system is a composite video image showing relative radiation field strength, the technology is not directly comparable to the baseline because the baseline can only provide quantified results at specific locations.

CP-5 is a heavy-water moderated and cooled, highly enriched, uranium-fueled thermal reactor designed to supply neutrons for research. The reactor had a thermal-power rating of 5 megawatts and was operated for 25 years until its final shutdown in 1979. These 25 years of operation have produced activation and contamination characteristics representative of other nuclear facilities within the DOE Complex. CP-5 contains many of the essential features of other DOE nuclear facilities and can be safely used as a demonstration facility for the evaluation of innovative technologies for the future D&D of much larger, more highly contaminated facilities.

An AIL engineer operated the GammaCam™ system and provided digital images of the collected data. ANL personnel from CP-5 and the Environment, Safety, and Health (ESH) Division provided support in the area of health physics (HP). Argonne National Laboratory personnel wrote the test plan and generated a data report describing the information collected. Cost analysis was performed by the U.S. Army Corps of Engineers (USACE), and benchmark activities were performed by ICF Kaiser.

Key Results

The key results of the demonstration are as follows:

- The GammaCam™ system performed well during the CP-5 demonstration by successfully providing two-dimensional color images of gamma radiation fields superimposed on the corresponding visual black and white image. No significant problems with the system were identified in the 3-day test despite considerable movement and relocation of the device.
- The use of the GammaCam™ system in determining shielding requirements and in positioning shielding will result in a significant reduction in the radiation dose received by operating technicians. This benefit will be more pronounced in high radiation areas.
- The GammaCam™ system can provide useful information concerning the relative strengths of the various sources and their locations from outside the radiological area. This provides useful information for planning a decontamination process to be obtained with minimal radiation dose to the operator. It is also possible to use triangulation to determine the distance of the sources relative to the GammaCam™ sensor.



- The GammaCam™ system can provide information on floor and wall contamination from outside the contaminated area. This eliminates the need for extensive worker protection in obtaining these measurements. It will also reduce the radiation exposure to personnel if the floors and walls were highly radioactive.
- Training in the setup and use of the GammaCam™ is easy and can be done in a few hours. Because of some of the characteristics of the imaging system, a day of training in the use of the system is required to properly interpret the resulting images.

Contacts

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Licensing Information

No licensing or permitting activities were required to support this demonstration.

Web Site

The CP-5 LSDP Internet address is <http://www.strategic-alliance.org>.

Other

All published Innovative Technology Summary Reports are available online at <http://em-50.em.doe.gov>. The Technology Management System, also available through the EM50 Web site, provides information about OST programs, technologies, and problems. The OST Reference # for GammaCam™ is 1840.



SECTION 2

System Configuration and Operation

The GammaCam™ system provides a two-dimensional pseudo-color image of a gamma-ray radiation field superimposed on a corresponding black-and-white visual image. The GammaCam™ consists of a sensor head that contains both gamma-ray and visual imaging systems and a portable computer. The sensor head is approximately 60 lb and 19 in x 10 in x 15 in. Control of the data collection and image parameters such as field-of-view is done by the portable computer, which can be located as much as 200 ft from the sensor head. The measured images are displayed on the liquid crystal display (LCD) screen of the computer. Figure 3 shows the personal computer (PC) for controlling the system and a typical image displayed on the LCD display. Figure 4 shows an actual image from the screen and the corresponding scan information from a saved data file.



Figure 3. Image of the personal computer used to control data collection and to process data.

The sensor head can be mounted on a tripod or suspended by a sling from an overhead crane hook. The GammaCam™ uses standard 120 VAC at 60 Hz. Power consumption is approximately 250 watts. The television camera and the GammaCam™ system are air cooled. High-efficiency particle air (HEPA) filters are used on the air intake of the sensor head enclosure to minimize dust and contamination.

The visual image is acquired by a standard video camera. A framegrabber digitizes this image into a 370 (horizontal) by 260 (vertical) pixel image for display. The field-of-view of the camera is 73 degrees in the horizontal direction and 55 degrees in the vertical direction.

The gamma-ray imaging system uses a coded-aperture mask, a scintillator screen, an image intensifier, and a charged coupled detector (CCD) array to acquire an image of the radiation field. The CCD array is cooled to a temperature of approximately -40 °F to reduce noise. During a scan, the CCD integrates the light signal over a period of time varying from 10 milliseconds to 1 h. Longer collection intervals can be achieved by summing the data from a series of one hour images.



Figure 4 shows the visual and radiation images. The television image is in black and white, while the radiation field image is color coded based on intensity with red corresponding to the highest radiation and blue the lowest. The maximum and minimum signal intensities are given above and below the color key. The yellow square in the center corresponds to the GammaCam™ radiation field-of-view. After the data is collected, the radiation field at the position of the camera mask is calculated in terms of dose rate and integrated dose and displayed below the color key. The entire image is saved to disk using a PCX format. A typical file size is 200 kilo-bytes (kB).

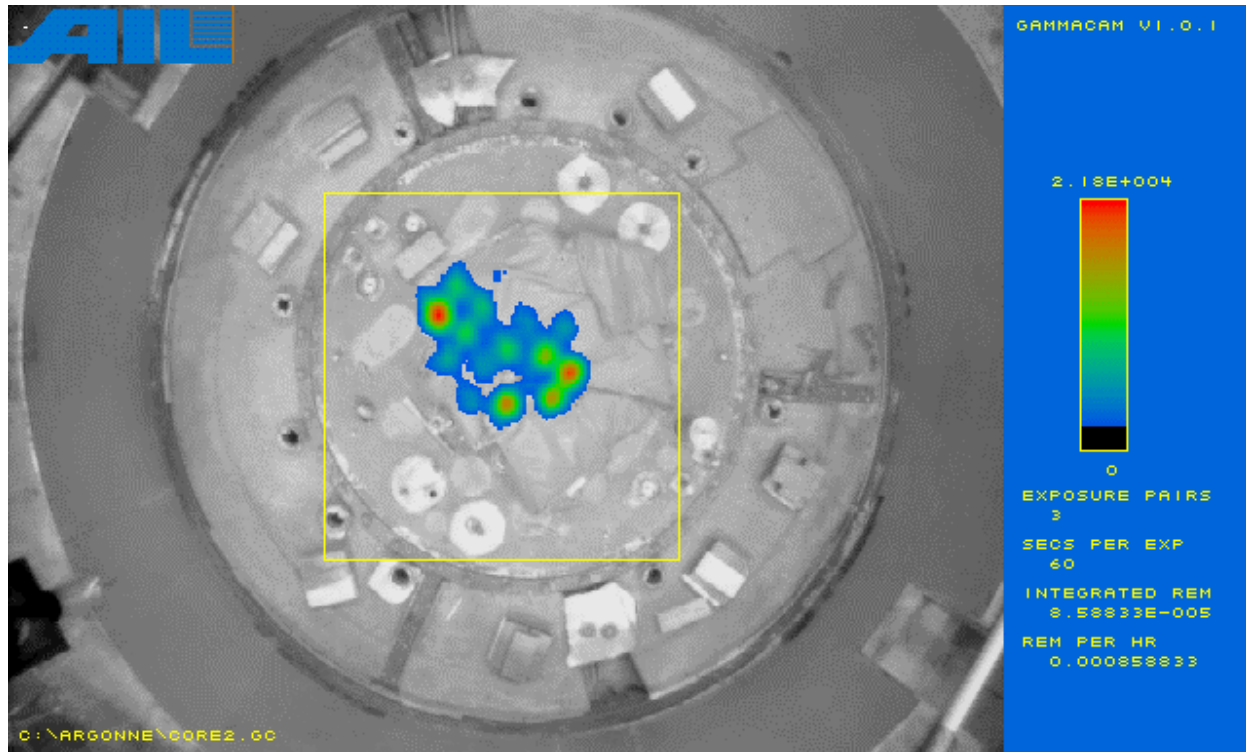


Figure 4. Display of CP-5 Reactor internals using GammaCam™ Imaging System.

The specification for the sensitivity of the system is 1 μ R integrated dose from a Cs-137 point source with a signal-to-noise ratio of 7:1. The system reports dose rate and integrated dose at the sensor head when the integrated dose exceeds 10 μ R. Visual images can be obtained at lower radiation exposures but with higher noise.

A coded aperture system distributes the radiation field over the surface of the detector system and then uses a mathematical transformation to obtain the actual spatial distribution. In this transformation, the presence of any uniform background is subtracted out of the image. Thus, large background fields that are uniformly distributed over the sensor head will have little effect on the measured gamma-ray distribution. This feature allows the GammaCam™ to image radiation fields even in the presence of large background fields. The effectiveness of the GammaCam™ in high radiation fields was not tested at CP-5, but has been demonstrated at other facilities.



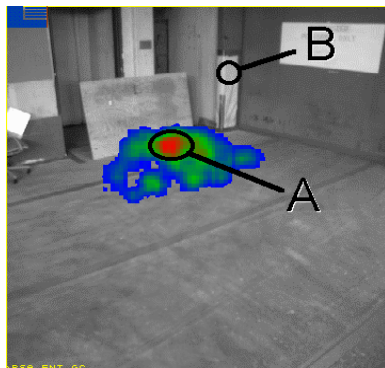
SECTION 3

Demonstration Plan

The testing of the GammaCam™ system covered three areas of interest. The first was in the use of the system to monitor and characterize large floor and wall areas. The second was concerned with using the system to characterize the position and relative intensities of radiation sources positioned within a concrete vault while minimizing worker exposure. The third was to use the device to characterize radiation areas for subsequent positioning of shielding to reduce radiation levels to workers. Over 24 images were obtained during the 3-day test. A complete set of images is available in the technical data report. The measured radiation fields were relatively low in the CP-5 demonstration. Tests of the GammaCam™ system at other locations in fields as high as 50 rad/h can be found in the references.

Setup of the device took approximately 30 min. The sensor head was mounted on a tripod or mounted to an overhead crane hook with a simple sling. During the 3-day testing period the entire system was loaded and unloaded from the crane and the tripod many times and moved between various locations within CP-5. It was also operated in several areas in which there was high electronic noise. No failure of any portion of the system occurred during the test period.

The advantage of using the GammaCam™ system to characterize floors or walls is that it can cover a large surface area in a relatively short period of time while minimizing the possibility of contamination of the sampling device or workers. Figure 5 shows the use of the GammaCam™ to characterize a floor space at the entry to the rod storage area in CP-5. The GammaCam™ was tripod mounted and positioned approximately 17 ft from the radiation area, which consisted of a cesium spill. The image in Figure 5 illustrates the system's ability to characterize large areas. The image shown was produced with an overnight exposure. The hot spot (A) corresponded to a contact field strength of 2.8 milli-Rad (mR)/h. The GammaCam™ measured 7.7 μ R/h from 16.7 ft away. All contact radiation measurements provided in this document were obtained from standard health physics instrumentation available at CP-5.



Exposure Time	16.5 h
Distance	16.7 ft
Measured Field at Source	2.8 mR/h (Contact)
Field Measured by GammaCam™	7.7 μ R/h
Field-of-View	50 degrees
Maximum Signal (Arbitrary Units)	4,280
Minimum Signal (Arbitrary Units)	1,580
Noise Level (Arbitrary Units)	527
Signal-to-Threshold Ratio	2.6 to 1

Figure 5. Image of rod storage entry area and GammaCam™ parameters of the image.

A second hot spot (B) was not seen in the image. The fixed contamination at this location had a field of 800 μ R/h (contact). Calculations indicate that this source was below detection threshold for the measured signal-to-threshold ratio. Note: Actual output is in color, not black and white as shown above.

The system's dynamic range depends upon several factors including source strength, distribution, distance, exposure time and background radiation conditions. The limited dynamic range in this image is largely a result of the length of integration time. Since the hot spot (A) identified in the image was visible on the system display after the first 10 min of exposure, an exposure of 2 to 3 h would have had a better dynamic range. Future generations of the system's software will not discard the image with the maximum signal-to-threshold ratio, but preserve it in memory in addition to the current image.



A series of images were taken of sources located in the Cave room. The Cave consists of a large room surrounded by thick concrete shielding. A shield plug in the ceiling of the Cave had been removed and the GammaCam™ was used to image the various radiation sources located within the room through the shield plug opening. The system was rigged to a crane and suspended above the shield plug opening, which is located below the rectangular steel plate shown in the image of Figure 6. This image is a good example of how the system is able to identify and locate separate sources in a situation in which a conventional radiation meter with no directional sensitivity is unable to resolve the individual sources.



Exposure Time	2 min
Distance	6 ft to cover
Measured Field at Source	200mR/h (Contact)
Field Measured by GammaCam™	10 mR/h
Field-of-View	50 degrees
Maximum Signal (Arbitrary Units)	187,000
Minimum Signal (Arbitrary Units)	11,100
Noise Level (Arbitrary Units)	3,700
Signal-to-Threshold Ratio	23.8 to 1

Figure 6. Image of two sources in Cave area.

It is possible to use the orientation of the objects in different images as the camera is moved to perform triangulation to determine how far each source is below the steel plate. In these tests this triangulation effort was complicated by the changes in the orientation of the camera relative to the floor. It was possible, however, to use a least squares technique to show that both objects were located approximately 14 ft below the steel plate. Note: Actual output is in color not black and white as shown.

Several images of the CP-5 Reactor were acquired with the sensor head suspended from the crane directly over the center of the reactor core (Figure 4). The top shielding plug of the reactor had just recently been removed and the shielding shown in Figure 4 has been placed to reduce radiation streaming from various holes in the remaining shield plug. Figure 7 shows a close-up image of the top of the core with seven well defined sources that had not been completely shielded. Figure 8 shows the result of placing a lead brick (indicated by arrow) on the most intense source in Figure 7. The discrepancy between the radiation and visual source position is due to parallax between the two imaging systems. Once the highest radiation source shown in Figure 7 had been eliminated, the remaining sources have a higher contrast. In addition, a new hot spot (indicated with a circle) is now detectable.

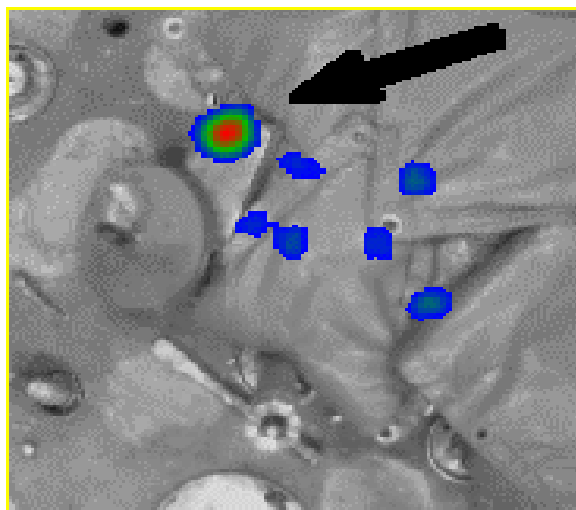


Figure 7. Radiation field before placing lead brick.

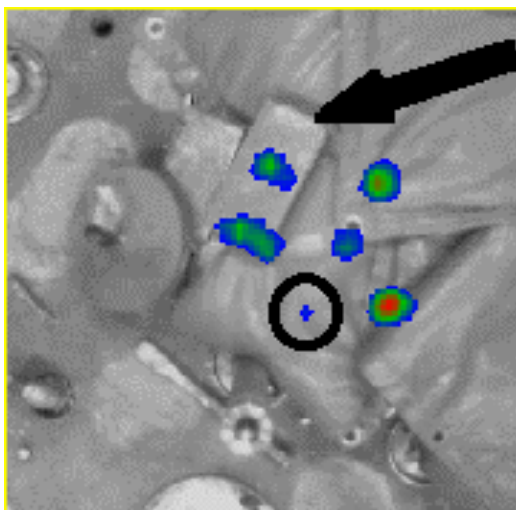
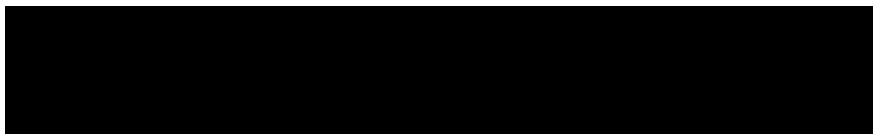


Figure 8. Radiation field after placing lead brick.



SECTION 4

**Technology Applicability**

Any site that needs to locate radiation sources would benefit from the use of the GammaCam™ system. In decommissioning a room containing glove boxes or an area containing extensive piping, a gamma camera can provide useful information on the number, location, and intensity of radiation sources. This information can be used to locate hot spots and position shielding to minimize worker exposure. Since much of this information is obtained with minimal radiation exposure to personnel, this is a useful tool in implementing As Low as Reasonably Achievable (ALARA) programs. The GammaCam™ system enables characterization of high radiation sources when manual surveys would be impossible because of personnel dose constraints.

Another useful application is in piping or processing systems to locate accumulation of radioactive materials. Similarly, the effectiveness of various techniques on removing buildup can also be monitored. A GammaCam™ is especially useful if the systems are in a high radiation area or in an area that contains contamination.

Similarly the GammaCam™ is ideal in determining the radiological conditions on floors or walls in contaminated areas. The ability to place the camera outside the contaminated area greatly reduces the technician time in donning protective clothing or in providing radiation shielding.

Competing Technologies

The baseline technology with which the GammaCam™ system competes is manual surveys by trained health physics technicians (HPTs). Manual surveys are time consuming, tedious, and directly expose the personnel to radiation. This leads to high labor costs, unreliable data, and potentially unnecessary worker exposures. The GammaCam™ system is not a directly comparable technology to manual surveys as its output is a composite video image showing relative radiation field strength rather than quantified results from specific locations.

Similar, but not identical competing technologies include:

- In Situ Gamma Spectroscopy with ISOCS (an In Situ Object Counting System) developed by Canberra Industries, Inc.;
- Integrated Characterization and Archiving System developed by Coleman Research Corporation;
- RadScan 600 developed by BNFL Instruments, Ltd.

Data comparing the performance of GammaCam™ to the competing technologies listed above is not available.



SECTION 5



Introduction

This analysis provides an estimate of cost for the GammaCam™ technology. The GammaCam™ technology provides characterization data, which is different from the conventional method of manual radiological survey, and these data are used differently in planning future D&D work. GammaCam™ identifies where a source is located as well as the radiation field strength at the sensor. Manual surveys can only indicate the radiation field strength at a specified location and do not identify source location. Consequently, direct comparison of the cost for GammaCam™ with conventional radiological survey methods has limited value. An estimate of baseline cost for conventional survey methods is provided in this analysis to give the reader a sense of the relative costs of the GammaCam™ and baseline technology. Refer to Appendix B for more information on cost comparisons.

Methodology

The GammaCam™ technology was demonstrated at ANL under controlled conditions which facilitated observation of the work procedures and typical duration of those procedures. The cost analysis is based on those scans using the GammaCam™, which appear to be representative of typical work.

The manual survey was not demonstrated concurrently. The baseline is developed from recollections of previous manual surveys under similar conditions to those of the demonstration. Labor, equipment, production rates, and productivity loss factors (PLF) were provided by site personnel at ANL or from similar work being performed elsewhere.

Since the baseline costs are not based on observed data, additional efforts are applied in setting up the baseline cost analysis to ensure unbiased and appropriate production rates and crew costs. Specifically, a team consisting of members from the Strategic Alliance (ICF Kaiser, an ANL D&D technical specialist, and a test engineer for the demonstration) and the USACE review the assumptions to ensure a fair comparison.

The selected basic activities being analyzed come from the *Hazardous, Toxic, Radioactive Waste Remedial Action Work Breakdown Structure and Data Dictionary* (HTRW RA WBS), USACE, 1996. The HTRW RA WBS, developed by an interagency group, is used in this analysis to provide consistency with the established national standards.

Some costs are omitted from this analysis to facilitate understanding and comparison with costs for the individual site. The ANL indirect expense rates for common support and materials are omitted from this analysis. Overhead and general and administrative (G&A) rates for each DOE site vary in magnitude and the way they are applied. Decision makers seeking site specific costs can apply their site's rates to this analysis without having to first retract the rates used at ANL. The impact resulting from this omission is judged to be minor because overhead is applied to both the innovative and the baseline technology costs. Engineering, quality assurance, administrative costs, and taxes on services and materials are also omitted from this analysis for the same reasons indicated for the overhead rates.

The standard labor rates established by ANL for estimating D&D work are used in this analysis for the portions of the work performed by local crafts. Costs for site owned equipment, such as trucks for transport or HPT radiological survey equipment, are based upon an hourly rate for Government ownership that is computed using Office of Management and Budget (OMB) Circular No. A-94. Quoted rates for the vendor's costs are used in this analysis for performing training of the site's personnel and include the vendor's G&A, overhead, and fee mark up costs. Additionally, the analysis uses an 8-h work day with a 5-day week. The production rates and observed duration used in the cost analysis do not include "non-productive" items such as work breaks, donning and doffing clothing, loss of dexterity [(due



to cumbersome personnel protective equipment (PPE)], and heat stress. These “non-productive” items are accounted for in the analysis by including a Productivity Loss Factor (PLF). The PLF is an historically based estimate of the fraction of the workday that the worker spends in non-productive activities.

Cost Data

The prices shown in Table 1 are based on recent quotes from the vendor. These prices will change as the vendor refines the cost for manufacturing and the market potential is better understood.

Table 1. Innovative technology acquisition costs

ACQUISITION OPTION	ITEM	COST
Equipment Purchase	GammaCam™	\$163,000 - \$ 200,000
Vendor Provided Service	Instruction	\$ 5,817
Equipment Lease	1 Month 2 Month 3 Month	\$ 30,000 \$ 25,000 /month \$ 20,000 / month

Observed unit costs and production rates for principal components of the demonstrations for both the innovative and baseline technologies are presented in Table 2.

The unit costs and production rates shown do not include mobilization, set-up, or other losses associated with non-productive portions of the work (such as suit-up, breaks, etc.). The preliminary survey, shown below, is intended to locate the “hot spots” while the detailed survey provided mapping of the source. The preliminary and detailed surveys, using GammaCam™, have different field of views and set-up distances. Consequently, the detailed survey covers a smaller area per unit of time relative to the preliminary survey.

Table 2. Summary of unit costs and production rates observed during the demonstration

INNOVATIVE TECHNOLOGY			BASELINE TECHNOLOGY		
Cost Element	Unit Cost	Production Rate	Cost Element	Unit Cost	Production Rate
Preliminary Survey	\$9.00 each	2 min each	Preliminary Survey	Not Predictable	
Detailed Survey	\$0.28/ft ²	15 ft ² /min	Detailed Survey	\$0.34/ft ²	5.6 ft ² /min

Summary of Cost Variable Conditions

The DOE complex presents a wide range of D&D work conditions because of the variety of functions and facilities. The working conditions for an individual job directly affect the manner in which D&D work is performed and, as a result, the costs for an individual job are unique. The innovative and baseline technology estimates presented in this analysis are based upon a specific set of conditions or work practices found at CP-5, and are presented in Table 3. This table is intended to help the technology user identify work differences that can result in cost differences.



Table 3. Summary of cost variable conditions

Cost Variable	GammaCam™	Manual Survey
Scope of Work		
Quantity and Type	One preliminary scan to cover 205 ft ² and two detailed scans to delineate hot spots to cover 62 ft ²	Manual survey using an Eberline RO-7 with preliminary survey of area and follow-up survey of hot spots covering 62 ft ²
Location	Vault located below the reactor floor (Cave Room) and reactor core	Assumed to be reactor core
Nature of Work	Preliminary survey performed at a distance identifies hot spots and follow-up survey provides detailed survey at close range of any identified hot spots	Preliminary survey from walkway across reactor moving extended probe around the reactor area to determine where sources are located, shielding and plans for follow-up survey are developed based on the preliminary survey, and the follow-up survey sweeps the probe over the hot spot surfaces
Work Environment		
Worker Protection	Anti-contamination coveralls with hood and respirator	Anti-contamination coveralls with hood and respirator
Level of Contamination	Classified as a contaminated area and a radiation area	Classified as a contaminated area and a radiation area
Work Performance		
Acquisition Means	Equipment leased and operation performed by site personnel (initial instruction in operation provided by vendor)	Site personnel with site owned equipment
Production Rates	Rates for preliminary surveys varied from 205 ft ² /min to 1,584 ft ² /min (cost analysis based on 205 ft ² /min) and detailed survey varied from 21 ft ² /min to 51 ft ² /min (cost analysis based on 31 ft ² /min)	Preliminary survey is not a structured procedure (no production rate) and the detailed survey uses a production rate of 5.5 ft ² /min (observed in manual surveys of the fuel storage basin, C-Reactor, Richland Operation Office)
Equipment and Crew	One HPT and one D&D worker for setup and operation	Two HPTs using one RO-7
Work Process Steps	1. Ship equipment to site 2. Transport from receiving to work location 3. Instruction for operators (one time) 4. Setup equipment and wrap with plastic 5. Preliminary survey 6. Detailed surveys 7. Data evaluation 8. Decontaminate and release 9. Transport to Shipping/Receiving 10. Shipping to New York	1. Prepare survey plans 2. Transport to work area 3. Setup 4. Conduct preliminary survey 5. Decontaminate and release 6. Return transport 7. Develop shielding and plans for follow-up survey 8. Transport to work area 9. Setup 10. Conduct detailed survey 11. Decontaminate and release 12. Return transport 13. Data Evaluation and Report
End Product	Characterization for planning work	Characterization for planning work



Potential Savings and Cost Conclusions

Innovative Technology

The costs elements for the GammaCam™ are shown in Figure 9. A significant portion of the cost is related to a one time expense for instructing the site personnel who will operate the equipment and for mobilization and demobilization of the equipment (where the equipment is leased). The costs for the GammaCam™ are sensitive to the rates charged for leasing the equipment which is related to the length of time for the lease (rates used in this analysis were based on a one month lease). The number of hot spots identified will control the number of setups and surveys and affects costs substantially. Additionally, the cost for shipment can vary, depending upon distance and location of site. The time required to ship, which can vary from 3 to 10 days, will also impact the length of time required for leasing. Another factor that can result in significant cost variation is the geometry of the area being scanned. Lower survey production rates may result from columns or objects that block the view of the scanner due to additional setups or less than optimal distances from the object. Production rates for scans at a distance of 11 ft and 50 degree field of view were 137 ft²/min while scans at distances of 6 ft and 25 degree field of view were 6.2 ft²/min. Finally, depending on the strength of the source, the production rate may vary due to time required to achieve the proper resolution.

The GammaCam™ technology may be more cost attractive for use in radiation fields higher than those measures in CP-5 demonstration. In situations where the radiation field severely limits work time and requires substantially more preparation for entry than was assumed in the baseline for this analysis, then the GammaCam™ could have substantial advantages. In some instances of extremely high radiation doses, the GammaCam™ is an enabling technology, allowing location and relative quantification of source term strength in areas where the baseline technology (manual surveys) is not an option.

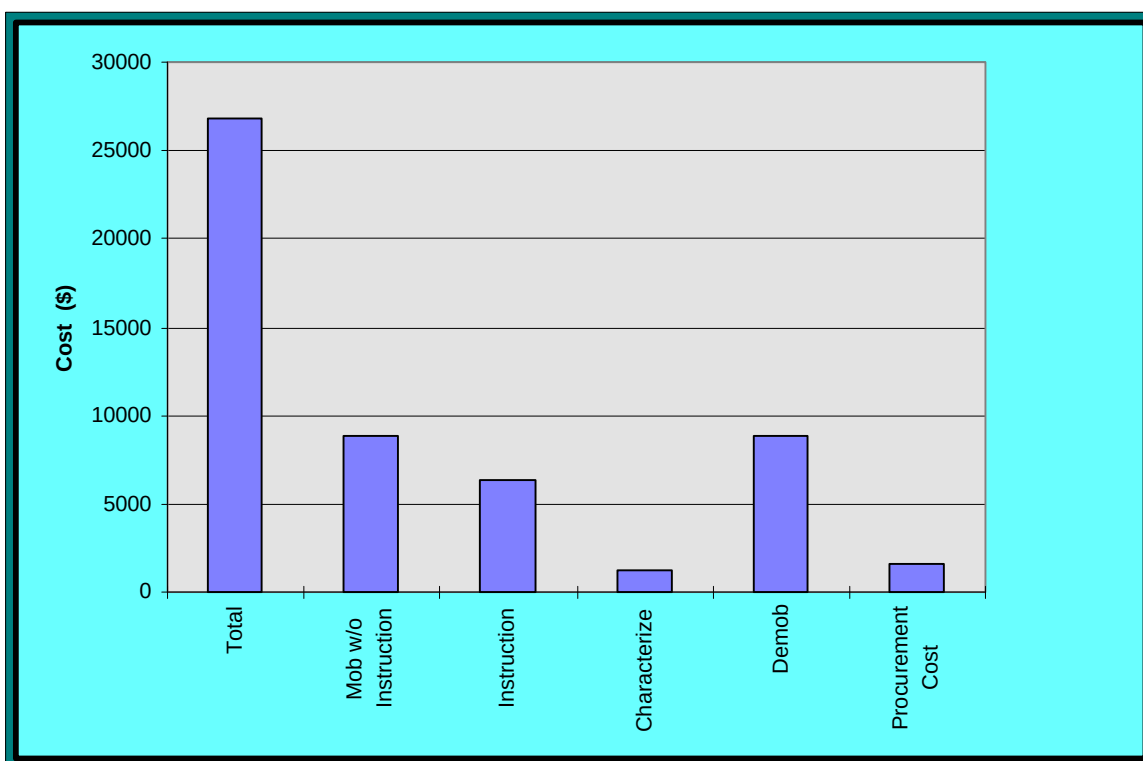


Figure 9. GammaCam™ cost.



Baseline

The costs for the baseline approach are shown in Figure 10. These costs are based on surveys being performed in areas of relatively low personnel exposure where few limitations of worker stay times need to be imposed. The costs for performing work in more severe radiation fields will be substantially greater than the cost shown in this analysis.

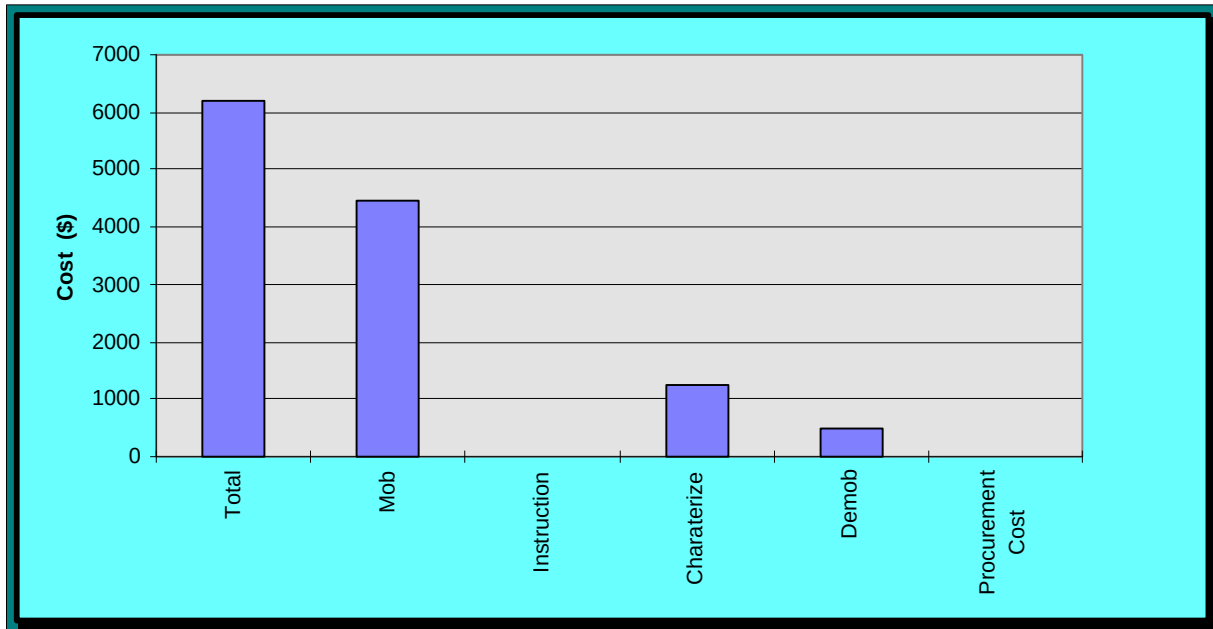


Figure 10. Baseline cost.

Comparison

The innovative cost is compared with the baseline cost as a function of the size of the job in Figure 11. Two situations are analyzed: 1) typical (set-ups for 200 ft² is 3 and 15 for 1,000 ft²; and 2) obscured where columns and equipment require more set-ups (assume 10 at 200 ft² and 100 for 1,000 ft²). The baseline method is not sensitive to this parameter and is shown as a single line.

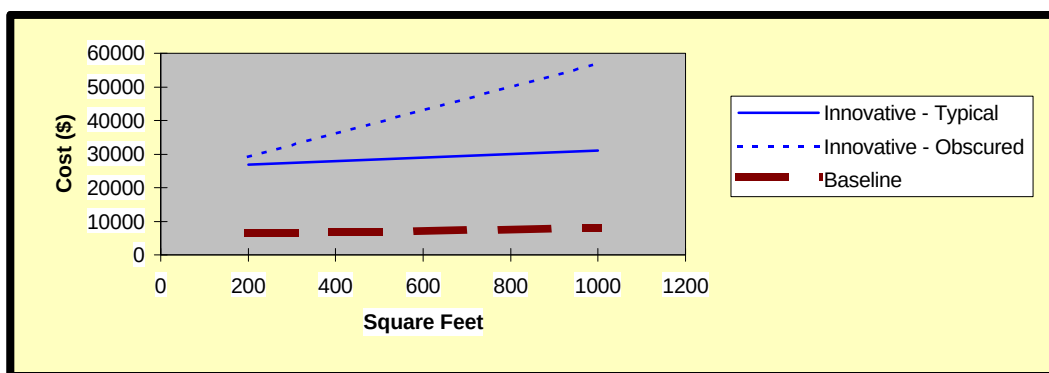


Figure 11. Comparison of innovative and baseline.



SECTION 6

Regulatory Considerations

The regulatory/permitting issues related to use of the GammaCam™ technology at the ANL CP-5 Research Reactor consist of the following safety and health regulations:

- Occupational Safety and Health Administration (OSHA) 29 *Code of Federal Regulations* (CFR) 1926
 - 1926.300 to 1926.307 Tools - Hand and Power
 - 1926.400 to 1926.449 Electrical - Definitions
 - 1926.28 Personal Protective Equipment
 - 1926.52 Occupational Noise Exposure
 - 1926.102 Eye and Face Protection
 - 1926.103 Respiratory Protection
- OSHA 29 CFR 1910
 - 1910.101 to 1910.120 (App E) Hazardous Materials
 - 1910.211 to 1910.219 Machinery and Machine Guarding
 - 1910.241 to 1910.244 Hand and Portable Powered Tools and Other Hand-Held Equipment
 - 1910.301 to 1910.399 Electrical - Definitions
 - 1910.95 Occupational Noise Exposure
 - 1910.132 General Requirements (Personal Protective Equipment)
 - 1910.133 Eye and Face Protection
 - 1910.134 Respiratory Protection
 - 1910.147 The Control of Hazardous Energy (Lockout/Tagout)
- 10 CFR 835 Occupational Radiation Protection

Since GammaCam™ is designed for use when decontaminating structures, there is no regulatory requirement to apply CERCLA's nine evaluation criteria. However, some evaluation criteria required by CERCLA, such as protection of human health and community acceptance, are briefly discussed below. Other criteria, such as cost and effectiveness, were discussed earlier in this document.

Safety, Risks, Benefits, and Community Reaction

The safety issues with the GammaCam™ system are limited to those routinely encountered in an industrial environment.

Reduction in personnel radiation exposures should also be realized by reducing the amount of time personnel are required to collect data in a radiological area.

A benefit of GammaCam™ is that superimposed radiation and visual images can provide the public with an improved understanding and confidence in the measured data.



SECTION 7

Implementation Considerations

The GammaCam™ system demonstrated at CP-5 is a commercially available instrument. During the tests, the sensor head and data processing unit were moved many times within the facility and no problems were encountered. The distance between the sensor head and the control computer is limited to 200 ft. As configured, the system requires 120 VAC power, which may be a problem in remote areas or in facilities where the power has been disconnected. A key advantage of the system is that it provides images even if the sensor head is located in a high background radiation field. The primary weaknesses of the system are that GammaCam™ cannot directly measure a uniform radiation field and there is a need to watch for image artifacts under certain conditions.

As compared to the baseline of manual surveys, use of the GammaCam™ system may:

- increase the speed at which HPTs can survey radiation fields;
- result in lower exposures to personnel performing surveys, particularly in high radiation areas;
- provide better characterization information on the position and relative strength of gamma radiation sources; and
- aid public acceptance that remediation efforts were complete and successful.

Technology Limitations and Needs for Future Development

There are several limitations associated with the use of coded aperture system that need to be considered in planning a radiation survey. The first is that a radiation field with a uniform intensity will not be detected. This problem can be overcome by making sure that the field-of-view includes a non-uniform region. The second is that the system can introduce image artifacts for objects near the edge of the field-of-view. For example, a source located on the left side of the image can produce an image where there is an artifact image on the right side. The size and position of the artifacts are well known and the impact of the artifact can be minimized by operator training. The coded aperture system also has some limitations in terms of the maximum-to-minimum signal that can be detected across the field-of-view in the presence of noise. This is a result of each signal being distributed across the scintillator screen. The transforming of the measured detector spatial distribution into an actual radiation-field distribution requires separating these various components from each other and this can lead to limitations on the ratio of the maximum-to-minimum signal detected. Typical values for the maximum-to-minimum signal ratio varied from 2.6 to 30 in these tests with a mean value of 14.

The GammaCam™ system technology would benefit from the following design improvements:

- Indication on the final image of the parallax between the radiation and visual field-of-view.
- Implementation of a range meter to provide the distance between the sensor head and the radiation source to allow more reliable estimates of the actual source strength.



Technology Selection Considerations

Any large nuclear site can use this technology. The GammaCam™ system is used to provide visual information on the location and relative strengths of radioactive sources. It will reduce radiation exposures since this information can be obtained with minimum radiation dose to the technician. This information can also be obtained without construction of elaborate shielding and will therefore reduce costs in situations that would normally require substantial preparation before entry. The system is also well suited to monitor a radiation field over time. One application is to use the system to monitor the radiation changes within a piping system during the decontamination process. The system has some minor limitations in regards to imaging uniform fields and artifacts, but these can be minimized by operator training.



APPENDIX A



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APPENDIX B

TECHNOLOGY COST COMPARISON

This appendix contains definitions of cost elements, descriptions of assumptions, and computations of unit costs that are used in the cost analysis.

Innovative Technology - GammaCam™**Mobilization (mob) (WBS 331.01)****Ship Equipment**

Definition: Transport GammaCam™ equipment from Deer Park, New York to Shipping/Receiving at Argonne National Laboratory. This cost element includes the added time required for lease of the equipment due to time spent in shipment.

Assumptions: Based on quoted rates from United Van Lines of \$307.90 one way plus \$411 for insurance (covers both ways) and 7 to 10 days for shipping ($\$307.90 + \$411/2 = \$513.40$). Additional costs include equipment stand-by time for 7 days. For a one month lease (\$30,000 per month/22 days per month/8 hours per day = \$170.45/h). The lease rate for 3 months is \$20,000 per month and for 2 months is \$25,000 per month.

Unload and Transport

Definition: Transport GammaCam™ equipment from receiving area to CP-5. This cost element includes the added time required for lease of the equipment due to time spent in transport.

Assumptions: Assumed to include one heavy truck and driver for 2 h. Rate for truck driver based on rental rate from Means (1996 Means) of \$19/h. Standby for GammaCam equipment is included.

Unpack, Survey, and Prepare

Definition: Equipment is unpacked, surveyed for radiological contamination, and prepared for use (includes wrapping cables and body with plastic to minimize potential contamination).

Assumptions: Assumed duration of 4 h and crew make up based on judgment of the test engineer. Crew consists of one HPT and one D&D worker ($\$56/h + \$33.60/h = \$89.60/h$) for 4 h.

Instruction for Site Crew

Definition: Instruction to ensure proper use and interpretation of characterization results. This is an estimated activity and was not observed during the demonstration.

Assumptions: It assumes that the vendor provides one operator to perform on-the-job training during the first day of operation of the equipment. Cost is based on quote from vendor for \$5,817. It is assumed that the instruction is conducted concurrent with performing work. Consequently, there are no allowances for the ANL crew in the instruction time.



Characterization (WBS 331.17)

Set Up and Move for Next Survey

Definition: Time required for setting up, allowing equipment to reach operating temperature, and moving from one survey location to the next.

Assumptions: The duration is assumed to be 1/2 h (15 min required for reaching operation temperature). Crew is assumed (based on judgment of the test engineer for what would be normal practice for work) to consist of one HPT and one D&D worker.

Preliminary Survey

Definition: A survey of a large area at low resolution for the purpose of identifying "hot spot" locations.

Assumptions: A preliminary type of survey was assumed to use a 50 degree field of view. The scan for Cave 4 was used to represent this type of preliminary survey. Wall area scanned was 205 ft². Crews were assumed (based on the judgment of the test engineer for what would be normal practice for D&D work) to consist of one D&D worker and one HPT.

Detailed Survey

Definition: After the preliminary survey has identified the hot spot locations, the GammaCam™ equipment is moved to a closer proximity to the hot spot for detailed survey.

Assumptions: The surveys for Cave 5 and Core 4 were used for detailed scans. Even though these surveys did not necessarily cover the same area as the preliminary scan, they were assumed to be representative of detailed type of scans because they had a 25 degree field of view and had adequate resolution. The analysis uses the total of the duration for each of these scans and the total of the area covered by each of these scans in the analysis. Consequently, the unit cost for the detailed scan is based on an average 4 min/62.6 ft². Crews were assumed (based on the judgment of the test engineer for what would be normal practice for work) to consist of one D&D worker and one HPT.

Evaluate Data and Produce Final Report

Definition: This activity includes review of the data and summarizing into a final report.

Assumptions: The duration and crew for this activity are assumed to be 1 h for one HPT.

PPE

Definition: This cost element provides for the personal protective clothing used during the work activity.

Equipment	Quantity in Box	Cost Per Box	Cost Each	No. of Reuses	Cost Each Time Used	No. Used Per Day	Cost Per Day
Respirator			1,933	200	10	1	10.00
Resp. Cartridges			9.25	1	9.25	2	18.50
Booties	200	50.00	0.25	1	0.25	4	1.00
Tyvek	25	85.00	3.4	1	3.4	4	13.60
Gloves (inner)	12	2.00	0.17	1	0.17	8	1.36
Gloves (outer)			7.45	10	0.75	1	0.75
Glove (cotton liner)	100	14.15	0.14	1	0.14	8	1.12
Total							46.33

The PPE costs are predominantly from the ANL activity cost estimate (ACE) sheets for 1996. (Costs for outer gloves, glove liners, and respirator cartridges are from commercial catalogs.)



Daily Meeting

Definition: This cost element provides for safety meeting and project planning meetings during the work.

Assumptions: The estimate assumes one 15 min safety meeting per day (based on typical practice at ANL).

Productivity Loss Factor

Definition: Losses from productive work occurring during the course of the work due to PPE changes, ALARA, height of reach inefficiencies, etc.

Assumption: The duration used for the preliminary survey and the detailed survey do not account for work breaks or PPE changes, and were not observed and recorded during the demonstration. Consequently, these types of costs are estimated and added to the cost for the innovative technology in this cost element. The duration of work performed in the controlled area (activities outside the controlled area, such as evaluation of the data, are not included in the computation) is adjusted by a factor of 1.27 to account for these losses (particularly work breaks and suiting up) based on the factors shown below (AIF, 1986):

Base	1.00
+Height	0
+Rad/ALARA	0 (not considered since most work is waiting)
+Protective Clothing	0.15
= Subtotal	1.15
X	
Resp Prot	1.00 (no factor used, losses included in observed times)
=Subtotal	1.15
X	
Breaks	1.10
=Total	1.27

Demobilization (WBS 331.21)**Survey Equipment and Decontaminate**

Definition: GammaCam™ equipment is surveyed for contamination and decontamination is performed as needed for free release.

Assumption: The assumed duration of 4 h was used for a crew of one HPT.

Load and Transport Equipment

Definition: Same as Mobilization - Unload and Transport

Shipping

Definition: Same as Mobilization - Shipping



Procurement Costs

Definition: This cost element accounts for the 9.3 percent costs charged to the project for award of the GammaCam™ equipment lease and administration of that procurement.

Costs for demonstration of the GammaCam™ innovative technology are based on assuming a preliminary survey (using Cave 4) followed by more detailed surveys of hot spots identified by the preliminary survey (Cave 5 and Core 4). This scenario is intended to represent the cost for normal D&D work using the GammaCam™ (normal being defined by the vendor experience and judgment of the test engineer) and does not follow the sequence of events of the demonstration. Other adjustments of the observed data from the demonstration are shown below:

- Work will be performed assuming the equipment is leased and operated by site workers (rather than purchase of equipment or vendor provided service) because of the relatively large capital expense, the limited number of opportunities to use the equipment, cost for mobilizing vendor personnel and the relative ease of learning to operate the equipment.
- GammaCam™ equipment hourly rates were based on vendor quotes (based on one month lease).
- During the demonstration, the vendor personnel as well as the HPT and D&D personnel were present throughout the demonstration and this is assumed to not represent normal work (assume one HPT and one D&D worker).

The activities, quantities, production rates and costs observed during the demonstration are shown in Table B-1, Cost Summary: Innovative Technology-GammaCam™.



TABLE B-1 Cost Summary: Innovative Technology-GammaCam™

Work Breakdown Structure (WBS)	Unit Cost (UC)					Total Quantity (TQ)	Unit of Measure	Total Cost (TC) note	Comments	
	<u>Labor</u> HRS Rate		<u>Equipment</u> HRS Rate		Other					Total UC
MOBILIZATION 331.01								Subtotal	\$15,208	
Ship Equipment	0.00	\$ -	40.00	\$170.45	\$ 513	\$7,331	1	Each	\$ 7,331	Shipping from Deer Park, NY to Argonne National Laboratory (ANL) (equipment lease period extended by shipping time of one week) lease rate is \$170.45/h
Unload & Transport	2.00	\$49.67	2.00	\$189.45		\$ 478	1	Each	\$ 478	Teamster and Truck to transport equipment from receiving to CP-5 plus standby for GammaCam equipment
Unpack, Survey & Prepare	4.00	\$89.60	4.00	\$170.45		\$1,040	1	Each	\$ 1,040	One Health Physics Technician (HPT) @ \$56/h and one D&D worker at \$33.60/hr (includes wrapping instrument with plastic sheeting, instrument check out and initialization)
Instruction for Site Crew					\$6,358	\$6,358	1	Each	\$ 6,358	One time cost for vendor to travel to site, participate in site required training, provide on the job training to site crew, and return home (includes 9.3% additional cost for ANL procurement)
CHARACTERIZATION 331.17								Subtotal	\$ 1,223	
Set-Up & Move	0.50	\$89.60	0.50	\$170.45		\$ 130	3	Location	\$ 390	Initial setup, move equipment to next survey location, and prepare for next survey (preliminary and 2 detailed survey) 1/2 h includes required time for equipment to reach operating temperature crew is 1 HPT and 1 D&D
Preliminary Survey	0.0002	\$89.60	0.0002	\$170.45		\$ 0	205	Square Feet	\$ 9	Identify location of hot spots from a distance of 6 ft with 50 degree field of view (205 ft ² surveyed in 2 minutes), crew includes one HPT and one D&D worker



TABLE B-1 Cost Summary: Innovative Technology-GammaCam™ (cont.)

Work Breakdown Structure (WBS)	Unit Cost (UC)					Total Quantity (TQ)	Unit of Measure	Total Cost (TC) note	Comments	
	<u>Labor</u>		<u>Equipment</u>		Other					Total UC
	HRS	Rate	HRS	Rate						
Detailed Survey	0.0011	\$89.60	0.0011	\$170.45		\$ 0	62.6	Square Feet	\$ 17	Detailed survey of two hot spots, distance of 6 ft with field of view of 25 degrees (2 scans of 31.3 ft² each and 2 minutes each survey), crew includes one HPT and one D&D worker
Evaluate Data & Final Report	1.00	\$56.00				\$ 56	1	Each	\$ 56	One HPT
PPE					\$ 46	\$ 46	2	Man Day	\$ 93	Assumed cost per person per day of \$46.33
Daily Meeting	0.50	\$89.60	0.50	\$170.45		\$ 130	1	Each	\$ 130	One safety meeting each morning prior to beginning work
Productivity Loss Factor	2.03	\$89.60	2.03	\$170.45		\$ 528	1	Each	\$ 528	Duration in controlled area X 1.27%
DEMILITIZATION 331.21	Subtotal								\$ 8,821	
Survey Equip & Decon	4.00	\$56.00	4.00	\$170.45	\$ 106	\$1,011	1	Each	\$ 1,011	Survey equipment for free release and remove protective plastic wrap, other costs include waste disposal of 2 ft³ of low level waste @ 52.78/ ft³
Load & Transport Equipment	2.00	\$49.67	2.00	\$189.45		\$ 478	1	Each	\$ 478	Teamster and Truck to transport equipment to shipping/receiving
Shipping	0.00	\$ -	40.00	\$170.45	\$ 513	\$7,331	1	Each	\$ 7,331	Return to Deer Park, NY
PROCUREMENT COST									\$ 1,601	
Procurement Cost					\$1,601	\$1,601	1	Each	\$ 1,601	Cost for procurement of equipment of 9.3% of amount of procurement (standard rate for ANL contracting)

Note: TC = UC * TQ

TOTAL: \$26,853


Baseline Technology — Mechanical Scabbling of Concrete and Disposal**Mobilization (WBS 331.01)**

Preliminary Survey Plans

Definition: This cost element is for planning the initial manual survey and developing the necessary documentation that is needed to allow that work to begin.

Assumption: The effort is assumed to be 4 h for 1 HPT @ \$56.00/h.

Transport Personnel and Equipment

Definition: The on-site transport to the CP-5 is provided in this cost element.

Assumption: The effort is assumed to be 1 h for a crew of two HPT's. This work will be performed twice, once for the preliminary survey and once for the detailed survey.

Source Check Instrument

Definition: Response check for Eberline RO-7.

Assumptions: The effort is assumed to be 10 min. This work will be performed twice, once for the preliminary survey and once for the detailed survey.

Detailed Survey Plans

Definition: This cost element is for planning the follow-up survey, which will provide detailed surveys of the hot spots identified in the initial survey and provide the necessary documentation needed for that work to begin.

Assumption: The effort is assumed to be 8 h for one HPT.

Shielding Preparation

Definition: This cost element provides for collecting the shielding for the detailed surveys and getting it in place.

Assumptions: The effort is assumed to be 2 days for a crew of two HPTs. Costs for the shielding is assumed to be \$ 1,739 for twenty 12 inch X 72 inch lead wool blankets (based on historic costs from previous D&D projects at ANL).

Characterization (WBS 331.17)

Set-Up and Move

Definition: Time required for setting up in one location, initializing the GammaCam equipment, waiting for the operating temperature to stabilize, and moving from one survey area to the next.

Assumptions: The duration is ½ h per location (one preliminary and two detailed) and the crew is assumed (based on the judgment of the test engineer) to be one D&D worker and one HPT.



Preliminary Survey

Definition: RO-7 probe is attached to a long rod (provides distance between HPT and the source) which is moved around within the volume of the area being surveyed. Areas having strong sources are identified for follow-up survey. Readings are noted as the probe is moved.

Assumptions: Total duration of survey is assumed to be 15 min. The crew is assumed to be two HPT's.

Detailed Survey

Definition: Detailed survey of previously identified hot spots using the RO-7 with extended probe. The probe is swept over the surface and readings are manually recorded.

Assumptions: The production rate used is 5.5 ft²/min based on observed duration of similar work (with the RO-7) in the fuel storage basin at the C-Reactor, Richland Operations Office. Crew is assumed to be two HPT's.

Daily Meeting

Definition: This cost element provides for safety meeting and project planning meetings during the work.

Assumptions: The estimate assumes one 15 min safety meeting per day (based on typical practice at ANL). This work will be performed twice, once for the preliminary survey and once for the detailed survey.

PPE

Definition: This cost element provides for the personal protective clothing used during the work activity.

Equipment	Quantity in Box	Cost Per Box	Cost Each	No. of Reuses	Cost Each Time Used	No. Used Per Day	Cost Per Day
Respirator			1,933	200	10	1	10.00
Resp. Cartridges			9.25	1	9.25	2	18.50
Booties	200	50.00	0.25	1	0.25	4	1.00
Tyvek	25	85.00	3.4	1	3.4	4	13.60
Gloves (inner)	12	2.00	0.17	1	0.17	8	1.36
Gloves (outer pair)			7.45	10	0.75	1	0.75
Glove (cotton Liner)	100	14.15	0.14	1	0.14	8	1.12
Total							46.33

The PPE costs are predominantly from the ANL activity cost estimates for 1996 (costs for outer gloves, glove liners, and respirator cartridges are from commercial catalogs).



Productivity Loss Factor

Definition: Losses from productive work occurring during the course of the work due to PPE changes, ALARA, height of reach inefficiencies, etc.

Assumption: The duration used for the preliminary survey and the detailed survey do not account for work breaks or PPE changes, and were not observed and recorded during the demonstration. Consequently, these types of costs are estimated and added to the baseline cost in this cost element. The duration of work performed in the controlled area (activities outside the controlled area, such as evaluation of the data, are not included in the computation) is adjusted by a factor of 1.27 to account for these losses (particularly work breaks and suiting up) based on the factors shown below (AIF, 1986):

Base	1.00
+Height	0
+Rad/ALARA	0 (not considered, most work is waiting)
+Protective Clothing	0.15
= Subtotal	1.15
X	
Resp Prot	1.00 (no factor used, losses observed)
=Subtotal	1.15
X	
Breaks	1.10
=Total	1.27

Data Evaluation and Report

Definition: This cost element provides for review of the survey results and development of survey reports (including maps of the maximum readings).

Assumptions: The effort for this is assumed to require 10 hours.

Demobilization (WBS 331.21)**Decontaminate and Survey Out**

Definition: Equipment and personnel are surveyed for contamination and decontamination is performed as needed for free release.

Assumption: The duration of 1 h is assumed for two HPT's. This work will be performed twice, once for the preliminary survey and once for the detailed survey.

Transport for Return

Definition: Same as Mobilization - Unload and Transport

Assumption: This work will be performed twice, once for the preliminary survey and once for the detailed survey.

- The manual survey of the reactor core area is assumed to consist of a preliminary survey from the walk way crossing the reactor top where the location of potential hot spots are identified. This is followed with planning for the follow up survey of the hot spots and development of shielding to protect the HPTs during the detailed survey. The survey work is performed using an RO-7 with extended probe.



- The hourly rates for government owned equipment are based on amortizing the initial purchase price, including its shipping costs, over the service life of the equipment using a discount rate prescribed in the OMB circular No. A-94 of 5.8%. Service life of 5 to 15 yrs (depending on the individual piece of equipment) is used with an assumed use of 500 hours per year.
- The radiological data collected will not be used for compliance with closure requirements, but will be used in planning D&D work.

The activities, quantities, production rates and costs utilized in the baseline are shown in Table B-2.



TABLE B-2 Cost Summary: Baseline Technology - Manual Survey

Work Breakdown Structure (WBS)	Unit Cost (UC)				Total Quantity (TQ)	Unit of Measure	Total Cost (TC) note	Comments
	Labor Hour	Labor Rate	Equipment Hour	Equipment Rate	Other	Total UC		
Mobilization (WBS 331.01)	Subtotal						\$ 4,467	
Preliminary Survey Plans	4	\$ 56.00	0	\$ -	\$ -	\$ 224.00	1 Each	\$ 224 Labor for one health physics technician (HPT) @ \$56/h standard rate for Argonne National Laboratory (ANL)
Transport to Work Area	1	\$112.00	1	\$ 1.25		\$ 113.25	2 Each	\$ 227 Two trips (for preliminary survey and again for detailed survey) crew of two HPTs plus one Eberline RO-7
Source Check Instrument	0.1666	\$112.00	0.1666	\$ 1.25		\$ 18.87	2 Each	\$ 38 Two trips (preliminary and detailed surveys)
Detailed Survey Plans	8	\$ 56.00	0			\$ 448.00	1 Each	\$ 448 One HPT
Shielding Preparation	16	\$112.00			\$1,739	\$ 3,531.00	1 Each	\$ 3,531 Two HPTs and 20 lead blankets at \$87 each.
Characterization (WBS 331.17)	Subtotal						\$ 1,268	
Setup and Move	0.5	\$112.00	0.5	\$ 1.25		\$ 56.63	3 Each	\$ 170 Crew of two HPTs and an Eberline RO-7 includes setup in survey area for preliminary survey and detailed surveys
Preliminary Survey	0.25	\$112.00	0.25	\$ 1.25		\$ 28.31	1 Each	\$ 28 Crew of two HPTs quickly determine which areas are hot and which are not
Detailed Survey	0.003	\$112.00	0.003	\$ 1.25		\$ 0.34	62.6 Square Feet	\$ 21 Crew of two HPTs survey identified hot areas, based on a production rate of 5.5 ft ² /min
Daily Meeting	0.25	\$112.00	0.25	\$ 1.25	0	\$ 28.31	2 Each	\$ 57 Typical daily meeting for D&D work at ANL is 15 min (for 2 events, preliminary and detailed surveys)
Personal Protection Equip	0	\$ -	0	\$ -	\$ 46	\$ 46.33	4 Man Day	\$ 185 Assumed cost per person per day of \$46.33 (for 2 events, preliminary and detailed surveys)
Productivity Loss Factor	2.4634	\$ 98.90	2.4634	\$ 1.25		\$ 247	1 Each	\$ 247 Productivity Loss Factor (adjusts for changes, breaks, respiratory protection, and ALARA and extends the work duration by 127%)
Data Evaluation and Report	10	\$ 56.00				\$ 560.00	1 Each	\$ 560



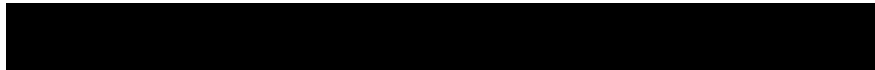
TABLE B-2 Cost Summary: Baseline Technology - Manual Survey (cont.)

Work Breakdown Structure (WBS)	Unit Cost (UC)					Total Quantity (TQ)	Unit of Measure	Total Cost (TC) note	Comments	
	Labor Hour	Rate	Equipment Hour	Rate	Other					Total UC
Dernobilization (WBS 331.21) Subtotal								\$ 479		
Decon and Survey Out.	1.00	\$112.00	1	\$ 1.25	\$ 13	\$ 126.45	2	Each	\$ 253	HPT labor and ¼ ft³ of Low Level waste disposal for swipes @ \$52.78/ft³ (for 2 events, preliminary and detailed surveys)
Transport for Return	1	\$112.00	1	\$ 1.25	\$ -	\$ 113.25	2	Each	\$ 227	Same as Mobilization cost element
Note: TC = UC * TQ								TOTAL	\$ 6,215	

Note: TC = UC * TQ



APPENDIX C



ACE	Activity Cost Estimate
ALARA	As Low As Reasonably Achievable
ANL	Argonne National Laboratory
CCD	Charged Coupled Detector
CFR	Code of Federal Regulations
CP-5	Chicago Pile-5 Research Reactor
Cs ¹³⁷	Cesium - 137
D&D	decontamination and decommissioning
DDFA	Deactivation and Decommissioning Focus Area
DOE	Department Of Energy
ESH	Environment, Safety and Health
FCCM	Facilities Capital Cost Of Money
FETC	Federal Energy Technology Center
ft	foot (feet)
ft ²	square feet
G&A	General and Administrative
HEPA	High Efficiency Particulate-Air
H&S	Health And Safety
HP	health physics
HPT	Health Physics Technician
h	hour (s)
HTRW	hazardous, toxic, radioactive waste
Hz	Hertz
kB	kilo-bytes
ICT	Integrating Contractors Team
LCD	Liquid Crystal Display
lin ft	linear feet (foot)
LLW	low-level waste
LS	lump sum
LSDP	Large-Scale Demonstration Project
MeV	Mega-electron Volts
min	minute (s)
μR	micro-Rad
mR	milliRad
NESP	National Environmental Studies Project
OMB	Office of Management and Budget
OSHA	Occupational Health and Safety Administration
PC	personal computer
PLF	productivity loss factor
PPE	personnel protective equipment
RA	Remedial Action
USACE	United States Army Corps of Engineers
VAC	Volts - Alternating Current
WBS	Work Breakdown Structure



GammaCam Portable Gamma Ray Imaging System

The **GammaCam** is a portable gamma ray imaging system that revolutionizes the assessment of radiological environments by providing accurate two-dimensional spatial mappings of gamma ray emitting nuclides in real time. Remote operation and control allows safe image acquisition in high radiation environments, minimizing operator exposure.

FEATURES

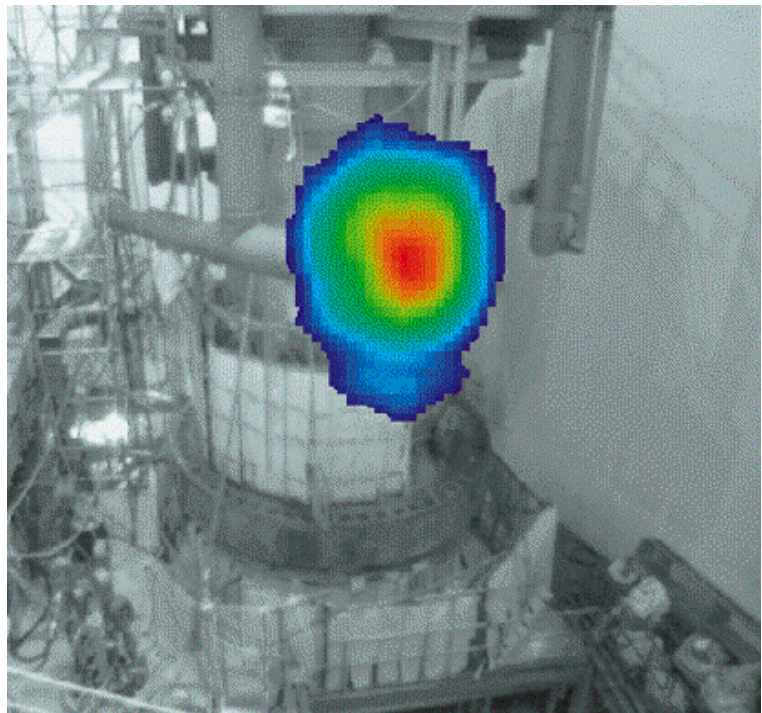
- Portability
- Easy Setup
- High Spatial Resolution
- High Sensitivity
- User Friendly

APPLICATIONS

- Nuclear Power
- Homeland Security
- Decontamination and Decommissioning (Site Clean up)
- Nuclear Navy
- Safe Guards

GammaCam is comprised of a sensor head and a portable PC compatible computer. Data analysis, data storage, and all aspects of sensor operation are controlled from the computer. The unique system architecture uses proven technology to provide high sensitivity and high spatial resolution in a compact package. Its small footprint and light weight allows for easy setup and portability which are essential for efficient cost effective usage in a wide range of applications. In addition, the **GammaCam** is capable of operating in high background fields without requiring the use of heavy and bulky shielding.

Consistent with ALARA principles, a user's exposure to radiation fields



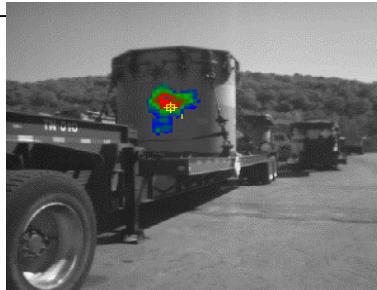
Actual GammaCam Image Showing Unsuspected Leakage

are minimized because of the sensor's ability to operate at large stand-off distances, typically 10 to 30 feet (or more) from the area being imaged. In addition, the portable computer can be positioned up to 100 feet from the sensor head.

APPLICATION CONCEPTS

Nuclear Power

- Critical Path Survey Management
- Safe, Remote Surveys of Large Areas
- Evaluation of Shielding Requirements and Implementation
- Monitoring of Dynamic Radiological Conditions
- Cost Effective Sorting of Radioactive Waste

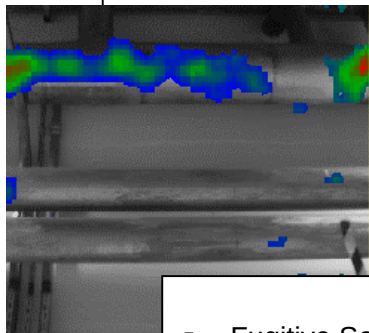
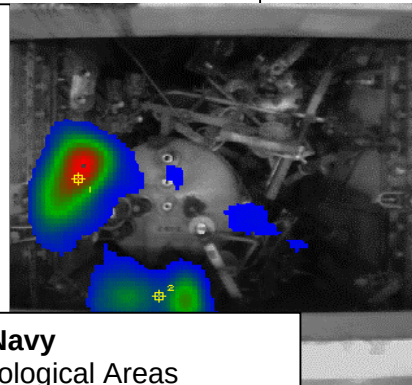


Homeland Security

- Emergency Responders
- Port of Call/Border Protection
- Characterize Suspect Vehicles, containers

Decontamination and Decommissioning (Site Clean-up)

- High Radiation Environments
- Source Term Determination In Curies
- Survey Hard to Access areas
- Evaluate Effectiveness of Decontamination Activity

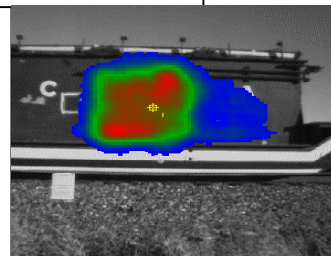


Nuclear Navy

- Safe Evaluation of Radiological Areas
- ALARA tool to reduce personnel exposure
- Clarify Complex Radiological conditions

Safe Guards

- Fugitive Sources Located
- Validates DOT guidelines
- Characterize "Mystery" Sources



ADVANTAGES OF REMOTE IMAGING

Time, distance and shielding are the principals of the ALARA (As Low As Reasonably Achievable) philosophy. The GammaCam gamma ray imaging system reduces the collective exposure of personnel in a cost effective manner by using the ideals of ALARA. The primary benefit of the GammaCam system is its ability to remotely image gamma radiation at typical distances of 10 to 30 feet (or more). Using the system as a general ALARA tool, a health physicist (HP) can rapidly perform a preliminary characterization of an area and identify the precise location of the strongest sources while minimizing exposure. Job control surveys are optimized when the HP uses the system generated radiation images to design the survey approach. The detailed spatial map would indicate specific areas to concentrate the survey effort thereby increasing the survey utility. Job planning for work crews can be more effective if the Radiation Work Permit (RWP) included an image of the radiological conditions together with the survey of the area. Consistency and quality of radiological surveys would improve.

Imaging radiological environments simplifies the task of characterizing large areas, reducing both time and exposure. Unlike point sensors like Geiger counters and ion chambers which quantify radiation intensity at the single location of the sensor, an imaging device measures the radiation intensity of a two dimensional scene. Large areas can be imaged efficiently with the GammaCam. For instance, using the systems 50° wide field of view (FOV) mode at a distance of 30 feet, the system images a square area 28 feet on a side, or approximately 780 square feet.

The imaging approach increases the distance between the user and the radiation source significantly reducing dose. Additional dose savings are achieved with the remote control features of the PC compatible processor which provides complete sensor control at distances of 100 feet (200 feet available) from the sensor head.

PLAYING IT SAFE

Remote imaging allows investigations into hazardous areas such as glove boxes, storage drums or storage compartments, where unknown radiological conditions coupled with significant airborne and surface contamination may be present. In these applications, the GammaCam can accurately localize an inaccessible source quickly without having to put personnel or the sensor in a hazardous area.

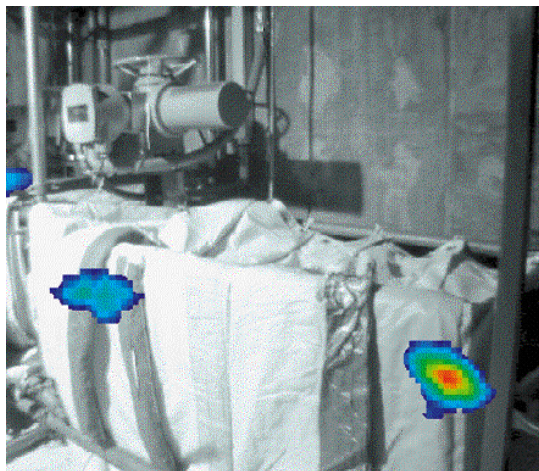
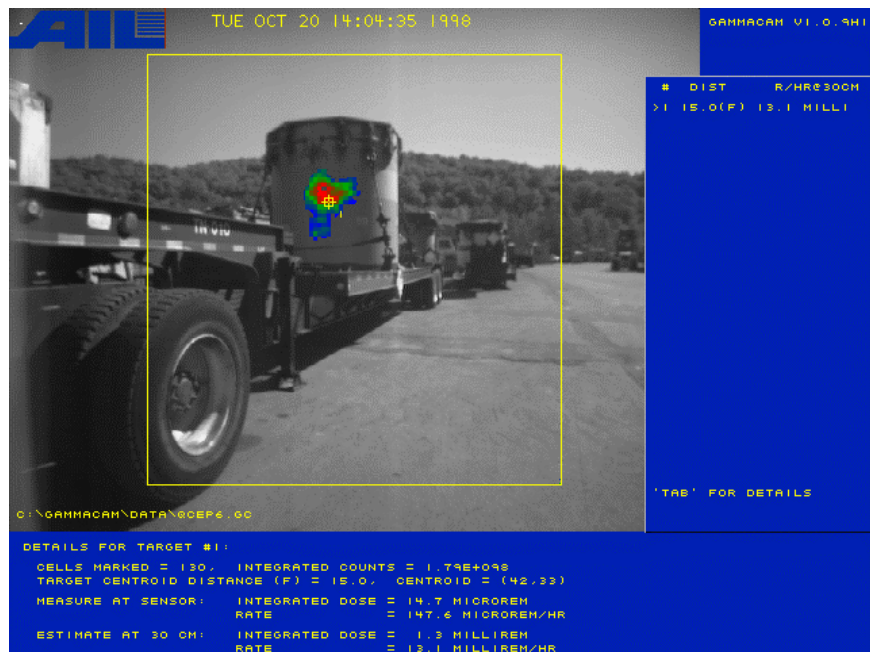
The GammaCam provides valuable insight in identifying source locations, which maximize shielding benefits and also maximize the efficiency of shielding utilization. Safely quantifying the effectiveness of shielding such as lead blankets, pigs and cement casks from comfortable ranges is another substantial benefit of the system.

USER REQUIREMENTS

System setup is simple, connect the sensor head to the computer and aim the **GammaCam** sensor at the area of interest. Image acquisition can begin after an initialization period of a few minutes. All sensor head functions are controlled remotely from the portable computer. The **GammaSoft™** system control software provides the operator with a complete image acquisition and analysis environment using simple menu driven commands.

Composite images generated by the system are presented on the computer display with radiation intensity shown in pseudocolor over a conventional black and white video image. The range of gamma ray intensity with a particular image is automatically scaled to indicate the highest radiation levels as red and the lowest levels as blue.

A yellow border indicates the gamma ray field of view (FOV) which is user selectable at 25° (narrow FOV) or 50° (wide FOV).



for a 1 μ R integrated dose.

The exposure time required to visualize a given radiation source depends upon several factors including gamma ray energy, source strength, distance to the source, and the distribution of the source. As a rule of thumb, for Cs-137 point sources, the sensor must receive an integrated dose of approximately 1 μ R integrated in minimum of 10 minutes to acquire an image. As an example, consider a 50 mR/hr Cs-137 point source (measured at 1 foot as per 10CFR20) at a distance of 30 feet from the **GammaCam** sensor head. The field strength at the sensor's input aperture is approximately 60 μ R/hr ($1/r^2$ loss) so that an exposure time of 1/60 or 1 minute would be required

SPECIFICATIONS

Spectral Range:	<50 keV to >1.5 MeV
Detector:	High density terbium-activated scintillating glass
Sensitivity:	1 μ R integrated dose for Cs-137 point source and 7:1 SNR
Exposure Time:	User selectable: 1 milliseconds – 10 minutes Software Summing for > 10 minutes
Field of View:	25° Narrow FOV Mode
Spatial Resolution:	1.3° Narrow FOV Mode 2.6° Wide FOV Mode
Dynamic Range:	Instrument: >10 ⁸ Single Image: >10:l
B&W Video FOV:	73° Horizontal 55° Vertical
Temperature:	Operation: 5°C-40°C Storage: -20°C-50°C
Humidity:	0 – 99% noncondensing
Detection Head:	Weight: 45 Pounds Size: 20 in. Length 10 in. Width 10 in. Height
Processor:	Tripod Mountable Rugged Portable Computer (IBM PC Compatible) Intel Pentium CPU 256 Megabytes RAM (Minimum) Active Matrix LCD Color Display Internal Hard Drive CD-RW
Standard Software:	GammaSoft™
System Power:	120 Watts 110-240 VAC 50/60 Hz

**We have a strong presence in the National Laboratories,
Nuclear Power Plants, Waste Storage Facilities and
Defense Forces (International)**
Contact us for additional information and a list of Satisfied Users

POINT-OF-CONTACT

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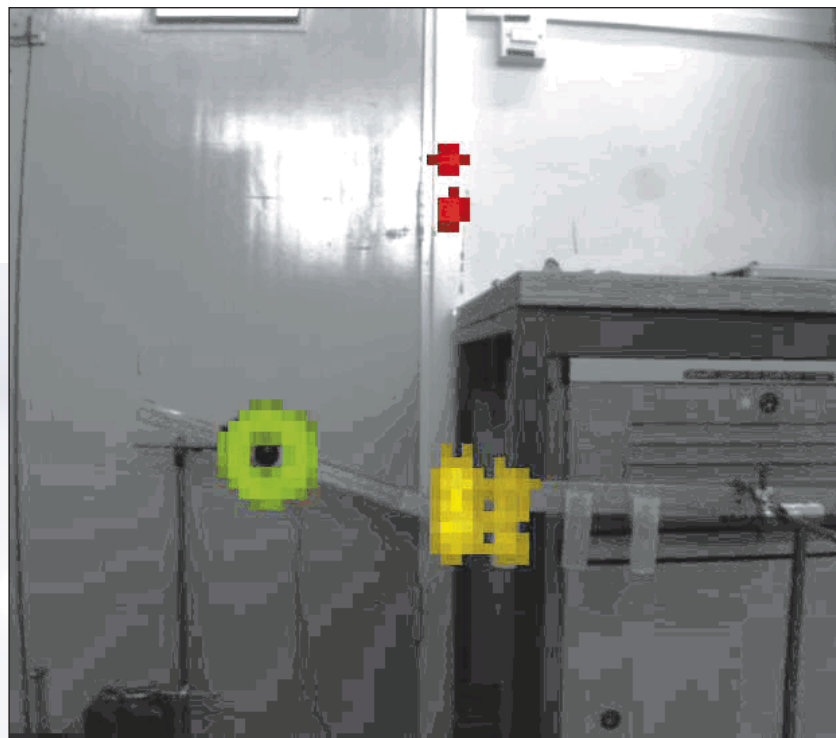
EDO Corporation GammaCam Representative 1-800-944-1180

Gamma Camera

- High spatial resolution location of radioactive material.
- Isotope identification by gamma spectroscopy.
- Near real-time imaging.
- Facilitates efficient classification of waste for disposal.
- Facilitates process control.
- Permanent storage of images on disc.

Features

- Transportable
- Operates from outside containment through a pin hole collimator
- Gamma ray image overlays video image
- Windows™ based software
- No moving parts
- On-screen isotopic information
- High sensitivity
- High count rate performance
- High spatial resolution
- Fibre optic communications



Single exposure gamma image overlaid on optical image.

■ ^{137}Cs point sources	■ Kr^{85} distributed sources	■ Eu^{152} distributed sources

Applications

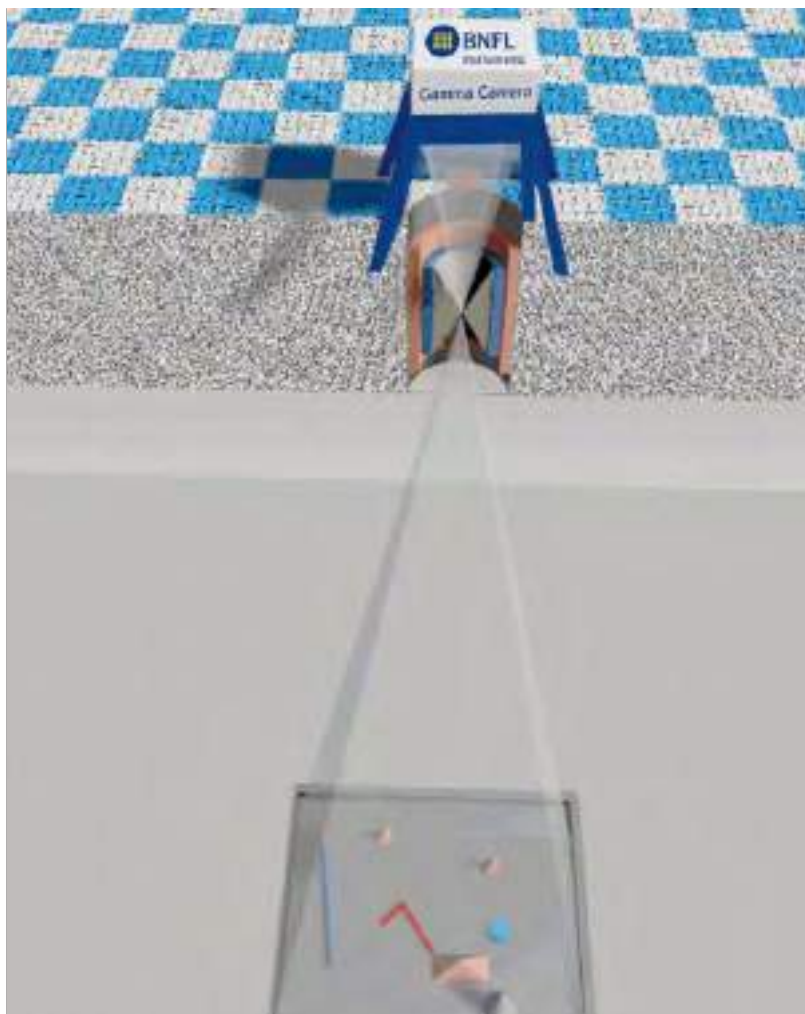
BNFL Instruments' Gamma Camera offers a new dimension in process control, allowing plant operators to see the distribution of radioactive material. Decontamination can be speeded up and waste sorted more efficiently, greatly saving time and cost.

A typical application involves the identification and removal of fragments of irradiated fuel from waste which has been retrieved from long term storage. The unique combination of high spatial resolution, wide dynamic range and isotope identification maximizes the opportunity for the operator to identify waste in these potentially complex matrices.

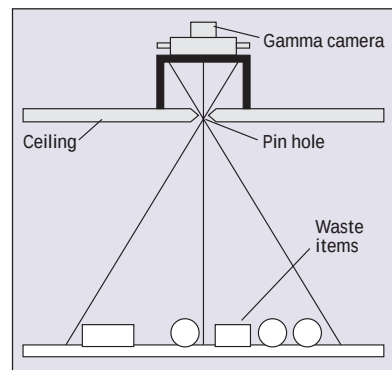
Deployment and operation

The pin hole collimator can be engineered into the wall or roof of a cell. The imaging plane is mounted outside the cell, in a low dose environment and views the process through the pin hole. The field of view is determined by the distance between the pin hole and the imaging plane.

For decommissioning the collimator can be fitted into the wall of the cell. The Gamma Camera can then pan and zoom its field of view by moving its position relative to the hole.



Radioactive waste is imaged and characterized through the pin hole collimator by the ceiling mounted Gamma Camera.



Overall geometry of pin hole arrangement

Operating modes

The Gamma Camera may be set to acquire a single image with a fixed exposure time or continually update the image to give near real-time performance.

Images formed, from selected regions of interest in the energy spectrum, can be generated to show the distribution of different isotopes by the use of colour overlays or contour plots.

Energy calibration

Periodic energy calibration is performed using a sealed source.

Data recording

Composite gamma and video images may be stored on disc, printed or transferred electronically to a data management system.

Specification

Detector head size	H 500 mm x W 600 mm x D 200 mm
Detector mass	60 kg in chassis form
Detector	Nal (T1) scintillator with PMTs
Noise level	<100 keV
Energy range	>1.3 MeV
Efficiency	50% at 662 keV (total interactions)

Performance

Count rate	Up to 200,000 cps into image
Viewing angle	Variable
Energy resolution	<10% at 662 keV
Dynamic Range	>100:1
Spatial resolution	5 mm in image plane
Active area	400 mm x 300 mm
Remote operation	Via fibre optic link
Digitisation	Up to 256 x 256 pixels
Spectrometry	256 channels

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High Efficiency Passive Neutron Counter (HENC)

Features

- 208 liter (55 gallon) drum counter
- >30% efficiency
- <0.7 cps coincidence background at sea level
- MDAs of less than 20 nCi/g
- Automated loading and unloading
- Add-A-Source correction
- Coincidence or multiplicity counting

Description

The High Efficiency Neutron Counter (HENC) represents the ultimate in Canberra's family of passive neutron coincidence counters. Combining a detection efficiency of over 30% with increased shielding to reduce backgrounds, the HENC is designed to assay 208 liter (55 gallon) drums to detection levels on the order of 1.6 mg of ^{240}Pu -effective in a 1000 second count time. With the addition of enhanced correction and analysis techniques such as Add-A-Source and multiplicity counting the HENC is also an extremely accurate assay system.

Components of the proposed system include the neutron counter with ^3He detectors, Amptek-based fast preamplifier/discriminator circuit boards (Model JAB-01), coincidence electronics, computer hardware, and application software. The turnkey system is designed for ease of operation and minimal maintenance.

Spontaneous fission neutrons from the even isotopes of plutonium will be measured using passive neutron coincidence or multiplicity counting techniques. The neutron counter consists of a high-density polyethylene (HDPE) moderator with ^3He tubes embedded in the HDPE on all six sides of the counter with optimal spacing for maximum detector efficiency.

The software converts the corrected count rate to ^{240}Pu -effective (combination of ^{238}Pu , ^{240}Pu , and ^{242}Pu) and calculates the total measurement uncertainty.

The counter's neutron detection efficiency is 30% for ^{252}Cf neutrons emitted in the center of the assay cavity. The spatial response of the counter is uniform. Variations from the mean efficiency are less than 3% for totals (non-coincident neutrons). An optional drum rotator provides additional smoothing of non uniformities in response due to the rectangular shape of the assay chamber.

It is possible to reduce the matrix effects by the use of the Add-A-Source (AAS) technique. An illustration of the AAS measurement is shown in Figure 1. The AAS introduces a small ^{252}Cf source into the sample chamber at the end of the passive assay and compares this result with an empty chamber value. The impact of the waste matrix is evaluated from this relative measurement and an appropriate correction is applied. The ^{252}Cf source for the AAS correction is stored above the counter in a HDPE shield. Measurements indicate that the presence of the ^{252}Cf source has no significant impact on the background readings. The source positioning is controlled by the software.



Operation of the Counter

The HENC counter automatically loads and unloads drums into the assay chamber. The general sequence of events for the system in the analysis mode is as follows:

- Sliding doors open and drawbridge lowers into position. The conveyor moves the drum into the assay chamber.
- Drawbridge raises and the counter doors close.
- Operator enters the pertinent information on the sample.
- Rotation motor is switched on.
- A passive neutron count is performed for the preset time.
- Add-A-Source Option: Following the passive count the AAS measurement begins.
- AAS source movement is automatically controlled by PLC.
- Upon completion of the passive assay and AAS measurement, the door opens and the drawbridge lowers.
- Sample automatically exits the rear of the counter for two-door configuration or the front door for the one-door configuration.

Software

The HENC systems are provided with Canberra's S430 Neutron Analysis Software. This software is based on our Genie-PC platform. The assay data is stored in the standard CAM file format. This format stores all relevant information for the given assay including calibration parameters, raw data, results, error flags and QA check results. This ability to retain all data allows reanalysis of the data at a later time for accountability purposes or if any irregularities are uncovered. The software makes use of pull down menus and predefined parameter entry to simplify operation of the system.

Phone contact information

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Japan 81-3-5844-2681 • Russia (7-095) 429-6577 • United Kingdom (44) 1235 838333 • United States (1) 203-238-2351

For other international representative offices, visit our Web Site: <http://www.canberra.com> or contact the Canberra U.S.A. office.

M0755 1/03 Printed in U.S.A.

Performance

The counter is provided with a complete mapping of the chamber response. This data is useful in verifying the proper functioning of the counter and in defense of assay results. The extent of any positional variation is fully documented at delivery. This variation is less than $\pm 5\%$. The accuracy of a given measurement is determined primarily by the following factors:

Counting Statistics

The statistics are typically associated with the precision of the assay. The limits on the precision are count time, efficiency, SNM content, and background. The HENC has an advantage over other passive neutron counters because of its higher efficiency and lower background response. The lower background is derived from additional poly shielding and superior electronics. The background of the HENC is typically half that of other counters of the same size and efficiency. This leads to lower limits of detection for the Canberra drum counters.

The Lower Limit of detection of the counter at sea level with no additional overhead shielding is 1 to 3 mg of ^{240}Pu -effective corresponding to 3 to 10 mg of high burn-up Pu. This value is quoted at the 3-sigma level corresponding to about $\pm 33\%$ at one sigma. For Pu contents exceeding 1 gram this uncertainty drops to about 3.5% and at 30 grams Pu this further decreases to less than 1%.

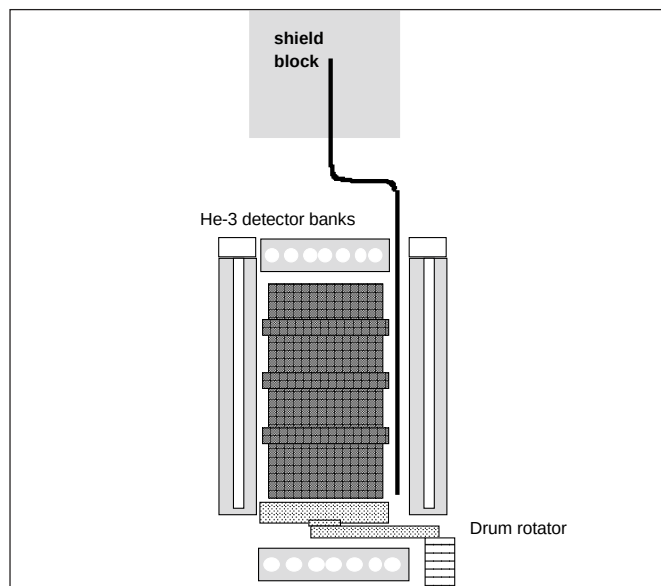


Figure 1
Schematic Diagram of the Side Scanning AAS.
(Other configurations are available).

Uniformity of the Chamber Response

The variation of the response with source location in the chamber can have a significant impact on the assay results. The flat response of the HENC, combined with the averaging effect of the turntable, essentially eliminates this effect for most sample matrices. The RSD variation in response for the HENC is approximately 2% throughout the normal sample volume.

Matrix Effects

Neutron counters are most impacted by the hydrogen content of the sample. Samples containing significant quantities of water or oil can be significantly impacted. This impact is seen as a lowering of the neutron response. The HENC counter includes the AAS Matrix correction option to reduce this effect.

Distribution of the Pu in the Drum

For homogeneously distributed samples, the AAS correction is highly accurate, providing values of $\pm 2\%$ (not including the effects of counting statistics). However, drums containing large quantities of hydrogen and localized concentrations of Pu will incur larger errors due to positioning effects.

Overall accuracy for a typical drum with a hydrogen content less than 10% of water (e.g. paper and process clothing) will be better than 20% for a sample with more than 1 gram of high burn-up Pu. (For samples with greater than 1 gram high burn-up Pu the counting statistics become negligible compared to other sources of error.)

Multiplicity Option

The multiplicity analysis option provides a correction for large Pu concentrations and for high alpha-n samples. The multiplicity analysis is already built into the NAS software. Where coincidence counting measures total neutron and coincidence events, multiplicity analysis records the frequency of occurrence of various neutron multiplicity events (i.e. whether 1, 2, 3 up to 128 neutrons were detected for any given event). This allows the determination of singles, doubles, and triples rates providing an extra parameter so that values for alpha, multiplication and ^{240}Pu -effective mass may be determined from the assay. This feature reduces the error introduced from the unknown sample isotopics or from concentrated Pu masses.

Multiplicity for Waste Assay

For traditional waste assay, the total fissile mass is often less than a few grams. For these samples, the multiplication is essentially one and the value of alpha has little impact on the assay. Multiplicity analysis provides two possible benefits over standard coincidence counting for waste assay. The analysis allows a measurement of the counter efficiency by assuming $M=1$ and solving the rate equations for ^{240}Pu -effective mass, the value of alpha, and the efficiency. In practice, the precision of the triples rate in these situations is poor and the precision of the overall measurement is decreased. However, LANL publications indicate that this result is more accurate than if determined by coincidence counting. In other words on average the results will be closer even if the statistical error is larger for a single assay.

Add-A-Source Option

The Add-A-Source (AAS) technique provides a means of measuring the impact of the waste matrix on the neutrons emitted within the drum. For homogenous distributions of Pu in the drum the AAS correction results in a typical error of $\pm 2\%$ from the expected values. Without this correction the errors can exceed 50%. The effectiveness of the AAS correction is illustrated in Figure 2.

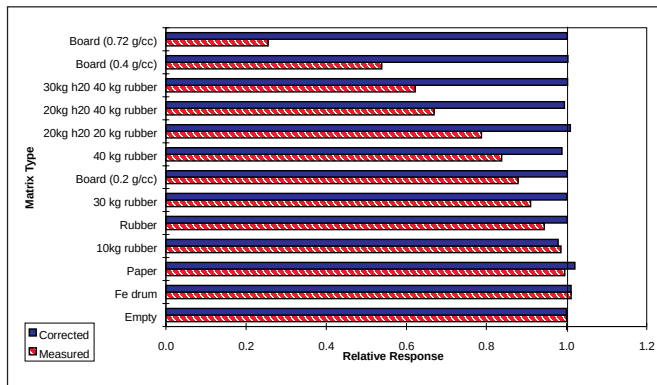


Figure 2
AAS correction example for a HENC counter.

It should be noted that the AAS assumes a uniform source distribution. When a point source is placed in a drum with high moderator content the positioning effects increase. However, experience has shown that for drums containing the equivalent of less than 40 kg of water will result in errors of less than 10% after the AAS correction is applied.

Specifications

DIMENSIONS

LENGTH – 362 cm

WIDTH – 195 cm (not including drawbridge)

HEIGHT – 270 cm

WEIGHT – 8200 kg

CONVEYOR

HEIGHT – 62 cm

³HE TUBES

NUMBER – 113

DIAMETER – 2.54 cm

PRESSURE – 7.5 atm





IQ3 Automated Low Level Waste System

Features

- ^{239}Pu detection levels <1 mg container sizes up to 300 L (85 gal) six large area LEGe detectors.
- GWAS quantitative assay software.
- MGA/MGAU U/Pu isotopics software.
- Transmission correction for matrix density.
- Fully automated system.
- Non Uniformity Correction Software.
- 15 cm (6 in.) low background steel shield.
- LN_2 autofill system.

Introduction

The IQ3 is Canberra's Automated Low Level Waste Assay System. The system is designed to quantify plutonium and uranium in 200 L drums at levels below 10 nCi/g and at the same time perform plutonium isotopics measurements on drums containing less than 10 mg of plutonium. At this level low level waste drums can easily be segregated from TRU drums.

For TRU drums the IQ3 system utilizes several techniques to provide accurate quantification of the fissile content of the drum. These include transmission correction to determine the drum matrix density, lump detection using multi energy assays, and non uniformity correction using Canberra's Non Uniformity Correction Software (NUCS).

Since most TRU waste is also quantified using neutron assay techniques, the IQ3 system utilizes the Multi-Group Analysis (MGA) software to determine the plutonium isotopics as well as the U/Pu ratio and the $\text{Pu}/^{241}\text{Am}$ ratio. MGAU provides uranium isotopics values for materials which do not contain plutonium. These numbers are critical for obtaining a good assay result from the neutron system.



The system is designed to be operated as an automated counting system which can process batches of drums, or can be incorporated into a complete NDA process line.

The following sections describe the various parts of the IQ3 system hardware, software and indicate typical performance characteristics.

Description

IQ3 Shield

The IQ3 shield provides a 4π , 15 cm thick, low background steel shield as a measurement chamber for the drums. The shield is one of the key features in enabling the low detection limits to be achieved. Special steel is used to eliminate the typical ^{60}Co contamination which is found in most steels, and other construction materials are carefully selected to minimize those which might contain naturally occurring gamma emitters. This provides

an assay chamber which eliminates outside radiation levels, and does not contribute radiation from contamination in the construction materials.

Inside the shield, the drum is placed on a rotator minimizing the effects of source and matrix non uniformities. An index signal at the start of rotation resets the indexing on the Dual Multi Spectrum Scaling (DMSS) module so that incremental spectra can be collected as the drum is rotating.

An automated absorber can be provided to extend the dynamic range of the assay system so that high fissile gram content drums can be assayed.

Loading System

The loading system is a fork mechanism on a vertical drive which is mounted onto the inside front of the shield door. The forks rest between the conveyor rollers at the beginning of a load sequence. Once the drum is positioned, the forks lift the drum from

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For other international representative offices, visit our Web Site: <http://www.canberra.com> or contact the Canberra U.S.A. office.

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the conveyor, the door closes, and the forks lower the drum onto the shield rotator.

The loading mechanism is designed for a working weight of up to 400 kg (880 lb) with a safety factor of 1.5. The mechanism can handle drum sizes up to 320 L (85 gal).

As a part of the loading system, a special load conveyor section is provided in front of the shield. This is used to stop the conveyor in the correct position for loading and to ensure that the drum is properly centered. This section is typically mounted on a set of load cells to automatically measure the drum weight during the loading sequence.

Transmission Source Mechanism

To the left side of the shield opposite one of the sets of detectors, is the transmission source shield and actuator mechanism. This mechanism houses three 5 cm long line sources which are located at the same heights as the germanium detectors. This provides an accurate determination of the average density of the matrix material in the drum near the top, center, and bottom.

The sources are interconnected by a rod and exposed by being pulled vertically up into the collimator slots. This design ensures that the sources will drop into the shielded position in the event of a power failure. Sensors verify the full open and full closed positions of the transmission sources and a red warning light indicates when the transmission source is open.

The sources which will be used for this system are ^{133}Ba sources. These have been chosen to provide a source with a reasonable half-life and gamma energies close to the key plutonium lines.

Detection System

All nuclides which must be quantified by the system have key gamma lines which are low to medium energy.

LEGe Detectors

Two sets of three high purity germanium detectors are provided for the data collection. These detectors are optimized to provide the necessary high resolution required for the MGA analysis while providing high efficiency for the quantitative analysis. One set of detectors will provide at least 2800 mm² surface area and 20 mm depletion depth. The detectors will be matched to within 10% for resolution and efficiency. The second set of detectors are typically 20% coaxial detectors to optimize the quantification of the high energy gamma emitters.

The detectors are mounted in Model 7935-7 multi-attitude cryostats. These cryostats are configured with Canberra's exclusive Remote Detector Chamber (RDC) which permits back shielding to be placed around the detector end cap. This helps to further improve the low background counting capability of the system.

The cryostats are filled with liquid nitrogen and typically have a five day holding time. Because of the number of detectors and the frequent filling required, the IQ3 system comes with an automatic liquid nitrogen filling system. This permits the detectors to be filled on a scheduled basis after hours when the system is not in use. The autofill system must be interfaced to either a 240 L portable storage Dewar or a fixed facility storage Dewar as an LN₂ supply.

Electronics

ICB NIM

All of the electronics specified for this system are based on Canberra's Instrument Control Bus (ICB) line of instrumentation. These modules eliminate all of the front panel controls so that all set up and control of the modules is handled through the application software. Routine setup and status checks by the software ensure that the software is properly set up and turned on.

The following is a list of the modules which are normally used for this system, along with a brief description of each of the modules.

- 2100 NIM Bin
- 9615 ICB Programmable Spectroscopy Amplifier
- 9645 ICB Programmable High Voltage Power Supply
- 9633 ICB Programmable ADC

DMSS

The DMSS module is a Dual Multi-Spectrum Scaling Module. This is used to collect incremental spectra on the drum as it is rotating. This data is used by the NUDS and NUCS software.

1614 Pulser

The Model 1614 pulser is a four channel pulser which can be used as a reference pulser to correct for counting losses which are not handled by the standard live time correction such as random summing correction during high count rate measurements.

556 AIM Module

Data collection is into Canberra's Model 556 AIM Module. This module interfaces to the application computer over an Ethernet connection. The AIM module is required for communication to the ICB modules and to provide adequate spectral data storage (32K channels per detector) for the DMSS spectra.

All of the NIM modules are mounted into a locking air conditioned industrial cabinet.

Computer Requirements

The computer is typically a rack mounted industrial computer from the Industrial Computer Source. The computer has the following minimum characteristics:

- 166 MHz Pentium* processor
- 24 MB of RAM memory
- 1.0 GB hard disk drive
- 1.44 MB floppy drive
- Ethernet interface card
- 14 in. SVGA monitor

*Pentium is a registered trademark of Intel Corporation.

PLC Control System

The PLC control system will handle the loading, and unloading of the drum from the shielded assay system. In addition it controls the transmission source actuator, the rotator, and the attenuator.

The PLC used in the system is a GE/ Fanuc Series 90 PLC. This is mounted into an environmental cabinet. All of the loading functions are powered by ac motors.

Specifications

The primary application software package which is used for this system is Canberra's Gamma Waste Assay Software (GWAS). This package is an extremely flexible package which can be used to setup and operate any Canberra gamma waste assay system. The GWAS software utilizes the Genie-PC software packages in addition to special routines unique to the GWAS software. The software operates from a top level menu structure which is common for all

Canberra application products. Some of the features of this software are described below.

- **Spectrum Summing**

By summing the spectra from several detectors, the overall detection efficiency is improved as well as the effective sample to detector geometry since the detectors cover more of the drum volume. To accomplish the spectrum summing, Canberra has developed a special calculational engine which matches the gains from each detector during the summing process so that there is no resolution degradation in the summed spectrum.

- **Transmission Correction**

Transmission measurements are used to measure the average density of the three main sections of the drum. Each of these measurements is used to correct the basic measurement results for matrix attenuation.

- **Non Uniformity Correction Software**

The non-uniformity correction software reduces the total measurement uncertainty caused by source and matrix non uniformities. As the drum density increases, the magnitude of these errors increases significantly. With the use of the NUCS software, the maximum error based on these non uniformities is typically less than 20%.

- **System Security**

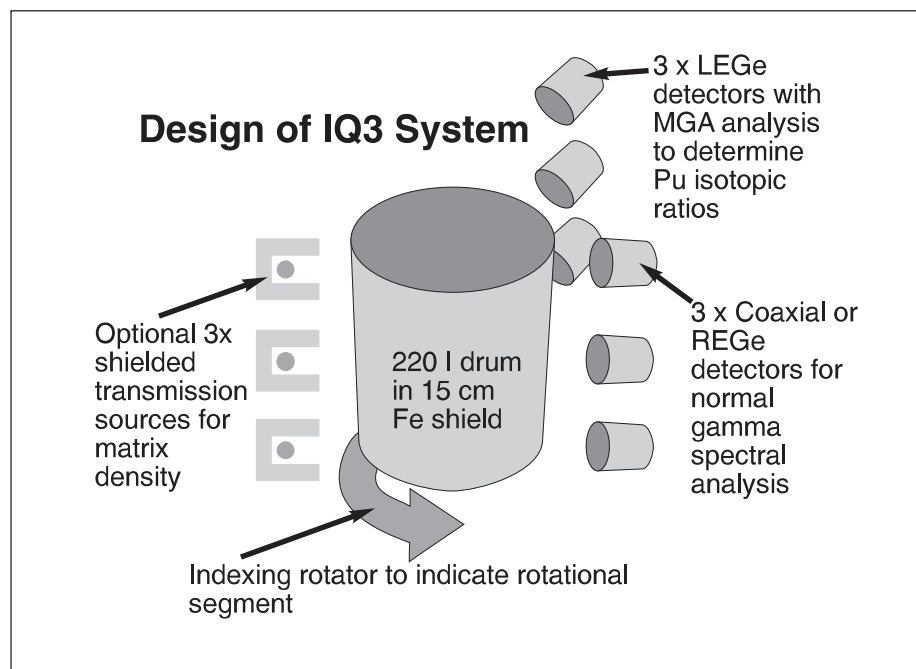
The software contains multiple security levels which can be accessed under password control. These can be modified to permit access to various functions depending on the operator training level. Any number of operator accounts can be created.

- **Relational Database**

The GWAS software contains a relational database (DB/2) to store container information and results, calibration runs, background runs, and calibration checks. These can be reported, sorted, retrieved, etc. based on date and time, count type, or I.D. number. The database entry can be used to retrieve raw data, results, analysis parameters, etc.

- **Quality Control and Control Charting**

The software uses Canberra's Genie-PC QA software package to handle quality control measurements on the system. Any number of parameters can be tracked for a calibration check drum including, resolution, peak centroid, net areas, activities, background count rates, etc. to ensure that the system is operating within its control limits on a routine basis. Tests of the data can use user specified bounds, standard deviations, or other test parameters. Control charts for each parameter are automatically generated from this data and can be called from the top level menu.



• Analysis and Correction Techniques

The GWAS software provides a wide range of analysis and matrix correction techniques which can be used for assaying the spectral data. These analysis engines are selected and setup to best handle the specific application. For this particular application some of the key analysis engines would include:

- Library driven peak search engine for sensitivity.
- Spectrum summing for sensitivity.
- Transmission correction for accuracy.
- MGA analysis for plutonium isotopics.
- NUCS for accuracy.

• Error Log

An error log is maintained for any error generated by the system. This permits the system manager to review the cause of problems after they have occurred.

• MGA

Multi-Group Analysis (MGA) is a plutonium isotopics analysis software package which was developed at Lawrence Livermore National Laboratory by Dr. Ray Gunnink. This package can provide plutonium isotopics for very small sources in waste containers. In addition to the plutonium isotopics it will determine other actinides such as ^{235}U , ^{238}U , ^{237}Np , and ^{241}Am . This code is the most widely used isotopics code in the world. It is used extensively in safeguards applications by the IAEA and Euratom, as well as by the CEA and Cogema in France.

In the past several years Dr. Gunnink has worked under contract with Canberra to optimize this code for very low statistics measurements as are found in typical waste applications. This version of the code is only available through Canberra Industries.

Performance

The following are the expected performance parameters based on measurement data obtained in the factory, as well as results supplied by customers using this system.

MDAs

The following values are based on a 30 minute assay time, on a 200 L drum with a mass of 100 kg of low Z materials.

- The minimum detection level of the system for weapons grade plutonium is less than 1 mg at the 99.7% confidence level, based on a uniform distribution of activity.
- The minimum detection level of the system for ^{235}U is less than 10 mg at the 99.7% confidence level, based on a uniform distribution of activity.

Maximum Performance Levels

The system is capable of assaying drums with a maximum weight of 400 kg and a maximum fissile gram content of 250 gm of Pu.



Table 1.
Dimensional Specifications

Dimensions	Shield	Recommended Floor Space
Width	244 cm (96 in.)	356 cm (140 in.)
Depth	330 cm (130 in.)	432 cm (170 in.)
Height	260 cm (102 in.)	305 cm (120 in.)
Shield Weight	14515 kg (32 000 lb)	
Minimum Conveyor Height	61 cm (24 in.)	
Maximum Drum Size	76 cm (30 in.) diameter 100 cm (39.5 in.) high	
Maximum Drum Weight	400 kg (880 lb)	
Power Requirements	30 A at 110 V ac	

ORTEC[®]

ISO-CART[™]
Mobile Assay System

A Complete *In-Situ* NDA Gamma-Ray Analysis for a Wide Variety of Samples

- Measures all common geometries: pipes, cylinders, floors, ceilings, walls, drums, boxes, and soils
- Easy-roll cart for maneuvering over any surface
- Wide selection of collimators and shields available for different measurement situations
- Continuous height adjustment and variable tilt adjustment
- Easily disassembles to fit into your car
- ISOTOPIC software, proven results on thousands of real-world samples
- Simple to calibrate with a single inexpensive mixed isotope point source
- Flexible reporting: measurement results can be reported in grams or activity (Bq or Ci)

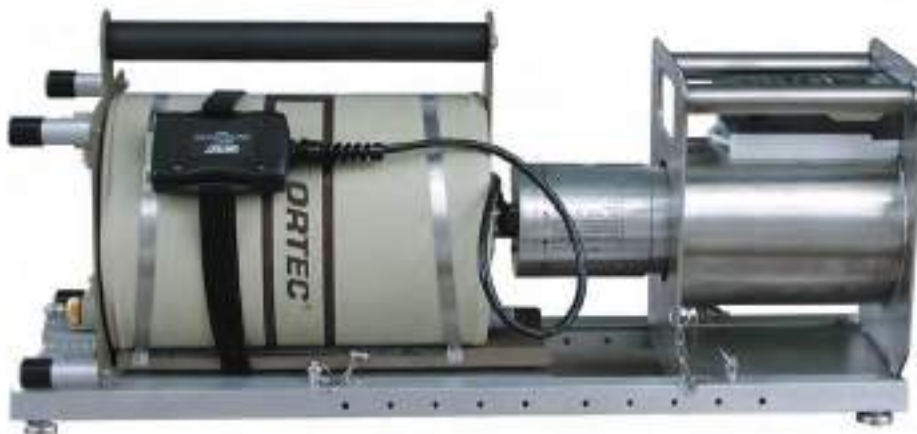


The ISO-CART Mobile NDA System is an ideal solution for a wide variety of *in-situ* gamma-ray measurement requirements. The hardware comprises a specially-designed cart which carries all the components: HPGe detector, shield and collimator, digiDART™ high performance multichannel analyzer, and laptop computer. The system software package provides everything necessary to produce quantitative results quickly and easily "right out of the box." The ISOTOPIC software can control up to eight ISO-CART systems at once for the measurement of large containers. One answer is given for each item measured.

Calibration is a simple procedure, requiring only the use of a single point, mixed isotope source. The patented ORTEC automatic energy calibration technique and automatic efficiency calibration make setup a breeze. ANY standard HPGe detector may be used with the ISO-CART system. No special factory calibrations are required.

The ISO-CART allows the entire assay system to be easily transported to any measurement location. The large wheels permit easy movement over rough surfaces. The detector support can be positioned at heights from 0.38 m (15 in.) to 1.2 m (48 in.). The pivot mechanism orients the detector at different angles from 0 to 180°. A sturdy adjustable shelf supports the electronics and the notebook computer for convenient on-the-cart operation. An additional shelf is available at the bottom of the ISO-CART, and is easily removed for *in-situ* soil measurements.

If the detector must be moved to a location where it is impractical to move the cart, the detector/collimator unit can be removed and carried. The collimator may be easily removed for "infinite-plane" soil measurements.



ISO-CART™ Mobile Assay System

ORTEC Portable HPGe Detectors

ORTEC HPGe detectors are the industry standard in terms of quality and performance. The ISO-CART system may be configured with a wide variety of ORTEC HPGe detectors from which relative efficiencies of over 200% are available. The latest SMART-1 technology raises the bar in ensuring spectral data acquired is of the highest quality, via an internal state of health function which monitors the detectors performance parameters.

Dewar Options

A portable, all-attitude HPGe detector is available with a 3-0 liter Gamma Gage dewar. A new 7.0-liter multi-orientation dewar (MOD) is also available. The MOD dewar allows near all attitude use while offering reduced size compared to the equivalent holding time Gamma Gage model. Typically, the HPGe detector chosen would be a large volume GEM (P-type) or GMX (N-type); however, a wide variety of detector choices are available.

Standard systems may be ordered by model number located on the back of this brochure. Contact us to suggest a configuration according to your detection limit and count-time requirements.

digiDART™ Data Acquisition Hardware

The digiDART is the ideal MCA for use with an ISO-CART system. It can acquire preliminary data in the field as a stand alone unit or perform a complete *in-situ* analysis with the use of a notebook computer.

- High-performance rugged HPGe grade spectrometer, 16k channels
- Digitally stable: consistent answers for long counts, changing count-rates and temperatures
- Operates with or without an attached PC
- Built-in backlit LCD display and control keypad — live display of acquiring data
- Energy calibration using keypad
- Nuclide ID and activity calculation for nine Regions of Interest (ROI)
- High throughput — over 100,000 processed pulses per second
- Fits in the palm of your hand or attaches to your belt
- Holds 23 16k spectra in internal memory (614 at 512 resolution)
- ~9 hour battery life, recharge internally
- Only 860 grams, including batteries
- Fast USB communications
- Supports the latest generation "SMART-1" HPGe detectors and all other detectors using the Detector Interface Module (DIM)
- Provides authentication of spectral data
- Optional 32k-channel resolution model



System Calibration

The system is designed to allow the user to calibrate the detector. For measuring items with discrete dimensions, the only calibration necessary is a traceable mixed-nuclide source positioned 30 cm or greater from the face of the detector. For fallout measurements, the length and diameter of the detector are used to determine detector efficiency. No additional sources are necessary.

Data Acquisition Analysis Software

Program ISOTOPIC V. 3.0 controls the data acquisition and the analysis. Most of the controls for data acquisition are similar to the standard GammaVision features. For ease of use Operator and Supervisor modes are available to combine the simplicity needed for operator use and versatility needed by the spectroscopist. Other features of ISOTOPIC include a modeling program which allows the user to easily configure the item to be measured for size, matrix content, container configuration and detector position. Data is stored in a Microsoft® Access™ database.

Sample Geometries: ISOTOPIC allows unlimited geometries for quick setup and analysis. In addition, any of these geometries can be adjusted by the operator at the time of analysis to accommodate any sample, any time.

Typical geometries include:

Cylinders (lined and solid): used for drums, pipes, and bottles

Boxes: used for large rectangular shaped containers such as B-25 boxes and crate

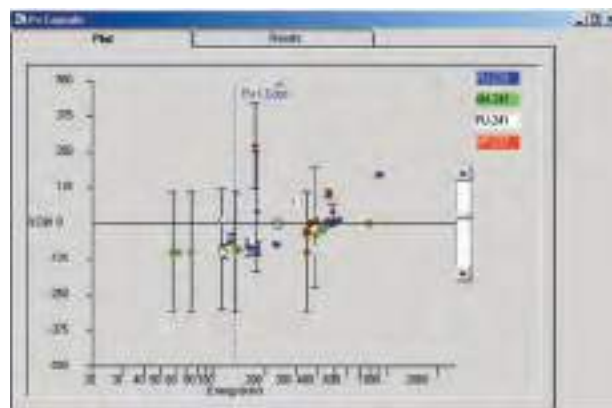
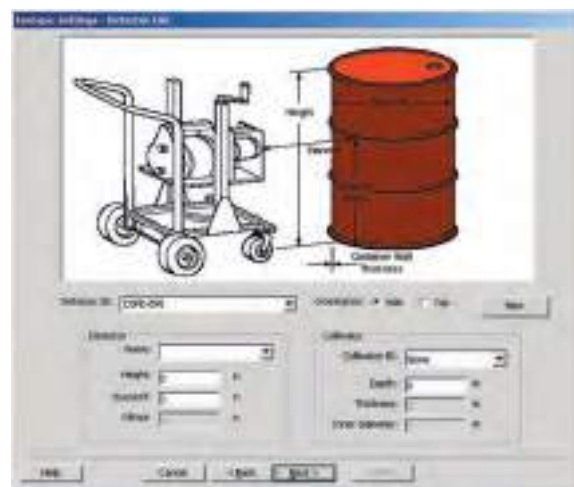
Discs: used for localized contaminated areas on floors and walls or down looking on cylinders

Point Sources: used for radioactive "hot spots" anywhere

Infinite Plane: used for fall-out measurements

Fine Tuning Adjustments: ISOTOPIC has a unique fine-tune adjustment of the correction factors. After all correction factors, including branching ratios, are implemented, all peak areas of a nuclide should be the same. These peak areas are plotted relative to a reference value and a trend with energy is noted. Adjustments to density and container attenuation and self attenuation (for uranium) can be made dynamically. When all points (corrected peak areas) are aligned, the user can be satisfied that the attenuation correction factors are correct.

Results: Many report options are available for printing and archiving. Alternately, the user can develop a customized report using the query feature of the Access database. Microsoft Access must be purchased separately to use the query feature. Results are displayed for the user to observe before storing or printing.



Nuclide	Activity	Weight	Units	Total Count	Waste Count
147Pm	1.00E+02	1.0	g	47.88	80
147Pm	1.00E+02	1.0	g	47.88	80
147Pm	1.00E+02	1.0	g	47.88	80
147Pm	1.00E+02	1.0	g	47.88	80
147Pm	1.00E+02	1.0	g	47.88	80

ISO-CART™

Mobile Assay System

ISO-CART™ Accessories

Collimators

Three different collimators are available for use in most analysis situations. The collimator thickness and length improves the sensitivity of the measurement system.

(1) The standard collimator is 1.6 cm (0.625 in.) thick and 20.3 cm (8 in.) long. It is composed of lead with a 2 mm (0.08 in.) copper liner.

(2) The medium-duty collimator is 1.3 cm (0.5 in.) thick and 20.3 cm (8 in.) long. It is composed of tungsten-copper alloy for better shielding characteristics while maintaining a small volume assembly.

(3) A heavy-duty collimator is available for high radiation areas. The collimator is 4.6 cm (1.8 in.) thick and 20.3 cm (8 in.) long.

The larger shields are made in sections, to allow the shield assembly to be removed from the cart by one person. No lead is exposed.

Laser Meter

The Laser Meter accurately determines the distance from the detector endcap to the measurement point. A sighting laser mounted on the collimator is used to center the detector on the measurement point. The range finder can be set to display the distance in meters or feet. A computer interface is included.

Wireless digiDART Control

This option includes a hand-held computer located near the digiDART on the ISO-CART. It is designed to operate with the laptop computer supplied with the ISO-CART system. Typical communications range is 150 ft. with a clear field of view.

Self-Pressurized Storage Dewar

Use to safely fill the detector from a 50-liter self-pressurized dewar. The system includes a 50-liter dewar, 6-foot transfer line, pressure-fill bayonet, and withdrawal device. Specify portable dewar type.

Turntable for Drums

Improved analysis results can be obtained if items are rotated. This option is necessary for measuring drums containing nonhomogeneous material.

Heavy Duty Shipping Crate

This box is necessary for frequent shipment of the ISO-CART. The box is designed for quick opening, easy ISO-CART removal and includes an air-tight instrument case for digital range finder, digiDart and additional small parts and tools.

System Calibration

A point-source calibration that is NIST traceable can be performed at the factory. The calibration covers a range from 59.5 keV to 1835 keV.



Specifications

Cart with SHD-1 1.6 cm (0.625 in.) lead shield: 122 cm (48 in.) H x 55 cm (21.75 in.) W x 101 cm (40 in.) D.
Weight: cart alone = 25 kg (55 lbs), cart and shield = 42 kg (92 lbs)

SHD-1 Shield (lead; includes mount for HPGe detector): 26.42 cm (10.4 in.) H x 20 cm (8 in.) W x 77.5 cm (30.5 in.) D; [shield/collimator section: 20 cm (8 in.) long, 1.6 cm (0.625 in.) wall thickness]. Weight: 16.82 kg (37 lbs)

SHD-2 Shield (tungsten copper alloy; includes mount for HPGe detector): 26.68 cm (10.5 in.) H x 20 cm (8 in.) W x 77.5 cm (30.5 in.) D; [shield/collimator section: 20 cm (8 in.) long, 1.3 cm (0.500 in.) wall thickness]. Weight: 27.27 kg (60 lbs)

SHD-3 Shield (heavy duty lead; includes mount for HPGe detector): 25 cm (9.75 in.) H x 20 cm (8 in.) W x 77.5 cm (30.5 in.) D; [shield/collimator section: 20 cm (8 in.) long; 4.6 cm (1.8 in.) wall thickness]. Shield is split in two sections for assembly purposes. Weight: 68 kg (150 lbs).

Laser Meter: 18.8 x 7.0 x 4.7 cm (7.4 x 2.8 x 1.9 in.). Accuracy: 3 mm.

digiDART: 12 x 8.2 x 3.3 cm (4.7 x 3.2 x 1.3 in.). Weight: 900 g (2.4 lbs) with battery.

Turntable: Diameter: 30 in.; Rotation Speed: 1 rev/min; Capacity: 1000 lbs.; Height: 9.5 in.



ISO-CART™

Mobile Assay System

Ordering Information

To fully specify your choice of ISO-CART system, select the model number below for the size of detector needed and replace the letters DDD in the model number with the desired choice of dewar, as follows:

3.0 = 3.0-liter Gamma Gage dewar; **M3L** = 3.0-liter MOD dewar; **M7L** = 7.0-liter MOD dewar

Other configurations may be supplied on request. Your existing detectors may be used. Contact your ORTEC representative or e-mail info@ortec-online.com with your requirements.

System Description

Complete ISO-CART system includes: pneumatic-tired CART, fitted with 5/8-inch copper-lined lead collimator, carrier and mounting plate, storage shelf, HPGe Detector with SMART-1 technology, bayonet pressure fill adapter, digiDART, ISOPLUS-B32 software and Laptop computer. System is integrated and tested and supplied with factory calibration.

Model No.

ISOCART-GEM25-DDD	ISO-CART Mobile Assay System incorporating GEM25 detector
ISOCART-GEM40-DDD	ISO-CART Mobile Assay System incorporating GEM40 detector
ISOCART-GEM60-DDD	ISO-CART Mobile Assay System incorporating GEM60 detector
ISOCART-GEM80-DDD	ISO-CART Mobile Assay System incorporating GEM80 detector
ISOCART-GEM100-DDD	ISO-CART Mobile Assay System incorporating GEM100 detector
ISOCART-GEM120-DDD	ISO-CART Mobile Assay System incorporating GEM120 detector
ISOCART-GMX25-DDD	ISO-CART Mobile Assay System incorporating GMX25 detector
ISOCART-GMX40-DDD	ISO-CART Mobile Assay System incorporating GMX40 detector
ISOCART-GMX60-DDD	ISO-CART Mobile Assay System incorporating GMX60 detector
ISOCART-GMX80-DDD	ISO-CART Mobile Assay System incorporating GMX80 detector

SHD-2-SUB Substitute SHD-2 for SHD-1 in system

SHD-3-SUB Substitute SHD-3 for SHD-1 in system

ISO-CART System Options

ISO-CART	Cart and Detector/Collimator Carrier only (collimator must be ordered separately).
ISO-DCC	Detector/Collimator Carrier.
ISO-DCC-X	Detector Carrier for X-COOLER detector. (Caution: ISO-CART should not be moved while X-COOLER is in use.)
ISO-CAL	Point-Source Calibration at the factory.
ISO-LASERMETER	Laser Range Finder.
ISO-WIRELESS	Complete set add-ons to replace PC-to-digiDART wiring by wireless networking. Includes remote computer.
ISO-DEWAR	STD50L dewar, WD/50 withdrawal device, and TL-6 6-ft. transfer line.
ISO-TURNTABLE	Turntable for drum rotation. Capacity = 445 kg (1000 lb.).
ISO-CASE	Transportation case for digiDART, laser range finder, and laptop.
ISO-BOX	Airworthy "roll-in" system transportation box for complete ISO-CART (detector ships in its own crate). Includes space for ISO-CASE.
ISOPLUS-B32	ISOTOPIC-32 Software.
M1-T1	Variable-length Tripod for In-Situ Soil Measurements.
SHD-1	5/8-inch Lead Shield/Collimator, copper lined.
SHD-2	Tungsten Shield/Collimator.
SHD-3	Heavy Duty Lead Shield (1.8" thick) for high backgrounds.

NOTE: Contact factory for ISO-CART systems based on alternate detectors types.



ISO-DCC-X

ISO-CART™

Mobile Assay System

Specifications subject to change
050907

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For International Office Locations, Visit Our Website

AMETEK®
ADVANCED MEASUREMENT
TECHNOLOGY



Model S573 Version 4.0 ISOCS* Calibration Software

Features

- No radioactive sources needed for accurate efficiency calibrations
- Works over a wide range of geometries
- Calibrations valid from zero distance out to 500 meters
- Calibrations valid from 45 to 7000 keV
- Calibrations accurate to within a few percent
- Calibrations accurate at any angle from detector, not just on centerline
- Eliminates the cost of purchasing radioactive standards, creating custom distributions, and radioactive waste disposal
- Results are available within a few seconds
- Operates with any size or type of Germanium detector which has been characterized by Canberra
- Ideal for *in situ* applications, where large and various sample types are often encountered
- Includes predefined geometry templates for twenty common container shapes and sample distributions
- Sample size can be point-like, or up to 500 meters in size
- Includes library of common materials and tools to create new materials
- Works with cylindrical collimators with conical holes, and rectangular collimators with trapezoidal holes
- Includes predefined collimator entries for ISOCS Shield
- Custom templates can be provided to meet special application needs
- Multi-Efficiency program allows creation of compound efficiencies for multiple detectors, multiple locations or multiple sources
- Easy to use Windows®-based graphical user interface with extensive automatic error checking
- User-defined templates containing all static information about a sample may be saved and easily be recalled
- Geometry Composer Report summarizing all information defined for a given geometry can be displayed and printed
- Only a few physical sample parameters (e.g. size, distance from detector, etc.) are needed to tailor a template to a sample
- Ability to vary assumed sample characteristics (e.g. density, container wall thickness, etc.) makes it ideal for "What if..." analyses
- Resulting calibrations may be stored, recalled, and used just like those generated by traditional calibration techniques
- Calibrations are in Canberra CAM file format, and can be transferred to any Genie software for analysis, e.g. Genie-ESP
- Companion software to S574 LabSOCS that is optimized for laboratory calibrations

Description

The ISOCS (*In Situ* Object Counting System) Calibration Software brings a new level of capabilities to Germanium gamma sample assay by eliminating the need for traditional calibration sources during the efficiency calibration process. By combining the detector characterization produced by the MCNP modeling code, mathematical geometry templates, and a few physical sample parameters, the ISOCS Calibration Software gives you the

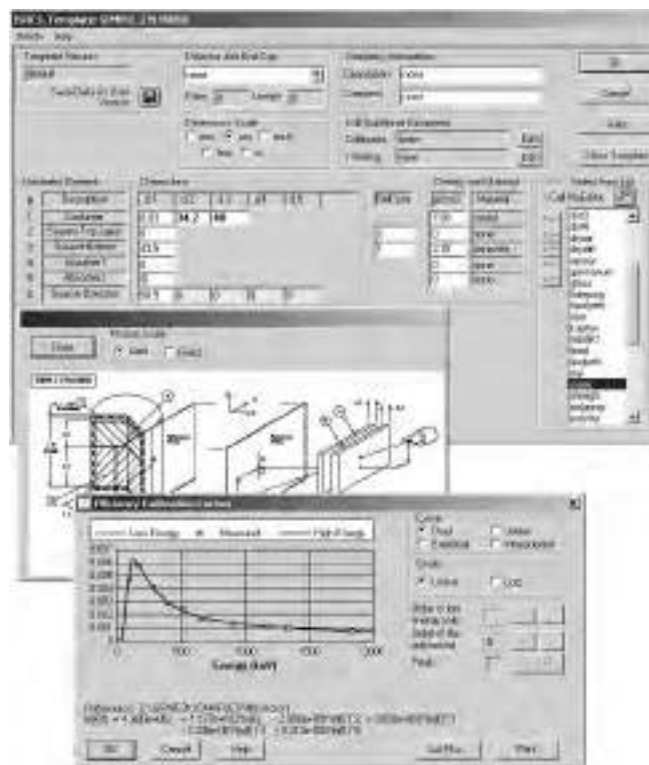


Figure 1
ISOCS Calibration Software with template diagram,
used for data entry to generate the Genie 2000 Efficiency Curve

ability to produce accurate qualitative and quantitative gamma assays of most any sample type and size (Figure 1).

In addition to saving money by eliminating the need to purchase (and later dispose of) many calibration sources, ISOCS Calibration also saves time. Instead of hours spent in traditional source preparation and long calibration counts, an ISOCS Calibration for a new geometry requires only a few seconds of computer calculations.

The secret to this capability is twofold:

1. The energy/efficiency/spatial response profile of the Ge detector has been characterized by Canberra with the well-known MCNP Monte Carlo modeling code.
2. Mathematical templates have been created for most of the sample geometries that will be encountered – planar surfaces, rectangular boxes, barrels, pipes, etc.

To a basic geometry template, add the specifics for a given sample – its size, density, distance from the detector, etc. – and the ISOCS Calibration Software generates a custom efficiency calibration specifically tailored for that detector and sample. The remainder of this document will describe how this is done and how the various standard geometry templates are used.

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For other international representative offices visit our Web Site: <http://www.canberra.com> or contact the Canberra U.S.A. Office.

*US Patent 6228664 B1

C9766 4/02 Printed in U.S.A.

THE ASSAY AND CALIBRATION PROCESS

To better understand how the ISOCS Calibration Software is used, it's necessary to look at the complete ISOCS sample assay process. In general terms, it's as follows:

1. Count the sample. Use a detector that has been characterized by Canberra, and the Model ISOXSHLD ISOCS Shield and Collimator System, if required.
2. Select the Geometry Template that best fits the sample type (such as planar surface, rectangular box, cylinder, pipe, etc.).
3. Measure the relevant physical sample parameters required by that template (such as size, density, distance to the detector, etc.).
4. Enter these parameters into the ISOCS Calibration Software and generate an efficiency calibration for those conditions in 15 seconds, typically. Examine/modify the shape of the resultant Genie 2000 calibration curve and store it.
5. Use this calibration for the analysis of the spectrum collected during the sample count in Step 1, yielding a qualitative and quantitative assay of the sample.

The sample parameters recorded in Step 3 are key elements to the process, for they allow the software to tailor the theoretical response of the detector for a given geometry to the specific sample being assayed. For maximum accuracy and flexibility, each template allows a wide variety of parameters to be specified.

In addition to the parameters mentioned in Step 3, provisions are included for things like container wall thickness, the presence of absorbers between the source and detector, non-homogenous source location within a container, variable sample densities, and off-axis detector placement. In short, most any factor that can impact the assay may be measured and specified. If a parameter is not known, various values can be tried to determine what, if any, influence that parameter has on the results of the assay.

CALIBRATION TEMPLATES INCLUDED WITH ISOCS

The basic Geometry Templates included with the ISOCS Calibration Software can be seen in the following series of drawings. For each, the various physical parameters that may be varied are shown as numbered callouts.

In addition to these standard templates, custom templates can be defined by Canberra to meet special application needs. For all templates, the presence or absence of a collimator or housing can be specified and accounted for automatically. Composite geometries can also be specified by combining multiple geometries with the Multi-Efficiency utility.

The basic templates and their applications are as follows:

SIMPLE BOX – A basic rectangular carton or waste shipping container, a truck filled with scrap iron, or even a small building.

COMPLEX BOX – The same as the Simple Box, but with a more complex sample matrix. It includes the ability to distribute the contamination across as many as four layers of material and/or to place an additional concentrated source anywhere in the container. Ideal for use in “What If?” analyses of non-uniform distribution in waste assay containers.

SIMPLE CYLINDER – A basic barrel, tank, or drum. In an emergency, it could also be used for a quick whole body contamination count.

COMPLEX CYLINDER – The same as the Simple Cylinder, but with a more complex sample matrix. It includes the ability to distribute the contamination across as many as four layers of

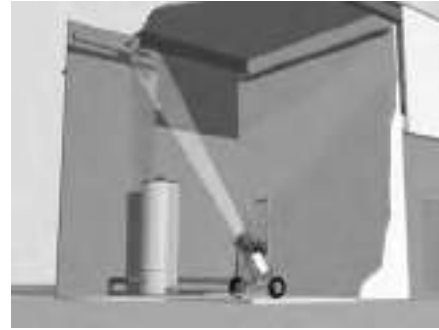


Figure 2
Using the ISOCS System to assay a pipe

material and to place an additional concentrated source anywhere in the container. Ideal for use in “What If?” analyses of non-uniformity in barrels and drums.

PIPE – A pipe, empty or full, including material that has plated out or built up on the inner walls, as shown in Figure 2.

CIRCULAR PLANE – The end of a barrel or tank, the bottom of a bottle containing a sample, or a filter cartridge. This would also be used for *in situ* measurements of ground. The radioactivity can be distributed in any manner in up to ten layers of sources/absorbers.

RECTANGULAR PLANE – A floor, wall, or ceiling, or soil *in situ*. The template allows for surface contamination as well as up to ten layers of internal contamination behind an absorber such as paint, paneling, or a floor covering.

EXPONENTIAL CIRCULAR PLANE – Similar to the Circular Plane, but here the radioactive source can be distributed to first increase in concentration and then decrease in concentration. Use this for fallout on soil, activation of concrete, analysis of resin beds, etc.

WELL OR MARINELLI BEAKER – Used for well logging applications, or for standard Marinelli beakers.

SPHERE – Internally contaminated spherical objects, like large pipe valves.

RECTANGULAR TUBE INT/EXT CONTAMINATION – Useful for ducting with surface contamination distributed on the four internal surfaces and/or four external surfaces.

CONE VIEWED FROM END – A truncated cone, like a beaker viewed from above or below with two source layers.

CONE VIEWED FROM SIDE – A truncated cone, like a beaker viewed from the side with one source layer.

L ANGLE EXTERNAL CONTAMINATION – An angle iron at any orientation with contaminated surface(s).

H/I BEAM EXTERNAL CONTAMINATION – Oriented as an I-beam or an H-beam with contaminated surface(s).

TANK PARTIALLY FULL OF FLUID – A cylinder on its side, viewed from side, below or end with one source layer.

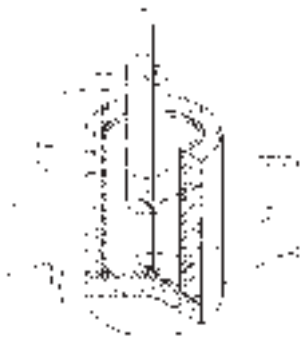
ROUND TUBE WITH INT/EXT CONTAMINATION – An open-ended tube on its side, viewed from the side with internal and/or external surface contamination.

ROOM/BOX WITH INTERNAL SURFACE CONTAMINATION – Detector inside a cube with contaminated surface(s).

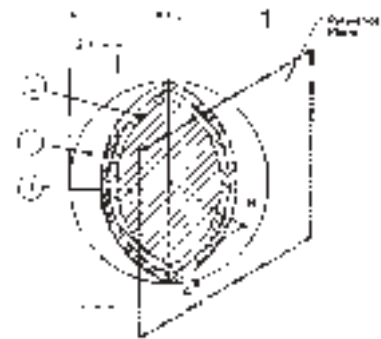
U CHANNEL WITH EXTERNAL CONTAMINATION – Square U-beam at any orientation with contaminated surface(s).

SPECIAL SPHERE – A multi-layer spherical source located inside a full drum or cylinder.

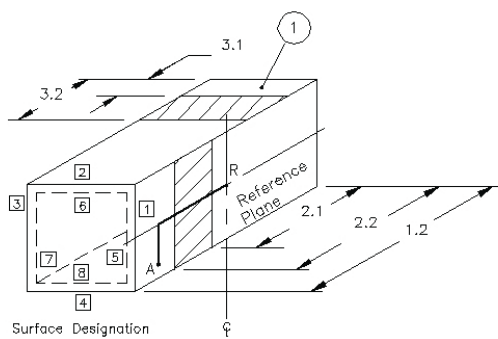




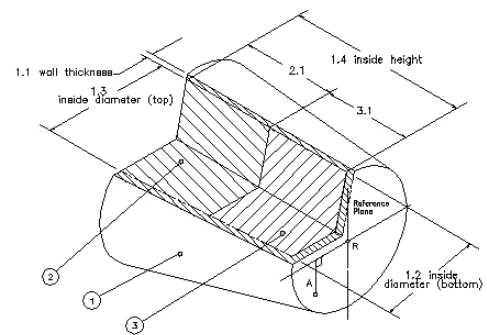
Well or Marinelli Beaker



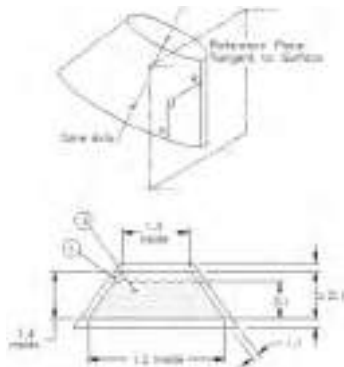
Sphere



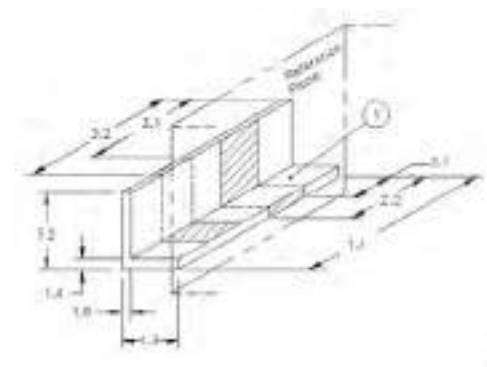
Rectangular Tube with Int/Ext Contamination



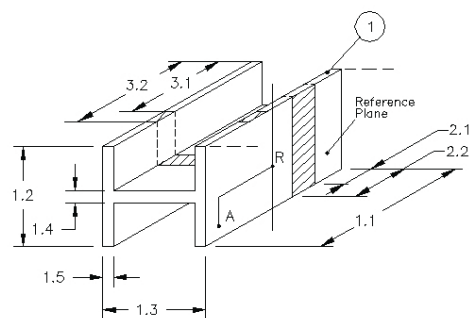
Cone Viewed from End



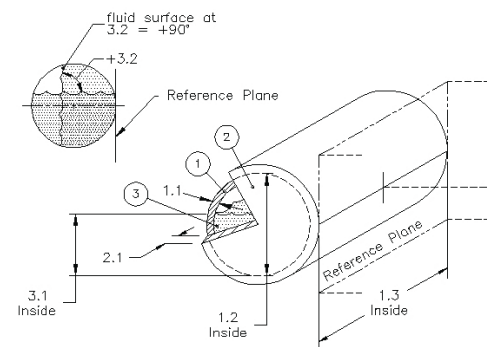
Cone Viewed from Side



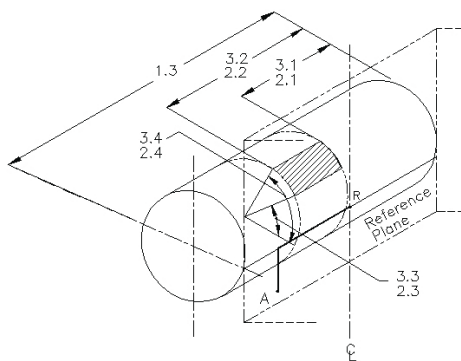
L Angle with External Contamination



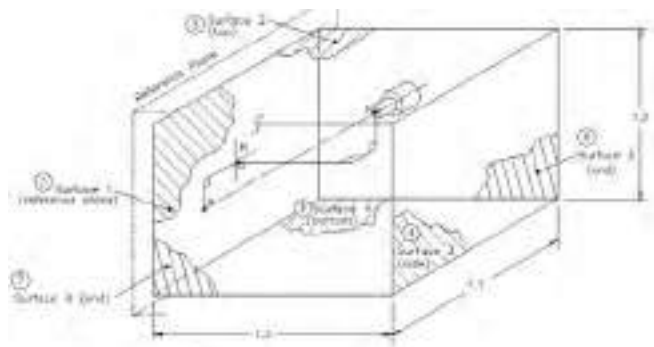
H/I Beam with External Contamination



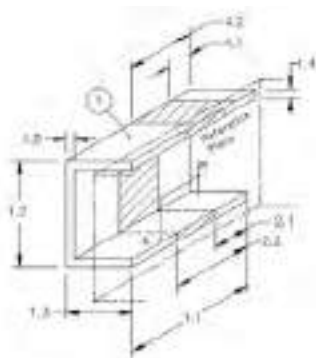
Tank Partially Full of Fluid



Round Tube with Int/Ext Contamination



Room/Box with Internal Surface Contamination



U Channel with External Contamination



Special Sphere

NOTE: Custom templates are also available. Consult the factory for details.

USING THE ISOCS CALIBRATION SOFTWARE

To illustrate how these templates and their related sample parameters are used, a typical ISOCS calibration will be described. It will be based upon the Simple Cylinder template, which would be one of the most commonly used to assay material contained in drums.

After installation, the ISOCS calibration software is accessed as a part of the Geometry Composer.

SELECTING THE TEMPLATE

Once a new file is opened in the Geometry Composer, the ISOCS group of geometry templates can be selected as shown in Figure 3. Selecting a template, such as the Simple Cylinder, brings up the geometry template window.



Figure 3
Selecting a Geometry Template

PARAMETER INPUT

The geometry template window, shown in Figure 4, facilitates entry of all geometry parameter values. These parameter entries include the selection of the detector, scale, dimensions, materials and the possible use of a detector collimator or underwater housing. Note that the window title always identifies the currently selected template, and the contents of the window are always tailored to that template.

To simplify the operation of the software, only a few of the parameters are mandatory; the others are needed only if you wish to have them used in the calculations. For example, the size of the sample is mandatory, but things like the size and type of any absorbers that may be located between the detector and the sample are only required when you wish to have them taken into account during the calibration process.



Figure 4
The Geometry Template Window

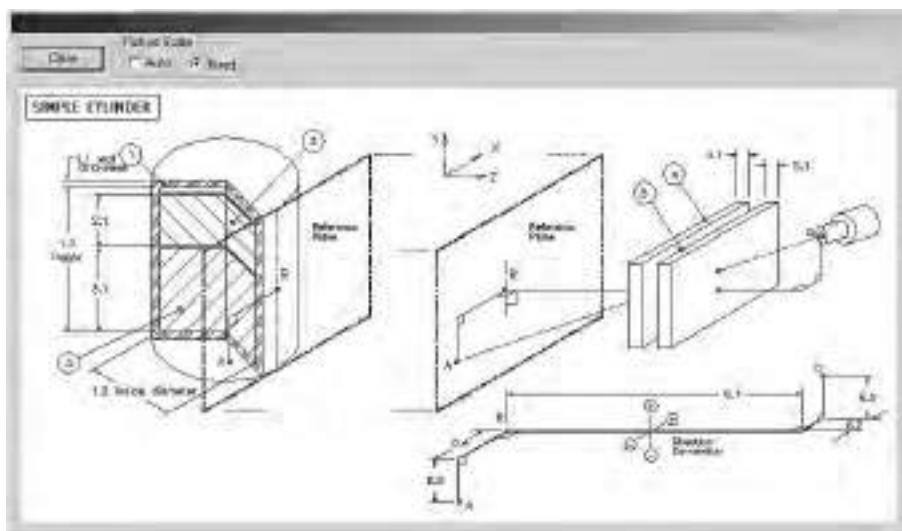


Figure 5
The Template Reference Diagram

DIMENSION ENTRY

The Dimensions Scale box in the geometry template window allows specification of the units for all dimensions entered. Changing the scale changes all of the entries on the form. Entry of dimension values is aided by referencing a detailed drawing of the template geometry, labeled with dimension indices. Figure 5 shows this drawing for the simple cylinder, accessed via the Show Template button.

MATERIAL ENTRY

During the entry of source parameters, the materials must be specified. The software performs absorption corrections for each of the object elements. An extensive library of available materials can be used to specify geometry component materials, with further composition information available by double clicking on the material of interest. Selection of the material also loads the default density, which can be edited if necessary. In addition, the MuEditor, shown in Figure 6, can also be called to create any custom materials. The program has all cross-sections of all the chemical elements stored in a library. Any material can be defined by atom fraction (chemical formula) or weight fraction.

COLLIMATOR/HOUSING ENTRY

The Housing and Collimator Edit buttons in the geometry template window can be selected to specify structures around the detector. A detector collimator can be detailed in the subsequent Edit Collimator window, shown in Figure 7, by indicating dimensions and materials or by choosing from a library of collimators. The Edit Housing window has similar types of specifications. These windows also can reference detailed diagrams, as shown in Figure 8, to aid in the entry of dimensions.

THE RESULTS

After entering the parameters, a preliminary check of the geometry validity is done before the data is formatted into a Geometry Composer Report, shown in Figure 9. Toolbar buttons allow editing of all aspects of the report, including environmental conditions affecting air quality. When satisfied, the file can be saved and converted to an efficiency CAM file – shown in Figure 1 – which can be stored, retrieved, and used for sample assay in exactly the same manner as those produced by traditional “calibrated source” calibration.

USING ISOCS TO DETERMINE THE ERROR LIMITS OF AN ASSAY

Another major benefit of the ISOCS Calibration is the ability to easily determine the error limits of the results of an in situ assay.



Figure 6
The MuEditor Window

“WHAT IF...?” ERRORS

This classification covers questions such as “What if the container walls are thicker than we think?”, “What if the container level is not as high as we think?”, and “What if the material matrix is different than we assumed?”

To test the impact of these types of assumptions on the results, all that must be done is:

1. Change the value of the parameter to be tested, such as Dimension 1.1 (container wall thickness).
2. Have a new efficiency curve generated.
3. Re-analyze the sample spectrum using this new curve.

In a matter of a few seconds you’ll see exactly what impact the new assumptions have on the assay.

NON-HOMOGENEITY ERRORS

This class of error is essentially the same as a sampling error in a traditional “take some random samples and send them to a lab for analysis” method of doing waste assay. That is, if the activity in a container is not homogeneously distributed, how do you know that the assay of your samples (or the results a single ISOCS measurement) truly represent the contents of the container?



Figure 7
The Edit Collimator Window

For the “sample and analyze” scenario, the only way to find out is to take a very large number of samples, and analyze the distribution.

Even then, the sampling results may not be correct for very non-uniform cases. If the sampling processes happened to completely miss a “hot spot”, there is no evidence of the error, nor any measure of the bounds of the error. With *in situ* Gamma Spectroscopy, none of the sample is missed, but some of it may have a different efficiency.

With the ISOCS Ge/Shield/Software System, just perform a few more sample counts with the detector positioned at different locations about the sample. Analyze against the best assumption of the sample definition. Examine the results. For nuclides with multiple energy lines, if all show the same activity, then most likely the calibration is good. If all of the nuclide results from the various source-detector geometries agree, then most likely the calibration is good.

On the other hand, if the results are not the same, just modify the parameters in the source geometry template and reanalyze. This won't take long, and the existing acquisition spectra can be used. This can all be done on site, with none of the turn-around delays inherent in the “sample and analyze” approach. Genie 2000 V2.1 has a utility that facilitates this process by plotting the activities from a nuclide's multiple energy lines to better evaluate their correlation and provide feedback for parameter adjustment.

TYPICAL RESULTS

Extensive testing and validation has been done on both the MCNP Detector Characterization and the ISOCS Calibration algorithms. The full MCNP method has been shown to be accurate to within 5% typically. ISOCS results have been compared to 119 results from both full MCNP and different radioactive calibration

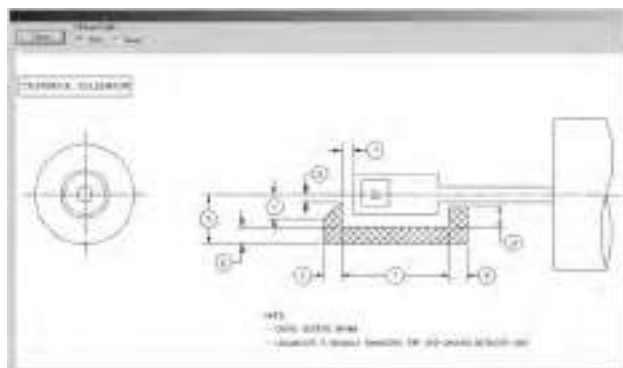


Figure 8
The Collimator Reference Diagram

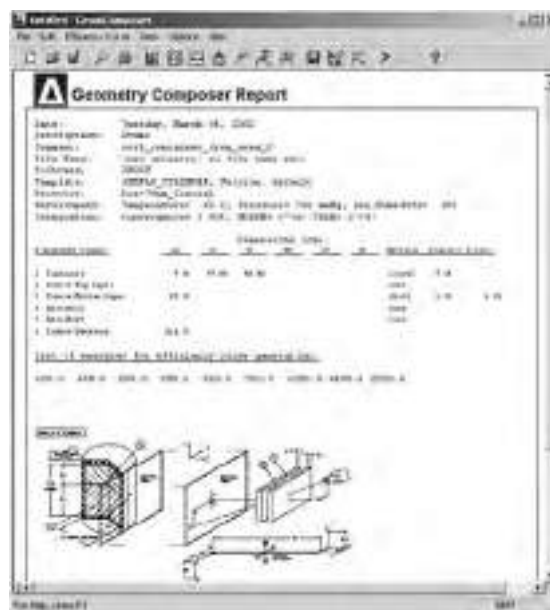


Figure 9
The Geometry Composer Report

sources. In general, ISOCS is accurate to within 4–5% at high energies and 7–11% at 1 s.d. for low energies. The full validation report showing the results of each of these tests is included with delivered software, and is available upon request to Canberra. A few of the comparisons are shown in Figure 10.

In addition to this generic validation document, Canberra offers Model ISOXVRFY. With the purchase of this product, the customer's Ge detector is used with the ISOCS calibration process to analyze a series of typical laboratory radioactive standards. A report of this process is provided.

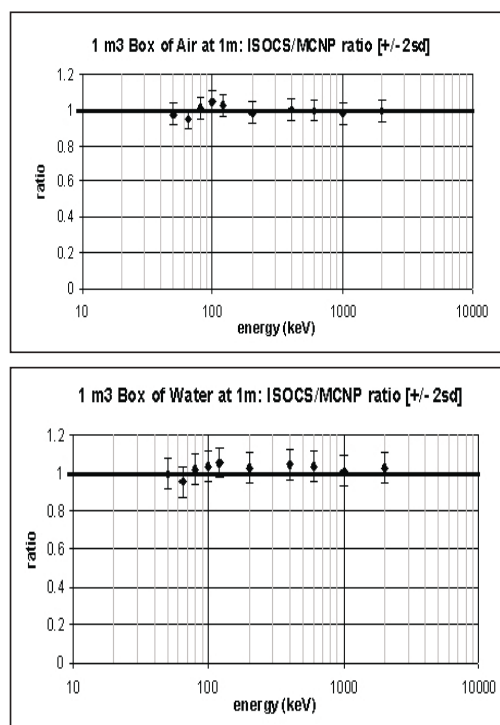


Figure 10
Extensive testing has shown that ISOCS and traditional calibrations typically agree within a few percent

ADDITIONAL INFORMATION

Additional information on ISOCS, its hardware and software components, and its applications may be found in the following publications, all of which are available from Canberra:

SPECIFICATION SHEETS AND MANUALS

- Model ISOXSHLD ISOCS Shield System
- Model 1300 InSpector 2000 Portable Spectroscopy Workstation
- Model S500/S502/S504 Genie 2000 Basic Spectroscopy Software
- Model S501 Genie 2000 Gamma Analysis Software
- Model S503 Genie 2000 PROcount Counting Procedure Software
- Model S573 ISOCS Efficiency Calibration Software User's Manual
- Model S573/S574 ISOCS/LabSOCS Validation and Verification Manual, Part ICN 9231205

APPLICATION NOTE

- *In Situ Gamma Spectroscopy with ISOCS, an In Situ Object Counting System*, Canberra Industries.

PUBLICATIONS

- *Ge Gamma Spectroscopy Characterization Tools for Contaminated Materials in Buildings, Boxes, and Dirt*, Bronson, Frazier, Canberra Industries, ANS/ENS International Winter Meeting '96.
- *ISOCS Mathematical Calibration Software for Germanium Gamma Spectroscopy of Small and Large Objects*, Bronson, F., and Young, B., Canberra Industries, Atraskevich, V., Verdansky Institute of Geochemistry and Analytical Chemistry, American Nuclear Society Annual Meeting '97.
- *Mathematical Calibration of Ge Detectors, and the Instruments That Use Them*, Bronson, F., and Young, B., Canberra Industries, NDA/NDE Waste Characterization Conference '97.
- *Nuclear Instrumentation Tools for Lower Cost and Higher Reliability Decommissioning of Buildings and Grounds*, Bronson, Frazier, Canberra Industries, TOPSEAL '96.
- *Validation of the MCNP Monte Carlo Code for Germanium Detector Efficiency Calibrations*, Bronson, Frazier and Wang, Ling, Canberra Industries, Waste Management '96.
- *Optimum Size and Shape of Laboratory Samples for Gamma Spectroscopy With Various Size and Shape Ge Detectors*, Bronson, F. CHP, Venkataraman, R. Ph.D., Young, B. Ph.D., 44th Annual Conference on Bioassay, Analytical and Environmental Radiochemistry.
- *Massemetric Efficiency Calibrations of Ge Detectors for Laboratory Applications*, Bronson, F. CHP, Venkataraman, R. Ph.D., Young, B. Ph.D., 44th Annual Conference on Bioassay, Analytical and Environmental Radiochemistry.
- *Mathematical Efficiency Calibration of Ge Detectors for Laboratory Sample Gamma Spectroscopy*, Bronson, F., Venkataraman, R. Ph.D., Young, B. Ph.D., 44th Annual Conference on Bioassay, Analytical and Environmental Radiochemistry.
- *In Situ Applications Experiences Gained in the Use of ISOCS, A Laboratory-Quality Nuclide-Specific Field Gamma Radioassay System*, Bronson, Frazier, Spectrum, '98 Conference.
- *Validation of In Situ Object Counting System (ISOCS) Mathematical Efficiency Calibration Software*, Venkataraman, R., Bronson, F., Atraskevich, V., Young, B. M., Field, M., Ninth Symposium on Radiation Measurements and Applications, '98.

- *ISOCS (In Situ Object Counting System) Portable Gamma Spectroscopy Instrument*, Booth, Leroy, CHP, (CP5) Research Reactor LSDP Project Report.
- *ISOCS, A Laboratory Quality GE Gamma Spectroscopy System that you can Take to the Source for Immediate High Quality Results*, Bronson, Frazier, CHP, Rapid Radioactivity Measurements in Emergency and Routine Situations Conference, '97.

SYSTEM REQUIREMENTS

To use the ISOCS Calibration Software, the following minimum system configuration is required:

DETECTOR

Any Germanium detector type or size, characterized by Canberra. For each detector, order one of the following:

Model ISOXCAL to characterize a Canberra detector that is on order; or ISOXCAL1 to characterize a previously ordered Canberra detector; or ISOXCAL2 to characterize a non-Canberra detector; or ISOXCALU to recharacterize a previous calibration. The same characterization works for both ISOCS and LabSOCS software.

SHIELD

Canberra Model ISOXSHLD ISOCS Shield, or equivalent, if applicable.

TRIPOD

Canberra Model INSITPOD lightweight tripod or Model 7413F heavy duty tripod.

SPECTROSCOPY SYSTEM

Any Canberra PC-based MCA system running the following software:

- Canberra Genie 2000 Basic Spectroscopy Software, V2.0 or later.
- Model S501 Genie 2000 Gamma Analysis Software.

The PC must have a math co-processor, and should be a 486DX or higher. For fast computations of large or collimated geometries, a high-end PC should be used.

RECOMMENDED OPTIONS

- Model ISOXVERFY Verification Counts with Laboratory Standards.
- Model 2324 QA Calibration Check Source.
- Model S503 Genie 2000 PROcount Counting Procedure Software.
- Model S505 Genie 2000 Quality Assurance Software.
- Model S506 Genie 2000 Interactive Peak Fit Software.
- Appropriate training on how to use the gamma spectroscopy software and the LabSOCS software, available at factory courses or on-site.

Model ISOXVERFY Verification Counts with Laboratory Standards is strongly recommended to provide proof of the validity of specific system results. When this model is ordered, the detector's characterization and LabSOCS are used to create a series of efficiency calibrations. Then, four different laboratory reference calibration standards are counted in seven different positions and analyzed as "unknowns" using these efficiency calibrations. A report is generated comparing the reported activity to the known activity. The sample types are two liter Marinelli beaker, 20 cc liquid scintillation vial, 50 mm filter paper, and 350 cc cylindrical container. These are all counted close to the endcap, and (except for the Marinelli beaker) at 10 cm from the endcap.



ORTEC®**ISOTOPIC-32 V4.0**Advanced Software Solution to
Gamma-Ray Waste Assay

ISOTOPIC V4 represents a SUBSTANTIAL move forward from previous versions of this program. Improvements to algorithms have been made, but in addition, great attention has been paid to improvements to useability.

ISOTOPIC V4 Benefits

- Provides quantitative assay of gamma-emitting waste samples with an emphasis on ease of use and practicality.
- Analyzes all types of gamma-emitting waste, fissile and non-fissile.
- Measure containers of many shapes and sizes, surfaces and even soils; via independently verified analysis methods; new algorithms for CLOSE geometry measurements.
- Use your own HPGe detector(s) and electronics or as part of an integrated ISO-CART™ system. Calibrate ANY detector on site, TRACEABLY, in minutes.
- Ideal for use with the revolutionary ORTEC trans-SPEC-100 portable HPGe spectrometer.
- Multiple measurements on a single object easily combined.
- Easy system expansion.
- New algorithm includes detector characterization parameters for improved accuracy.

ISOTOPIC-32 V4.0

Advanced Software Solution to
Gamma-Ray Waste Assay

For the uncollimated wide-area counting of soils, the "1-meter" methodology developed by the US DOE EML² and later extended³ is used. It is applicable in many situations:

- Decontamination assessment of previously used sites
- Assessment of nuclides deposited during emergencies
- Routine environmental monitoring near nuclear facilities

The EML methodology reduces a complex measurement problem to the product of three, simply-determined factors. The gamma-ray peak areas are related to the nuclide-specific activity by the product of the three factors. These factors have been determined for a range of detector types and soil conditions and are tabulated within the program. The efficiency calibration is determined using the stated efficiency according to the usual ANSI/IEEE 325-1996 convention at 1.33 MeV, and from the crystal length and diameter.

For improved accuracy at low energy, the user can use the same calibration used for container mode as an alternate to the EML method.

No special (and costly) Monte-Carlo characterizations of the detector are necessary. The attenuation correction is determined by selection of the soil type and type of nuclide distribution: recent (surface) deposits, older (washed-in) deposits or natural (uniform) deposits. The energy and peak shape calibration are performed using any multiline source and may be entirely automated. However you plan to use ISOTOPIC, there will be no unexpected detector calibration costs.

Support for Multiple Measurements of a Single Container

In the measurement of any large container of waste, several measurements are usually made from different directions to ensure the best results are obtained. This will be done sequentially if only one hardware system is available or simultaneously if there is access to multiple sets of hardware. ISOTOPIC can automatically combine the results taken either way by a user-defined weighted average. When multiple detectors are used at the same time, live spectra may be displayed on screen simultaneously from each detector, increasing user confidence.

Reporting

ISOTOPIC V4 provides GREAT flexibility in reporting within the standard product. All changeable parameters may be included in the standard output report. Analysis results are stored in an MS Access-compatible database, from which they are easily printed or exported for further processing into summary reports.

Hardware Support

ISOTOPIC V4, like all ORTEC CONNECTIONS-32 Applications software products, is compatible with all ORTEC MCA hardware. In particular, it is ideal for use in conjunction with the revolutionary trans-SPEC-100, a complete rugged and portable HPGe spectrometer system which does NOT require the use of liquid nitrogen.



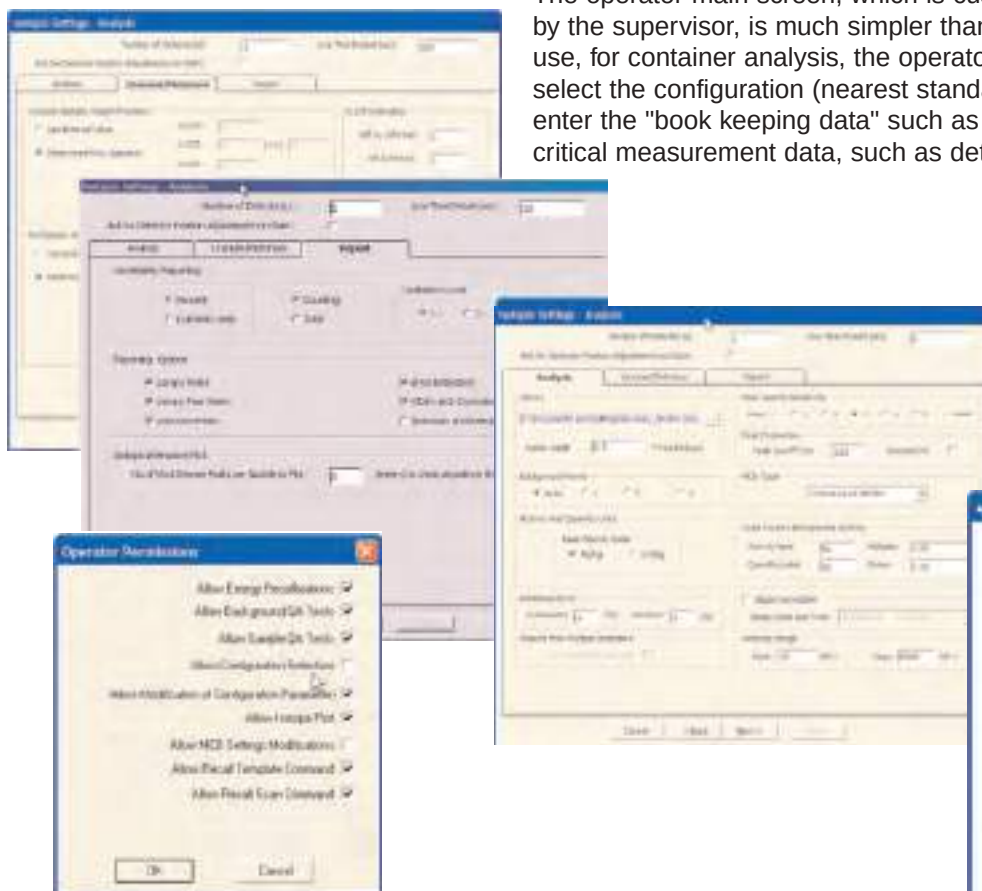
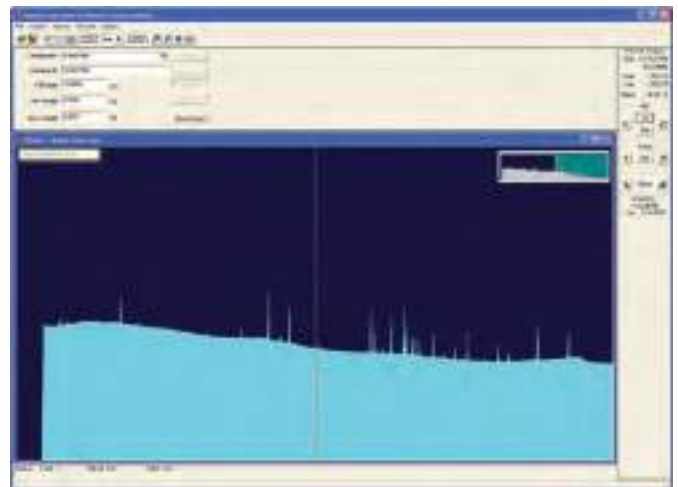
ISOTOPIC In Use

ISOTOPIC V4 has two modes: supervisor and operator. The operator need make choices only from the minimum subset of system options defined by the supervisor. The supervisor mode defines what operations the operator is allowed to carry out. A wizard guides the supervisor through the process of setting up the operator procedures. The wizard presents the parameters on logically grouped screens, with an emphasis on clarity of approach.

The supervisor/operator partitioning means that even semi-skilled operators in the field will collect good data with less wasted time for repeats (lower cost per measured item). Of course a skilled user may choose to run both modes.

Supervisor calibrates the system, creates libraries, defines sample geometries, matrices, collimators to be used, and other functions for later use by the operator. Supervisor can also define which features operator may access.

A handy "field of view" calculator provides a simple way to set up the detector-to-sample distance for the current collimator.



The operator main screen, which is customized by the permissions granted by the supervisor, is much simpler than the supervisor screen. In routine use, for container analysis, the operator need only start the acquisition, select the configuration (nearest standard container configuration), and enter the "book keeping data" such as container ID, type, weight, and the critical measurement data, such as detector-to-container distance.

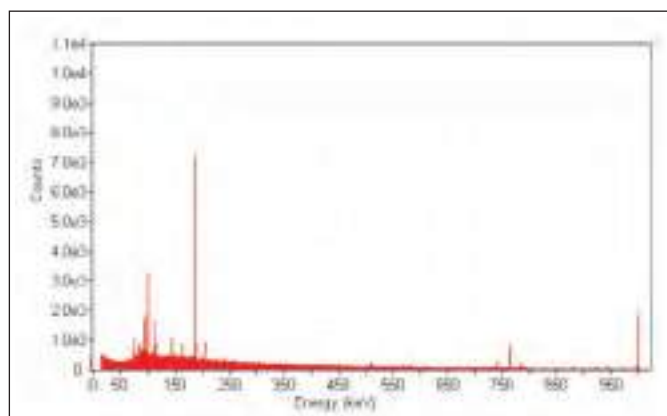
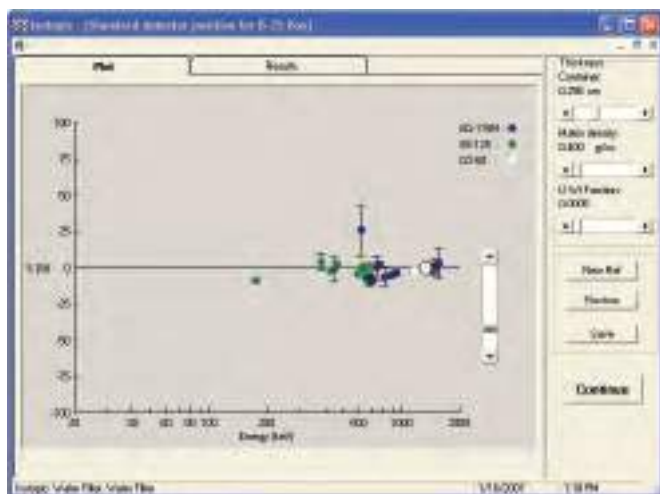
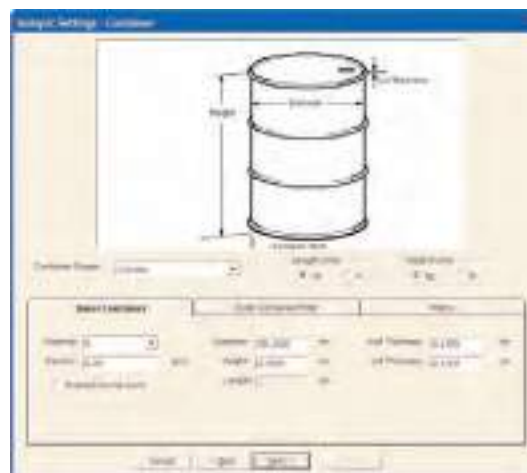
ISOTOPIC-32 V4.0

Advanced Software Solution to
Gamma-Ray Waste Assay

The standard container configurations and collimator configurations are defined and specified by the supervisor. A container configuration includes the default dimensions, materials, and matrix detail. Any number of these configurations may be specified and recalled by the operator when needed.

When the analysis is complete, the operator can adjust the container/matrix physical parameters (such as matrix density or container wall thickness) to optimize the results by use of the nuclide plot.

The plot shows the percentage difference between the corrected measured activity and the activity calculated for the reference peak for each nuclide. The supervisor selects the reference peak. The operator may optimize the analysis, adjusting the container, matrix, and weight fraction uranium, to refine the results. The visual evidence of a good result is immediately seen when the points from a multi-peaked nuclide are distributed normally about the "zero-line." In the case of uranium analysis, if the U-235 enrichment is known, it may be entered and then the U-238 and U-234 values are computed more accurately for samples containing weak uranium activity. Homogeneous and inhomogeneous samples are analyzed with increased accuracy by this method. A good indication that a package contains an inhomogeneous distribution of materials is that the user can obtain a combination of parameters which makes the activity plot flat for some nuclides but not others. This plot can form part of the output report, along with a plot of the spectrum itself.



Accuracy of Results

It is not easy to give a precise estimate for the accuracy to be expected. Several factors are influential: statistics and counting time, matrix density and inhomogeneity, calibration uncertainty, and the number of measurements carried out on a single container or object. A range of 10 to 50% accuracy should be considered representative, the smaller being for well-defined geometries in homogeneous and light matrices.

Reports

When the fine-tuning is finished, the operator selects a report for each nuclide showing the activity and weight. These results may then be printed and archived. The report files are written in either a database summary or as complete reports showing all input and correction information. Custom reports may be generated by the use of the report generator option. The tabulated components of error estimates can be used to help reduce overall uncertainties, for example, by extending count time or repositioning the detector. The user is also warned if any of the corrections appear to be excessively large. Minimum Detectable Activities (MDA) are calculated for each nuclide. Activities, grams of U or Pu, or MDAs from multiple measurements may be reported as weighted averages. The weighting is user definable.

Sample Name: Uranium from ISRA

Spectrum File Name: C:\User\Uranium from ISRA\B040400.Au3

Acquisition Information			
Start time	3/6/2001 12:54:38 PM		
Live time	1560	Real time	1570
Detector	DSPE-444No detector	Dead time (%)	1.72

Calibration			
File name	C:\User\Uranium from ISRA\CS		
Energy relationship	Created	3/6/2001 11:28:09 AM	
	Zero offset	0	
	Gain	0.3246744	
	Quadratic	0	
Efficiency calibration	Created	3/6/2001 10:17:31 AM	
	Type	Quadratic	
	Uncertainty Above Knee	20.41%	
	Uncertainty Below Knee	8.19%	
	Coefficients (Above the Knee)	-04.71318, 0.445302, -0.4633879	
	Coefficients (Below the Knee)	0, 0, 0	
	Detector (00000000 point-source reference distance)	30.0 cm	

Library	
Peak analysis library	C:\User\Uranium from ISRA
Library match with	0.5

Analysis parameters			
Start channel	20	Stop channel	18300
Peak cutoff (%)	50.0	Peak search sensitivity	5
MDA type	ORTEC Traditional	Background type	Auto
Base Activity Units	Bq/kg	Activity scaling factor	1.000E+0/1.000E+0
Activity Label	Bq	Quantity Label	
Random error (%)	0.0	Systematic error (%)	0.0
Debiased Fit	No	Uncertainty in percent	Yes
Counting uncertainty only	Yes	Confidence level (sigma)	1
U235 49-49 keV averaging	1	U235 1841001 keV averaging	1

Spectral corrections			
Decay correct to date	No	Decay corrected data/date	N/A
PdC correction	No	PdC File	N/A

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Library peaks								
Nuclide	Channel	Energy	Bkg Counts	Net Counts	CPS	1 Sigma	FWHM (keV)	Flags
U-235	252.94	25.28	4132	338	0.048	10.47	2.364	S
U-238	385.52	46.13	4237	493	0.197	23.98	1.039	S
U-234	430.00	53.71	2779	27	0.011	334.13	0.008	S
S - Peak fails shape tests D - Peak area deconvoluted M - Peak is close to a library peak								
Library peak matrix								
Nuclide	Ave. activity	Energy	Activity	Codes	MVA	Comments		
U-234	6.445E+6	53.71	0.037E+6	S	1.449E+6	G		
		128.83	5.445E+6	E	4.513E+6	GC		
General Configuration Info								
Configuration name:		Recall	Max Calibration:			N/A		
Orientation:		Side	Height:			19.0 cm		
Detector standoff:		23.0 cm	Collimator depth/center:			N/A		
Database:		C:\Users\Orion\Desktop						
Container								
Type:		Cylinder	Material:			Fe		
Thickness (entered):		0.10 cm	Thickness (effective):			6.10 cm		
Height:		28.0 cm	RI Height:			28.0 cm		
Diameter:		28.0 cm						
Tare weight:		9.0 kg	Container density:			7.80 g/cc		
Sample weight:		1.247 kg						
Matrix								
Material:		Conductible	Density (initial estimated):			0.300 g/cc		
U total fraction (initial estimated):		0.0	U total fraction (initial estimated):			0.0		
Thickness:		19.89 cm						
Weight fraction of U (eff.):		0.0						
Volume:		6.16E+3 cc						
Gross weight:		0.947E+0 kg						
Net weight:		1.047E+0 kg						
Density (measured):		0.300 g/cc						
Density (adjusted):		0.300 g/cc						

Peak Correction Factors

Energy	Nuclide	Activity* (Bq/Kg)	Air	Container Correction	Coll.	Activity** (Bq/Kg)
58.32	U-235	1.033E+04	1.010	1.68E+3	1.00E+0	1.75E+07
63.39	U-238	4.044E+03	1.009	9.08E+2	1.00E+0	3.70E+06
81.24	U-235	8.272E+03	1.009	2.16E+2	1.00E+0	1.80E+06
84.17	U-235	6.897E+03	1.009	1.84E+2	1.00E+0	1.28E+06
89.97	U-235	5.472E+03	1.008	1.39E+2	1.00E+0	7.69E+05
92.39	U-238	2.490E+04	1.008	1.25E+2	1.00E+0	3.14E+06
92.81	U-238	2.033E+04	1.008	1.23E+2	1.00E+0	2.52E+06
93.36	U-235	2.376E+03	1.008	1.20E+2	1.00E+0	2.88E+05

Uranium Analysis			
Gross of uranium			3.005E+3
Weight% U-235 (185 to 1001-keV region)			0.5 (+/-) 0.18%
U235 Enrichment calculated (%)			0.297 (+/-) 0.112
Isotopic results			
Nuclide	Weight(g)	Activity (Bq)	% Uncertainty (1Sigma)
U-235	1.170E+01	8.514E+05	25.2%
U-238	3.632E+03	4.722E+07	24.7%
U-234	5.995E-02	1.381E+07	45.9%
Total activity			
Total Activity		5.185E+07 Bq	
Total Alpha Activity		6.185E+07 Bq	

ISOTOPIC Specifications

General

The acquisition control and quantitative analysis functions are integrated into a concise package for use in PC-based *in situ* gamma spectroscopy systems for the determination of radioactive content of containers, objects, surfaces, and soils.

Operating System

32-bit application for Windows 2000/XP network capabilities; support for preemptive multitasking; and ORTEC *CONNECTIONS-32* compliant.

Spectroscopy Hardware Support

ISOTOPIC is recommended for use with the ORTEC digiDART® Portable MCA system. However, all ORTEC MCBs (past and present) and all other devices supported by ORTEC *CONNECTIONS-32* (see *CONNECTIONS-32* literature) are compatible. Support is built-in for advanced operations (where provided in hardware): amplifier gain/shaping control, Auto-PZ, "optimize" and InSight™ mode, digiDART field mode, graphical setting of MCB spectrum stabilizer and statistical uncertainty peaks. Specifically, the trans-SPEC-100 is recommended for *in situ* measurements (literature on request).

File Formats Supported

ORTEC .SPC and .CHN, and ASCII ".SPE" are supported as standard in file save, recall, and compare functions. Other file formats may be imported by the use of A49-B32 Data Master.

Quantitative Spectrum Analysis Methods

Peak Search

Peak Search by library direction for specified nuclides, plus Mariscotti peak search for non-specified nuclides, both main library and supplemental ("suspect") library are used.

Interactive Bulk Sample Parameter Adjustments

Interactive Matrix and container adjustments and automatic attenuation correction for new matrix. Easy to use graphical display of relative analysis results to show the best matrix.

Deconvolution Method

Both peak finder and library are used to direct the deconvolution process. Automatic recalibration of Energy/channel based on identified peaks where possible.

Choice of Detection Limit Formalisms

- ORTEC Traditional
- ORTEC Critical Level
- No MDA (report zeros if less than MDA)
- KTA Rule
- Detection Limit 2 sigma — Japan
- Detection Limit 3 sigma — Japan
- Currie Limit
- RISO MDA
- ORTEC LLD
- Peak Area
- Air Monitor — Gimrad method
- Reg. Guide 4.16 Method
- Counting Lab — USA
- DIN 25 482.5 Erkennungsgrenze
- DIN 25 482.5 Nachweisgrenze
- GTN5/CEA/EDF (France)
- Nureg 0472



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Decay Corrections

- Decay correct to any date/time, either back or forward

Spectral Corrections

- Peaked Background Correction
- Random summing (high-rate counting losses)
- Library-based peak interference correction

Reporting

Choose any ORTEC Standard report option:

- Direct to printer
- Automatically written to database
- Crystal Report formatted output
- Report in HTML format. From there it can be saved as a disk file.

Calibration

Energy Calibration

- Multipoint, quadratic for energy and FWHM
- Automatic Energy Calibration (Patent No. 6,006,162)

Semi-Empirical Efficiency Calibration Fit Options:

ISOTOPIC Mode

A point source calibration is established via one of the following methods:

- Single Function Polynomial (x-Point)
- Interpolative above and below "knee"
- Quadratic above or below user-set "knee"
- Linear above or below user-set "knee"

The point source calibration is extrapolated to the physical geometry-matrix situation via point-source Kernel calculations internal to the program.

Infinite Plane Mode (for Soils and Surfaces: Uncollimated Detector)

The Beck² 1-meter methodology, with extension to large detector sizes³, as used by US DOE Environmental Measurements Laboratory (EML). The EML methodology is used to produce an efficiency curve based on detector dimensions and IEEE efficiency value. The soil density and attenuation is specified in user-editable alpha/rho files.

Soil Attenuation Factors

In soil, attenuation depends on the soil thickness and density, which is modeled by the parameter α/ρ (*where α is the reciprocal of the relaxation length, defined to be the soil thickness required to reduce the flux at a particular energy by a factor of e, and ρ is the soil density in gm/cc*). For a surface distribution α/ρ is infinite, while for uniform (natural emitters) distribution, α/ρ is 0. Values of α/ρ ranging from 0.05 to 0.5 have been found to describe realistic fallout distributions accurately, the more aged fallout being represented by the smaller α/ρ values.

The α/ρ values are nuclide-specific and are stored in a table which may be edited by the user to reflect the measurement conditions.

Analysis Library Manager

ISOTOPIC includes a comprehensive library editor for building custom analysis libraries. The editor allows the operator to cut and paste nuclides and peaks from master libraries, add flags to individual peaks for identification (single escape peak, x-ray, or other) and analysis (key line or exclude from activity calculation), and save the library as any name. It also includes full integration of the Nuclide Navigator library tool (sold separately as model C53-B32). ISOTOPIC will use Nuclide Navigator if installed, and can read Nuclide Navigator libraries in Microsoft Access Database format (no conversion necessary), and save libraries in database format for use by Nuclide Navigator.

Quality Assurance

ISOTOPIC quality assurance complies with the demands of ANSI N13.30. For each detector the following are monitored:

- Total detector background
- Total (decay corrected) activity for all calibration nuclides
- Average FWHM ratio (spectrum to calibration standard)
- Average FW1/10M ratio (spectrum to calibration standard)
- Average peak shift from library values
- Actual peak centroid energies

Calculational Details

Summary of the ISOTOPIC Mode Methodology for Containers

The activity of an isotope in a container is given by:

$$A_{isotope} = \frac{PA_{meas} (CF_{item})(CF_{col})}{BR_{\gamma ray} (\epsilon_{det})}$$

where

- $A_{isotope}$ = activity of the isotope to be reported (Bq/μCi),
- PA_{meas} = measured peak area for a reference gamma ray of the isotope (c/s),
- CF_{item} = container, matrix, and sample self-attenuation correction factors
- CF_{col} = collimator correction factor,
- $BR_{\gamma ray}$ = gamma-ray branching ratio,
- ϵ_{det} = detector efficiency measured using a NIST-traceable point source (cps per Bq, μCi).

When gram quantities, $Mass_{isotope}$, of reported isotopes are needed, these are given by:

$$N = \frac{A_{isotope}}{\lambda_{isotope}} \quad Mass_{isotope} = \frac{N(At)}{Av}$$

where

- N = number of atoms of a reported isotope,
- $\lambda_{isotope}$ = decay constant of a reported isotope (sec⁻¹),
- At = atomic number of the measured isotope (g/Av),
- Av = Avogadro's number.

Result Averaging of Multiple Measurements

When results of multiple measurements are combined, a weighted average is calculated according to:

$$A_{average} = \sum A_i w_i / \sum w_i$$

where

- A_i = individual activity (gram or MDA) results,
- w_i = user-defined weighting factors.

ISOTOPIC-32 V4.0Advanced Software Solution to
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The specific activity, A (Bq/m² or Bq/g) is related to the net peak count rate N_f by:

$$A \text{ (activity)} = \frac{N_f \text{ (net peak count rate)}}{\left(\frac{N_f}{N_0}\right) \left(\frac{N_0}{\Phi}\right) \left(\frac{\Phi}{A}\right)}$$

where

- N_f/N_0 = angular correction factor of the detector at that energy for a given source distribution in the soil,
- N_0/Φ = peak count rate per unit uncollided flux for a parallel beam of gamma rays of the peak energy that is incident normal to the detector face (cpm/γ s⁻¹)
- Φ/A = total uncollided flux at the peak energy arriving at the detector per unit inventory or concentration of the nuclide in the soil (γ cm⁻² s⁻¹) or (γ g⁻¹ s⁻¹).

The method of estimating calibration factors uses information about the detector and the distribution(s) of radionuclides being measured:

- Detector Efficiency (expressed as %)
- Detector Orientation (up or down)
- Detector Aspect Ratio (calculated as crystal length/crystal diameter)
- Deposition Profile Parameter (α/ρ value(s))

α/ρ is assumed to be 0 (for uniform distribution) for all natural emitters. α/ρ is assumed to be infinite (for surface only distribution) for fallout on undisturbed soil.

Beck's method is implemented in ISOTOPIC by calculating values for each of the calibration parameters. The calculation is carried out for each gamma ray of all the nuclides identified.

Collimator Correction Factors

If a container is large enough, some gamma rays will penetrate any collimator that may be surrounding the germanium detector. The collimator correction factor is heavily dependant on the diameter of the collimator, the depth of collimation, and the wall thickness of the collimator.

The collimator correction factor is determined by computing the fraction of the activity that is not shadowed by the collimator and then computing the penetration length through the collimator for the remaining activity. This is determined for each voxel of the item being measured.

System Prerequisites

As a *CONNECTIONS-32* product, ISOTOPIC requires a Windows XP platform. Interfacing of MCB hardware to the system may be by USB, Ethernet, printer port, serial port, or ORTEC Dual-port Memory. (Check hardware literature for details). ISOTOPIC will run on any PC that supports the above Windows OS and has 20 MB of disk space.

Ordering Information

Model	Description
ISOPLUS-B32	ISOTOPIC-32
ISOPLUS-G32	Documentation for ISOPLUS-B32
ISOPLUS-K32	Upgrade from ISO-B32 or M-1-B32 to ISOPLUS-B32
ISOPLUS-N32	ISOPLUS-B32 Network Copies
ISOPLUS-U32	Update to ISOPLUS-B32

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Specifications subject to change
091907

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Model ISOXSHLD ISOCS Shield Systems

Features

- Portable Germanium detector shield system for *in situ* assays
- Includes 25 mm and 50 mm thick lead shields
- Reduces interfering 1000 keV radiation a factor of 7.5 (25 mm) and 60 (50 mm)
- Modular design for easy handling
- Epoxy paint on all exterior surfaces for ease of cleaning
- Includes 30°, 90°, and 180° collimators (each thickness) plus solid end caps for background measurements
- Includes a rear shield set (requires RDC option on detector)
- Wheeled mounting stand with brakes for ease in moving the shield from one sample to the next
- Large wheels for easy movement: 40 cm (16 in.) at rear, 20 cm (8 in.) in front
- Upper and lower detector mounting positions, with 180° detector rotation at either location
- Easy to assemble and to change detector positions
- Built-in laser aiming device
- Components from 25 mm and 50 mm shields may be combined to build a sample counting chamber

Description

This ISOCS (*In Situ* Object Counting System) Shield (Figure 1) has been designed as the optimum in convenience and functionality for *in situ* gamma spectroscopy with a germanium detector. The system is supplied with both 25 mm and 50 mm lead shielding which gives you the ability to utilize the sensitivity and low background capabilities of a laboratory grade germanium spectrometer directly on site, regardless of where that site is located.

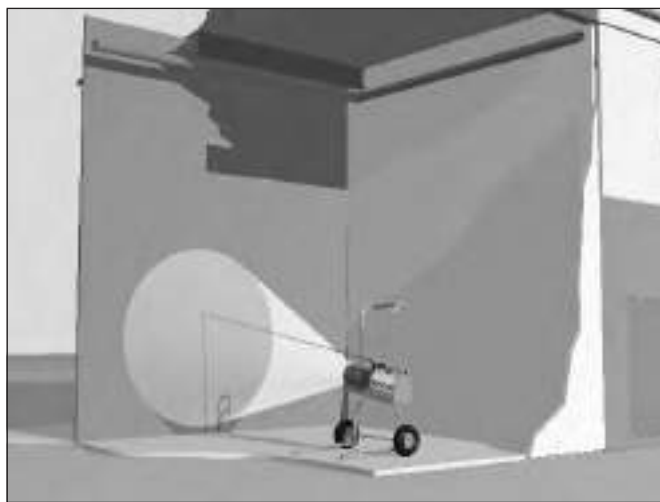


Figure 2
Using the ISOCS Shield System to assay a wall.

Unshielded, the detector has a nearly 360° field of view, and can be used for 4π counting of the walls/floors/contents of an entire room. The field of view can be reduced (Figure 2) by adding the shield and collimators to provide fields of view of 30°, 90°, and



Figure 1
The ISOCS Shield Systems and all of their available components installed on an RDC Ge Detector with a Big MAC Dewar. (See Figure 3 for more details.)

nearly 180° by simply sliding the appropriate shield components on the mounting rails. In addition, a completely shielded sample chamber can be assembled by combining the components from the two systems.

Its standard wheeled mounting frame makes it easy to move the shield to the assay site, and the individual rear wheel brakes keep it at the desired location.

The mounting frame features both an upper (for 1 meter detector/ground counting) and lower (normal) detector mounting location. The detector can be rotated 180° from down to up, and stopped at any position, not just a few fixed positions, for maximum positioning flexibility. The detector holder even includes a laser pointer to aid in aiming the detector at remote objects.

Whatever the sample and wherever it's located, the ISOCS Shield System has the versatility and flexibility to count it.

THE DETECTOR

A major benefit of the ISOCS Shield System is the ability to use most any type or size of detector for the intended application required. While the most typical would be a coaxial germanium with a 30-80% relative efficiency, the shield can easily accommodate detectors as large as 100-120% relative efficiency, and even larger ones with minor modifications.

Phone contact information

Benelux/Denmark (32) 2 481 85 30 • Canada 905-660-5373 • Central Europe +43 (0)2230 37000 • France (33) 1 39 48 57 70 • Germany (49) 6142 73820
Japan 81-3-5844-2681 • Russia (7-095) 429-6577 • United Kingdom (44) 1235 838333 • United States (1) 203-238-2351

For other international representative offices, visit our Web Site: <http://www.canberra.com> or contact the Canberra U.S.A. office.

M3567 2/03 Printed in U.S.A.

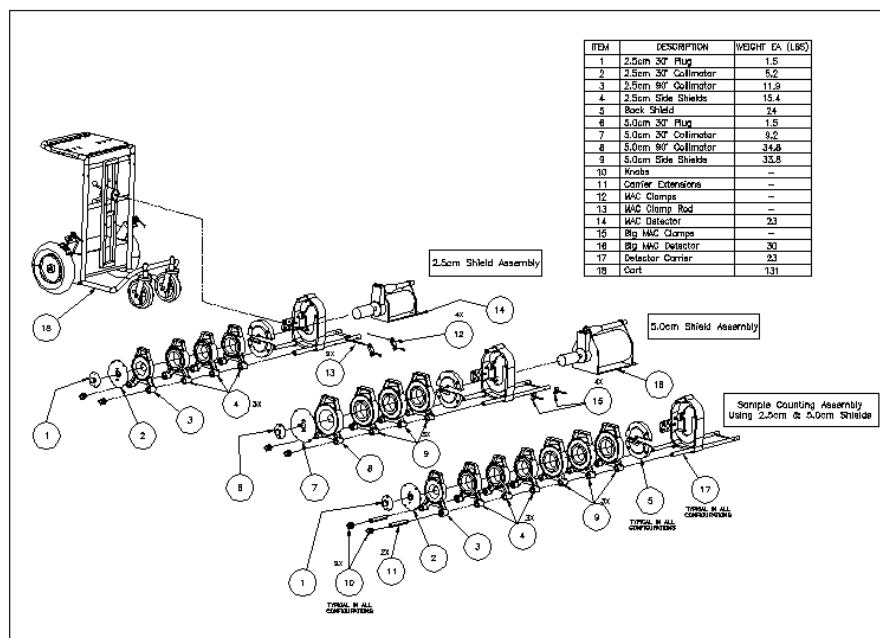


Figure 3
The components of the complete ISOCS Shield System.

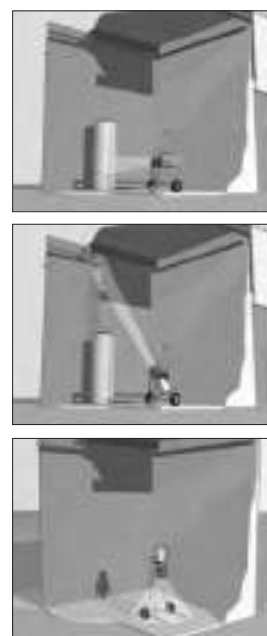


Figure 4
The flexible ISOCS Shield System adapts to most any *in situ* counting geometry.

A wide variety of detector types are also supported, including our new Broad Energy (BEGe) detector for both low and high energy counting at the maximum efficiency, plus also Reverse Electrode (REGe), Low Energy (LEGe), and Extended Range (XtRa) Germanium, giving the ISOCS user the flexibility to match the detector's response to the types of samples that are anticipated.

To take the maximum advantage of the ISOCS shield, the detector of choice should be mounted in a Remote Detector Chamber (RDC) cryostat. This allows the back shield to be used, minimizing any interfering radiation that may enter the rear of the detector. This is very useful for emergency measurements, for D&D measurements, and applications inside Nuclear Power Plants.

Whichever type and size of detector is chosen, its energy response must be fully characterized by Canberra if it is to be used with the Model ISOXSW ISOCS Calibration Software as part of a complete *in situ* assay system. All of the physical dimensions of the ISOXSHLD are pre-loaded into the ISOCS software for easy selection.

THE CRYOSTAT

The ISOCS Shield System is designed to accommodate either Canberra's MAC (Multi-attitude Cryostat) or Big MAC. The MAC provides two days LN₂ holding time and may be operated in any orientation with no LN₂ spillage or reduction in capacity. It can fit within the optional 702 shipping case, along with the PC and InSpector MCA. Alternatively, the Big MAC with a five day holding time may be used if LN₂ filling is inconvenient.

THE DETECTOR SUPPORT FRAME

The ISOCS Shield System (Figures 1 and 3) includes a wheeled mounting frame that is used both for transporting the system about a site and for sample assay. The frame features upper (for 1 meter downward looking orientation) and lower (for side-upward looking) mounting positions for the detector and shield. In either of the two positions, the detector may be freely rotated about its mounting axis, providing maximum flexibility in detector positioning. No tools are required for detector rotation or shield assembly.

To aid in positioning the detector, particularly when assaying a remote object like an overhead coolant pipe (See Figure 4b), a battery operated low power laser aiming device is built into the shield's mounting assembly handle.

THE SHIELDS AND COLLIMATORS

The two shield assemblies supplied with the ISOCS Shield System are essentially identical except for the thickness of the lead, 25 mm (1 in.) and 50 mm (2 in.), from which they are made. The components of the complete shield system, together with a detector in an RDC cryostat attached to a Big MAC Dewar, can be seen in Figure 3.

Each shield consists of the following modules:

BACKSHIELD SECTIONS – These two elements connect together and shield the rear of a detector mounted in an RDC cryostat. Its location is behind the detector chamber (Figures 5a and 5b). This shield is 35 mm thick and is used for both side shield sets.

MAIN BODY MODULES – These make up the side walls of the shield. There are three with the 25 mm shield; and three with the 50 mm shield. When counting Marinelli beakers, only 1 or 2 modules are used (Figure 6a).

COLLIMATORS – Includes collimators for 0°, 30° and 90° fields of view. With no collimators installed, the detector end-cap is even with the side shield and field of view is nearly 180°. A conical section reduced the field of view to 90°, and another conical section reduces it further to 30°. A final conical section completely closes the opening for the "0°" field of view, which is used for performing background runs and for use as a chamber closure when counting packaged samples (See Figure 6b).

Each module is manufactured from low background lead, and has an outer shell. All exposed lead and the outer shell have a durable baked epoxy coating for easy cleaning and decontamination.

Figures 8 and 9 show the radiation attenuation and background reduction of the various shields and collimators.



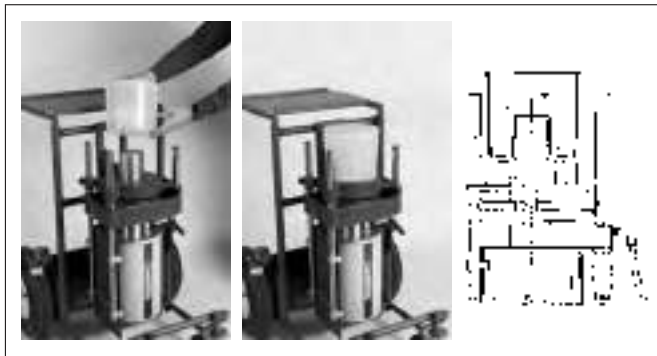
5a: The detector and mounting assembly. Note that the detector has the RDC chamber and that the backshield is installed.



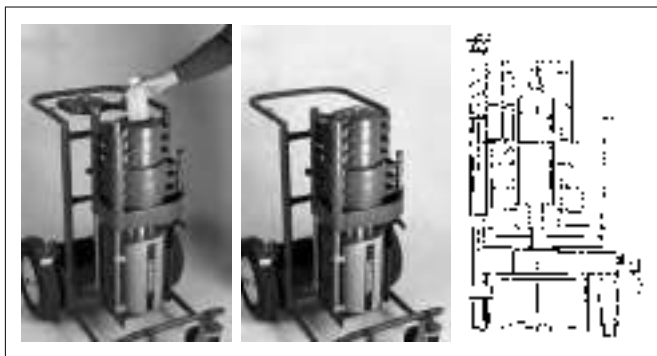
5b: The same detector with the 50 mm Shield and a 90° Collimator installed.

Figure 5
Details of the ISOCS Shield and Mounting System.

All of the sections are designed to slip onto the system's mounting rails, as shown in Figures 3 and 5, without the use of tools.



6a: Configured for a Marinelli beaker.



6b: Configured for a traditional sample.

Figure 6
The ISOCS Detector and Shield can be configured for counting both Marinelli beakers and traditionally packaged samples.

While the shields are normally used individually, the modules from the two may be easily combined to form a shielded sample chamber, as shown in Figure 6b. The 50 mm modules shield the detector, with the 25 mm modules forming the sample chamber. The sample size can be up to 10 cm diameter by 15 cm in height.

For assaying samples in Marinelli beakers, the configuration shown in Figure 6a is used. Note that this arrangement can be constructed from either the 25 mm or 50 mm shields.



7a: Unshielded and uncollimated.



7b: Shield and collimator installed.

Figure 7
When counting soil or floors, the ISOCS can be used uncollimated for maximum sensitivity, or collimated to reduce background and field of view.

For most every sample encountered in most any environment, the ISOCS Shield System provides the flexibility and performance for fast, accurate assays.

Specifications

DETECTOR REQUIREMENTS

TYPE – Any type of Canberra Germanium detector with an end cap diameter of 10 cm (4 in.) or less. Contact factory for larger diameter end caps.

CRYOSTAT WITH REMOTE DETECTOR CHAMBER – Not required, but strongly recommended, especially for projects with multiple radioactive sources in the area, e.g. D&D, or Nuclear Power Plant measurements. Greatest background reduction will be attained with the RDC-4 cryostat option.

DEWAR – Either a MAC or Big MAC may be used. Big MAC is recommended for most applications because of the 5 day holding time.

FRAME AND DETECTOR/SHIELD HOLDER

CONSTRUCTION – Baked epoxy painted carbon steel (stand) and cast aluminum (shields). Includes instrument shelf and shield carrying tray (Figure 10). The system can be easily disassembled for access to small areas, or shipping. For mounting the detector onto other platforms, e.g. boom truck, crane, lift truck, Jeep, the detector/shield module can be used without the frame.

SHIELDS

MATERIAL – 25 mm (1 in.) and 50 mm (2 in.) lead.

FINISH – Cast aluminum exterior with epoxy paint on all exposed lead.

BODY MODULES – Includes three 25 mm and three 50 mm modules.

COLLIMATORS – Includes 30° and 90° collimators. Custom sizes available.

END SHIELDS – Includes solid end shield for each thickness for background measurements.

BACKSHIELD – Includes a set at 35 mm for use with both lead shield sets.

FULLY ASSEMBLED SYSTEM – nominal values

74 cm wide x 102 cm high x 104 cm long (29 x 40 x 41 in.) fully assembled.

WEIGHT – nominal values, with full Big MAC cryostat

FRAME/DETECTOR/HOLDER – 83 kg (184 lb).

WITH ALL 25 MM SHIELDS – 123 kg (272 lb).

WITH ALL 50 MM SHIELDS – 160 kg (354 lb).

WITH BOTH SHIELD SETS – 190 kg (419 lb).

HEAVIEST SHIELD MODULE – 16.3 kg (36 lb).

ACCESSORIES TO CONSIDER; see separate “ISOCS *In Situ* Accessories” specification sheet for more details

MODEL INSITPOD – Light weight portable collapsible tripod for uncollimated *in situ* soil measurements (Figure 11).

MODEL 7413 or 7413F – Heavy duty tripod.

MODEL 7411 – Submarine Housing to protect detector and allow performance of *in situ* measurements under water or in other hostile environments (e.g. heavy contamination).

**ISO 9001
SYSTEM
CERTIFIED**

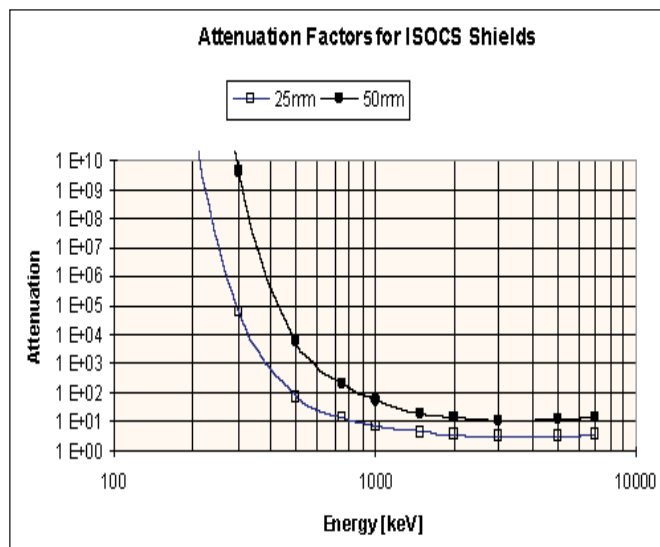


Figure 8
Attenuation vs. Energy for the ISOCS Shields.



Figure 10
ISOCS shield ready to move to new location; all shield accessories fit into carrying tray on back; computer and MCA can be strapped down to tray on top.

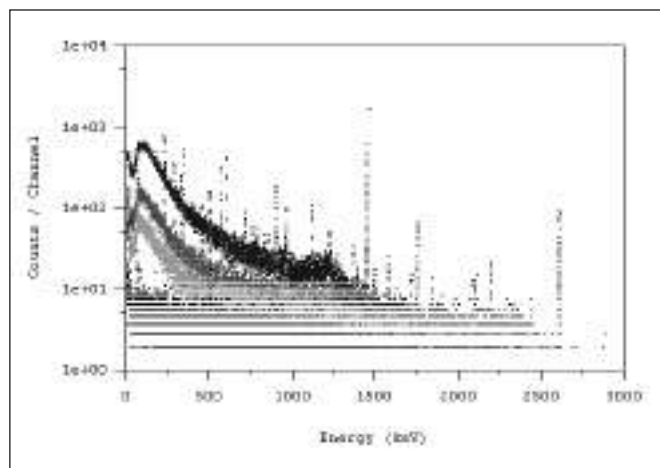


Figure 9
Background Radiation vs. Energy for the ISOCS 50 mm Shields. Data shown represents unshielded (top), side shield only (middle), 90° collimator and 30° collimator.



Figure 11
Optional accessory item: Model INSITPOD for light weight and portability.



Features

- Combines Multiple Assay Techniques
- Quantitative and Isotopic Gamma-Ray Analysis
- Passive Neutron Multiplicity Coincidence Counting
- Active Neutron Interrogation using Differential Die-Away Technique (DDA)
- 200 liter (55 gallon) drums and 320 liter (85 gallon) Over-Packs
- MDAs of less than 30 nCi/g
- Fully Automated Operation and Analysis
- 27% Efficiency for ^{240}Pu fission neutrons
- 2.8% Active Mode Detection Efficiency
- Multiple HRGS Detectors
- 10^8 neutron/second Zetatron
- AAS based Active Neutron Mode Moderator Correction
- NDA 2000 Non-Destructive Analysis Software
- Operates under Windows® NT®/2000

Integrated Waste Assay System (IWAS)

Introduction

IWAS, Canberra's Integrated Waste Assay System, is designed to quantify plutonium and uranium in 55 gallon drums and 85 gallon over-packs. The IWAS provides passive and active neutron interrogation and quantitative gamma analysis, allowing rapid characterization of TRU wastes for proper shipment and disposal.



Figure 1.
Integrated Waste Assay System (IWAS)

The IWAS provides a complete NDA instrumentation suite in a single assay cavity. The system offers performance, speed and ease of use while using a fraction of the floor space of three independent systems. The IWAS is based on the Canberra High Efficiency Neutron Counter (HENC) design with integrated Differential Die-Away (DDA) and High Resolution Gamma-Ray Systems. Results from individual assay modes are combined automatically by the NDA 2000 software to provide the best result for the sample. Because all assays are performed by the same system in a single assay sequence, there is no confusion over item ID or modification of drum contents between assays.

The system is designed to be operated as an automated counting system which can process batches of drums, or can be incorporated in a facility process line. The following sections describe the various assay sub-systems, hardware, software and indicate typical performance characteristics.

Description

Shield Assembly

The IWAS shield assembly provides a 4π , 40 to 55 cm thick High Density Polyethylene (HDPE) moderator/shield as a measurement chamber for the drums and over-packs. The thickness of the HDPE assembly provides the needed personnel protection against the Zetatron pulsed neutron source used in the active neutron analysis mode. The neutron shield also provides an assay chamber that minimizes the effects of outside gamma radiation levels.

As configured, the neutron shielding is also effective for the gamma-ray measurements and is equivalent to a 2.5 in. thick steel shield allowing detection levels in the gamma analysis mode similar to those obtained in Canberra's Q² system.

The shutter mechanism is interlocked with the neutron generator so that inadvertent damage to the HPGe detectors is avoided. All doors and access points are interlocked with the neutron generator to minimize the risk of inadvertent personnel exposure.

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Integrated Waste Assay System (IWAS)

Sample Handling Mechanism

In order to provide minimum personnel exposure from the neutron source and a uniform response within the assay cavity, the shield door extends below the assay cavity floor. Sample loading and unloading is provided by a bridge conveyor. Normally the bridge conveyor will mate with the facilities material handling conveyor system. The drum is presented to the bridge conveyor, signaling the IWAS system to start the assay sequence. (Note: A stub conveyor can be provided if a facility does not use an automated material handling system.) Once the drum is positioned at the start of the bridge conveyor, the drum is weighed, the door opens and the drum moves into the assay cavity. The loading mechanism is designed for a working weight of up to 545 kg (1200 lb) and drum sizes of 200 and 320 liters (55 and 85 gallons).

Passive Neutron Assay System

The IWAS utilizes the same basic design parameters for passive neutron assay analysis as Canberra's High Efficiency Neutron Counter (HENC)¹. The passive neutron counting system uses 122 ³He proportional tubes arranged in a 4 π counting geometry providing a total neutron detection efficiency of 27% for ²⁴⁰Pu spontaneous fission neutrons and a coincidence sensitivity of 47 cps/gram ²⁴⁰Pu effective. Due to its generally greater accuracy, the passive neutron analysis mode is the primary assay technique for plutonium over the range of 0.1 grams to several hundred grams.

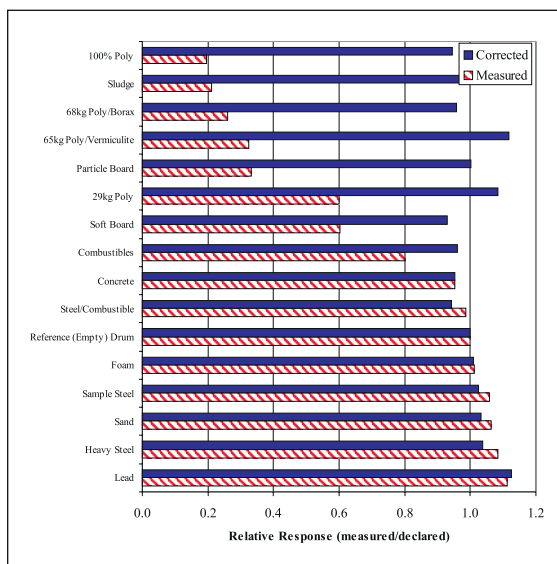


Figure 3.

Typical AAS correction results for the IWAS counter for a series of homogeneous and non-homogeneous matrix drums with a simulated uniform source distribution. The uncorrected response is reported as much as a factor of five too low while the corrected response has a standard deviation of only a few percent.

The detection level for the passive neutron analysis mode is approximately 4 mg ²⁴⁰Pu effective in 600 seconds at sea level and decreases to 1.7 mg for a 3600 second count time. This corresponds to a detection level of 30 mg weapons grade Pu (6% ²⁴⁰Pu) in 3600 seconds.

Add-A-Source (AAS) Matrix Correction

The Add-A-Source (AAS) technique provides a means of measuring the impact of the waste matrix on the neutrons emitted within the drum. In practice, a small ²⁵²Cf source (about 100 000 n/s) is introduced into the assay cavity with no sample in the counter. The measurement is repeated after the sample is loaded and the results compared. The difference in the measured count rates can be used to correct the measured sample rate. The IWAS includes a single position AAS matrix correction module. An illustration of the AAS measurement is shown in Figure 2. The ²⁵²Cf source is normally stored in a shield module located to one side of (or above) the counter. The source is automatically moved through a guide tube to the interrogation position and then retracted.

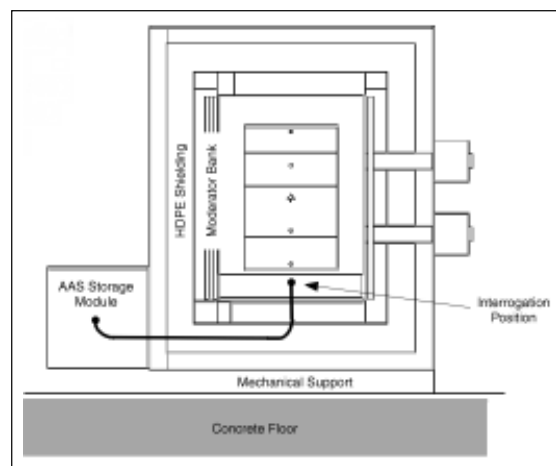


Figure 2.

Relative location of the ²⁵²Cf source interrogation position for the IWAS Add-A-Source measurement.

Integrated Waste Assay System (IWAS)

For homogeneous distributions of Pu in the drum, the AAS correction results in a typical error of $\pm 2\%$ from the expected values. Without the correction, the errors can exceed 50%. The effectiveness of the AAS correction is illustrated in Figure 3.

Passive Neutron Analysis Background Corrections

The coincidence neutron background has two primary sources: the presence of nearby fission sources and cosmic-ray-induced neutron events. The IWAS shielding is sufficient to remove most of the ambient neutron background, but cannot eliminate the neutrons generated by cosmic rays interacting with the counter's body or the contents of the sample. Drums containing lead or steel have an associated cosmic-ray-induced coincidence background (or interference) that results in a positive bias in the reported mass if not corrected. Conversely, highly moderating drums (e.g. sludges) tend to attenuate the cosmic-ray-induced coincident neutrons, potentially resulting in a negative bias. The IWAS can correct for these effects using the NDA 2000 software.

The NDA 2000 software has a suite of correction algorithms available. The Matrix Based Background Correction (patent pending) will adjust the background rates based on the moderator content of the drum determined from the AAS measurement. The cosmic-ray rejection (CCR) algorithms include the typical truncation techniques as well as a more sophisticated multiplicity analysis that can determine the high-Z material content of the drum and correct the measured coincidence rates (patent pending) for this effect and eliminate the bias.

Active Neutron Interrogation

The active neutron interrogation mode allows the IWAS to provide lower detection levels than would normally be achievable by a passive neutron assay system in a short counting time. The active neutron analysis uses an intense pulsed neutron source to induce fission in the plutonium and uranium contained within the drum. The neutrons from the induced fission events are detected in a sub-set of the ^3He tubes that are mounted in cadmium wrapped HDPE packages. The detection efficiency for induced fission neutrons within these Fast Neutron Detector Packages (FNDP) is 2.8%. The difference in the characteristic decay time for the source neutrons to thermalize and induce fission and the characteristic decay time for neutrons to be detected gives the technique its sensitivity and its name – Differential Die-Away (DDA). Figure 4 illustrates the relative time response for a drum with and without uranium.

The IWAS active neutron analysis mode is based on the Second Generation Differential Die-Away technique, but with enhanced matrix correction algorithms. Traditional second generation DDA systems rely on the passive neutron measurement to estimate the moderator correction factors and so cannot provide a measured correction for uranium only or for low Pu content drums. The IWAS provides both absorber and moderator correction factors for the matrix effects even when there is no fissile material within the drum. The absorber correction is based on the ratio of neutrons detected in the cavity and barrel flux monitors. The IWAS system uses the AAS measurement for the determination of the moderation correction, providing a more accurate measurement for the low fissile mass drums. The overall effectiveness of the matrix correction factors is illustrated in Figure 5.

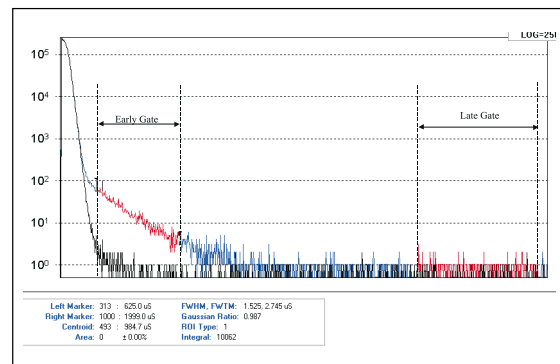


Figure 4.
Time response of the Fast Neutron Detector Packages for a zero matrix drum. The upper curve shows the response for a 1 gram ^{235}U source and the lower for a drum with no fissile material.

Gamma-Ray Assay System

The gamma-ray assay system is based on Canberra's Q² concept². Two or more High Resolution Germanium Detectors are mounted on retractable stands that allow the detectors to be inserted into the shield assembly during the passive neutron assay. The thick HDPE shield serves as an effective gamma-ray shield, allowing detection levels of less than 10 mg ^{239}Pu in a 600 second count time using two BE2820 detectors. Additional or larger detectors can lower this detection level substantially.

Integrated Waste Assay System (IWAS)

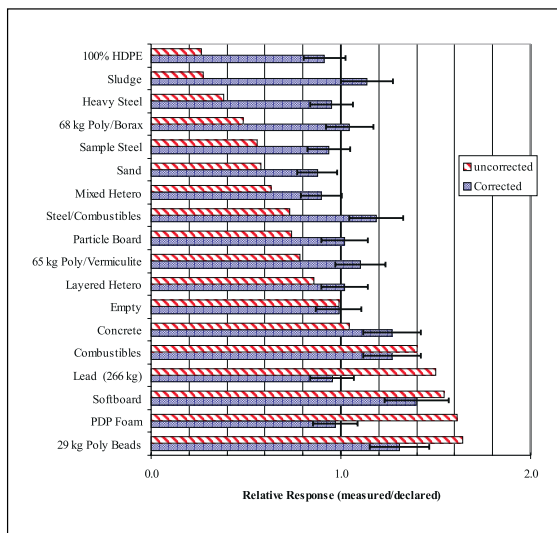


Figure 5.
DDA analysis results showing the corrected and uncorrected response from a uniformly distributed uranium source.

Gamma-Ray Transmission Matrix Correction (Option)

A transmission measurement option is available for the IWAS system to provide a measured matrix correction, rather than the density based correction approach of the Q² style systems. The transmission source shield and actuator mechanism houses one 5 cm long line

source for each HRGS detector. The sources are located across the assay cavity at the same height as the germanium detectors. This measurement provides an accurate determination of the average density of the matrix material in the drum at multiple positions in the drum.

The sources are interconnected by a rod and exposed by being pulled vertically up into the collimator slots. This design ensures that the sources will drop into the shielded position in the event of a power failure. Sensors verify the fully open and fully closed positions of the transmission sources, and a red warning light indicates when the transmission source is exposed.

Plutonium Isotopics Measurement

The IWAS is typically provided with Canberra's Broad Energy Germanium (BEGe) detectors. These detectors provide the efficiency required for quantitative gamma measurements and the resolution required for the most sensitive plutonium isotopics codes, such as the Multi-Group Analysis (MGA) software, developed at Lawrence Livermore National Laboratory by Dr. Ray Gunnink. Canberra's MGA code has been enhanced for waste assay applications and the complications resulting from poor counting statistics. This package can provide plutonium isotopics for very small sources in waste containers. In addition to the plutonium isotopics, it will determine other actinides such as ²³⁵U, ²³⁸U, ²³⁷Np, and ²⁴¹Am. (Note: other isotopics codes such as the Los Alamos FRAM code and TRIFID are available upon request).

Table 1. IWAS Gamma System Detection Levels.

Nuclide	Energy (keV)	Typical LLD (pCi/g) ^a Density (g/cc)				Worst Case LLD (pCi/g) ^b Density (g/cc)			
		0.1	0.3	0.8	1.8	0.1	0.3	0.8	1.8
¹³⁷ Cs	662	0.72	0.32	0.20	0.16	1.04	0.52	0.60	1.76
¹³⁴ Cs	800	0.75	0.35	0.20	0.15	1.05	0.55	0.55	1.35
⁶⁰ Co	1173	0.65	0.26	0.17	0.13	0.86	0.39	0.39	0.69
⁵⁸ Co	810	0.75	0.35	0.20	0.15	1.05	0.55	0.55	1.35
¹⁴⁴ Ce	134	12	5.6	4.1	4.0	17	10	27	198
²³² Th	908	2.2	1.0	0.6	0.5	2.9	1.6	1.5	3.2
²²⁸ Th	239	1.8	0.8	0.6	0.5	2.5	1.5	3.0	17.0
²²⁸ Th	583	2.1	0.9	0.6	0.5	2.9	1.5	1.9	7.7
²³⁸ U	1001	93	39	24	20	126	60	61	135
²³⁸ U	609	1.3	0.6	0.4	0.3	1.9	0.9	1.1	3.2
²³⁵ U	185	1.6	0.75	0.55	0.5	2.3	1.35	3.2	21.5
Pu detection levels in nCi/g									
²³⁹ Pu	414	19.9	9.0	8.5	5.6	30.1	16.4	25.2	124

a. Detection levels for a nominal 600 second passive assay.

b. Estimated detection levels for a non-self attenuating point source at the position of lowest sensitivity in the drum.

Integrated Waste Assay System (IWAS)

Table 2. IWAS Detection Levels for U and Pu for the three analysis modes.

Matrix (net weight)	Pu Detection Levels (mg total Pu)			HRGS Detection Levels ^d	
	DDA ^a	PNCC ^b	HRGS ^c	²³⁵ U (mg)	²⁴¹ Am (mCi)
Combustibles (54 kg)	10	70	10	16	1.0
Scrap Steel (220 kg)	20	80	40	61	4.5
Wet Soil (70 kg)	6	100	16	23	1.6
Sludge (150 kg)	45	250	35	50	3.5

- The ²³⁵U detection levels for the DDA mode will be 1.5 times greater than the Pu detection levels.
- Weapons Grade Plutonium ($\approx 6\%$ ²⁴⁰Pu), and the counter is installed near sea level with no additional cosmic-ray shielding.
- Limits for two BE2820 detectors.
- Quantitative gamma detection levels for ²⁴¹Am and ²³⁵U not keyed to neutron measurement.

IWAS Detection Levels

The typical detection levels for the three analysis modes of the IWAS are presented in Table 2. The detection levels are stated for a typical assay duration (Passive measurement: 700 seconds, Active Neutron: 120 seconds, AAS matrix measurement: 60 seconds). Sample load/unload and QA check measurements put the total assay sequence count time at 21.5 minutes. These detection levels are equivalent to 30 nCi/g.

Dynamic Range

Detection limits are only half the story for most waste assay systems. Typical applications require that the assay system accommodate wastes containing hundreds of grams of plutonium. The integrated assay techniques allow the software to determine the optimum analysis mode whether the drum contains a few mg or 200 grams of plutonium. At the low concentrations (a few hundred mg or less), the combination of active neutron and quantitative gamma analysis generally provides the best result. However, for high concentrations, the active neutron and quantitative gamma analyses suffer from self-attenuation effects so that the combination of passive neutron coincidence and gamma-ray isotopics provides the best result. The IWAS can accurately accommodate this entire mass range in a single instrument.

Total Measurement Uncertainty

IWAS reports the final assay values based on an analysis of the data from all available analysis modes. For each assay mode, the software performs a set of analytical tests (e.g. was gamma-ray self attenuation observed?) to determine the validity of the individual mode and its associated Total Measurement Uncertainty (TMU). The best assay result is selected based on the results of the diagnostic tests, mass range, and TMU for the analysis mode.

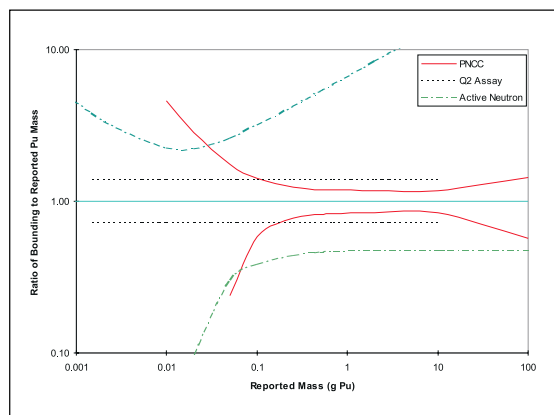


Figure 6.
Total Measurement Uncertainty estimate for a 50 kg combustibles drum (10 minute passive count time, at 1500 meters altitude) with no prior knowledge of the waste matrix. In the simple case, the assay choice selection is based predominantly on the reported Pu mass.

S529C NDA 2000 Software

The system is operated from Canberra's NDA 2000 software. NDA 2000 is a complete acquisition, analysis and archival package for use with all Canberra neutron and gamma waste assay counters.

Analysis Modes

NDA 2000 supports a variety of analysis types to provide flexibility in sample assay. With NDA 2000, it is possible to select which type or types of analysis are to be performed for a given sample. A selection of the system and analysis types supported by the IWAS operating under NDA 2000 are given in Table 3.

Integrated Waste Assay System (IWAS)

Table 3. IWAS Analysis Modes Under NDA 2000.

Quantitative Gamma-Ray Spectroscopy
■ Segmented Gamma-Scanning
■ Multi-Detector Analysis (Q^2)
■ Transmission Correction
■ Differential Peak Attenuation Correction
■ MGA/MGAU Isotopics Analysis
Passive Neutron Counting
■ Totals Neutron Counting
■ Passive Coincidence Counting
■ Passive Multiplicity Analysis
■ Add-A-Source Matrix Correction
■ Cosmic-Ray Neutron Coincidence Correction
Active Neutron Counting
■ Differential Die-Away
■ Add-A-Source Matrix Correction
Simultaneous Neutron-Gamma Assay
Total Measurement Uncertainty Analysis
Automated Drum Handling
Automated Waste Assay (AWA) Review

Setup

NDA 2000 offers Simplified Startup through the use of a wizard to step the user through the setup of a neutron assay system. For most standard system configurations, default counter profiles exist to facilitate initial system startup. To define a new counter, the user selects from a list of predefined systems or creates a new one. The wizard leads the user through the counter setup. To minimize setup errors, the wizard will prompt the user if a required parameter is omitted.

The setup utility provides a single location for the entry of sample and matrix parameters, assay sequence, and hardware definition. And it simplifies definition of new container and sample types as well as default isotopic and reference mass files.

Operations

Following setup, operation can be as simple as a single click of the mouse, where a full assay sequence is launched requiring little or no operator intervention.

The software accommodates neutron, gamma and integrated data acquisition systems. Integrated gamma-neutron assay sequences can acquire this data simultaneously, sequentially or independently. Following completion of the measurements, the neutron and gamma-ray assay results can be combined automatically even if the measurements were performed days apart.

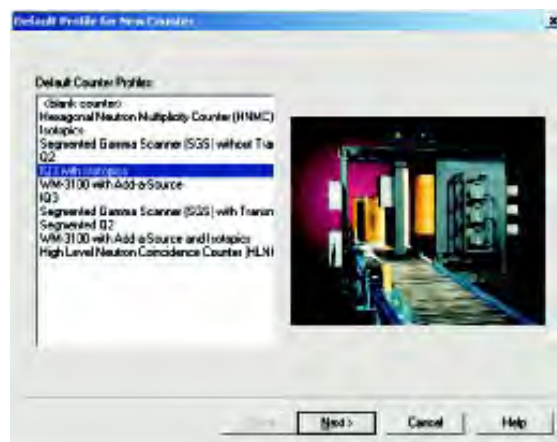


Figure 7.
NDA Setup Wizard simplifies software startup.

Physical

The overall dimensions of the passive active neutron counter are 645 cm long by 400 cm wide and 254 cm tall. This footprint includes the requirements for the door in the open position and the PLC control cabinets, plus a 150 cm long load conveyor. Overall weight of the counter is approximately 8000 kg.

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1. "The Design of a High Efficiency Neutron Counter (HENC) for Waste Drums to Provide Optimized Sensitivity for Plutonium Assay," H.O. Menlove, et al., Proceedings of the 5th Nondestructive Assay and Nondestructive Examination Waste Characterization Conference, Salt Lake City, UT, January 14-16, (1997).
2. " Q^2 - A Very Low Level Quantitative And Qualitative Waste Assay And Release Certification," F. Bronson, Proceedings of Waste Management '90, February 25-28, 1990, University of Arizona, Tucson, Arizona.



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Group NIS-5**

**Nonproliferation and International
Security Division**

Application Guide to Gamma-Ray Isotopic Analysis Using the FRAM Software

Edited by Heather L. Edwards, Weirich and Associates, for Group IM-1

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Application Guide
to Gamma-Ray
Isotopic Analysis
Using the FRAM Software

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Duc T. Vo

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List of Abbreviations and Acronyms

ADC	analog-to-digital Converter	MC&A	measurement control and accounting.
ARIES	Advanced Retirement and Integrated Extraction System	MeV	million electron volts
ASTM	American Society for Testing and Materials	MGAU	multi group analysis, uranium
AWCC	active well coincidence counter	MOX	mixed oxide
CRM	certified reference material	mfp	mean free path
DEC	Digital Equipment Corporation	MS	mass spectroscopy
DOE	Department of Energy	MUDPI	Multiple Detector Plutonium Isotopic System
ESARDA	European Safeguards Research and Development Agency	NDA	nondestructive assay
FRAM	Fixed energy, Response function Analysis with Multiple efficiencies. Also a Scandinavian word meaning “forward” or “onward.” The name of the Los Alamos gamma-ray isotopic analysis software.	NIM	nuclear instrumentation module
FWHM	full width at half maximum	PIDIE	Plutonium Isotopic Determination Intercomparison Exercise
HEU	highly enriched uranium	PANDA	passive nondestructive assay of nuclear materials
HPGe	high-purity germanium	ppm	parts per million
IAEA	International Atomic Energy Agency	R&D	research and development
IIU	intelligent isotopic unit	RF	Russian Federation
IRMM	Institute of Reference Materials and Measurements	ROBOCAL	Robotic Calorimetry and Gamma Ray Isotopic System
keV	kilo electron volts	ROI	region of interest
LAPIS	Los Alamos Plutonium Isotopic System	RSD	relative standard deviation
LA-UR	Los Alamos unlimited release	SAI	solution assay instrument
LANL	Los Alamos National Laboratory	SGS	segmented gamma scanner
LLNL	Lawrence Livermore National Laboratory	SNM	special nuclear material
MBA	material balance area	TASTEX	Tokai Advanced Safeguards Exercise
MCA	multichannel analyzer	TCPA	transmission-corrected passive assay
MCB	multichannel buffer	TGS	tomographic gamma scanner
		UMCBI	universal multichannel buffer interface
		US	United States
		WIPP	Waste Isolation Pilot Plant

Application Guide to Gamma-Ray Isotopic Analysis Using the FRAM Software

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ABSTRACT

The FRAM Application Guide discusses in detail the development, performance, and application of the PC/FRAM gamma-ray isotopic analysis code.

After discussing the basic principles of gamma-ray isotopic analysis, we describe the development of gamma-ray isotopic analysis at Los Alamos and the conditions that led to the development of PC/FRAM. The version and feature history of all four (as of this writing) versions of FRAM is outlined and is followed by a detailed discussion of how FRAM works.

We document the performance of FRAM (measurement bias and measurement precision and repeatability) for isotopic analysis of gamma ray spectra from a wide range of plutonium and uranium samples. Because good performance can only arise from high-quality data, we also describe and recommend measurement conditions and practices to assure the best possible data for FRAM analysis.

We also discuss the parameter file structure of the FRAM software and describe in detail how the experienced spectroscopist can tailor FRAM to essentially any isotopic analysis application.

The FRAM Application Guide concludes by describing automated systems, FRAM application to CdTe detector spectra, and the extreme measurement analysis problems successfully completed by FRAM.

I. INTRODUCTION

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A. Purpose of This Application Guide

This application guide is written to provide information and guidance to the users of the FRAM* gamma-ray isotopic analysis software, used in many nondestructive assay (NDA) and materials control and accounting (MC&A) applications. This guide will cover all aspects of the FRAM software, including usage, development history, algorithms, parameter files, performance, and measurement applications.

The Department of Energy (DOE), National Nuclear Security Administration, Office of Policy Integration and Technical Support (SO-13) is the sponsor for this application guide.

B. Isotopic Analysis Applications in Nondestructive Assay

1. Calorimetry.

A calorimeter (Likes 91a, Likes 91b, Bracken 02, ASTM 00) measures the heat produced by a sample of special nuclear material (SNM), the heat arising primarily from the alpha decay of the isotopes making up the SNM. Calorimetry is most widely used to quantify plutonium and americium in plutonium-bearing items. Elemental plutonium almost always contains a mixture of isotopes, with ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , and ^{241}Am present in most plutonium-bearing items. Each isotope produces a characteristic amount of heat proportional to its decay rate and decay energy. This decay heat, when quantified per gram of isotope, is called the specific power, has the customary units of watts/gram isotope, and is denoted by P_i . The specific powers can be calculated from fundamental principles and can also be directly measured from pure isotopes. The accepted values for the specific powers of the plutonium isotopes and ^{241}Am are given in Table I-1 (ASTM 00).

Table I-1. Specific Power Values for the Isotopes of Plutonium.

Isotope	Half Life (yr)	Specific Power (mW/g isotope)	Standard Deviation (mW/g isotope)
^{238}Pu	87.74	567.57	0.26
^{239}Pu	24119	1.9288	0.0003
^{240}Pu	6564	7.0824	0.002
^{241}Pu	14.348	3.412	0.002
^{242}Pu	376300	0.1159	0.0003
^{241}Am	433.6	114.2	0.42

* FRAM is the name of the gamma-ray isotopic analysis software developed over the years in the Safeguards Science and Technology Group, NIS-5, at the Los Alamos National Laboratory (LANL). FRAM is a word of Scandinavian origin meaning “forward” or “onward. It is also an acronym of the general features of the code, Fixed energy, Response function Analysis with Multiple efficiencies.

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The total power W from a mixture of isotopes is the sum of the power from each heat-producing isotope.

$$W = \sum_i m_i \cdot P_i \quad . \quad (I-1)$$

Here m_i is the mass of the i th isotope and P_i is the specific power of the i th isotope with the sum taken over all heat-producing isotopes, most usually those in Table I-1. Now, define R_i as the mass fraction m_i/M where M is the total mass of all the plutonium isotopes; Eq. I-1 becomes

$$W = M \sum_i R_i \cdot P_i \quad . \quad (I-2)$$

This equation allows us to define the effective specific power P_{eff} in units of watts/gram of plutonium by

$$P_{\text{eff}} = \sum_i R_i \cdot P_i \quad . \quad (I-3)$$

P_{eff} is the important factor required to convert the watts measured by the calorimeter to grams of elemental plutonium. In terms of P_{eff} , the mass of elemental plutonium (all the heat-producing isotopes) is given by

$$M = W / P_{\text{eff}} \quad (I-4)$$

where W is the measured watts from the calorimeter, and P_{eff} in units of watts/gram of plutonium is the effective specific power.

P_{eff} is most often determined from knowledge of the plutonium isotopic composition and ^{241}Am content of the measured item. The isotopic composition information can come from destructive mass spectrometry measurements or from nondestructive gamma-ray isotopic analysis measurements. The latter method is one of the principal applications of FRAM. The characteristics and errors involved in the measurement of P_{eff} by FRAM will be discussed in detail in other sections of this guide.

2. Neutron Coincidence Counting.

The even isotopes of plutonium (^{238}Pu , ^{240}Pu , and ^{242}Pu) have large spontaneous fission yields that dominate the spontaneous fission neutron output from plutonium. The spontaneous fission neutron yields of the plutonium isotopes are shown in Table I-2 (Ensslin 91a).

Table I-2. Spontaneous Fission Neutron Yields from the Isotopes of Plutonium.

Isotope	Spontaneous Fission Yield (n/s-g)
^{238}Pu	2.59×10^3
^{239}Pu	2.18×10^{-2}
^{240}Pu	1.02×10^3
^{241}Pu	5×10^{-2}
^{242}Pu	1.72×10^3

Spontaneous fission neutron emission, in conjunction with sensitive neutron-coincidence counting systems, provides a widely used measurement technique (Ensslin 98, Reilly 91). All three of the even

I. INTRODUCTION

isotopes contribute to the response of a neutron-coincidence counter. The contribution from ^{240}Pu dominates, however, for most plutonium-bearing materials. For this reason it is customary to define the effective ^{240}Pu mass by

$$^{240}\text{Pu}_{\text{eff}} = 2.52 * ^{238}\text{Pu} + ^{240}\text{Pu} + 1.68 * ^{242}\text{Pu} \quad (\text{I-5})$$

where $^{240}\text{Pu}_{\text{eff}}$ is the mass of ^{240}Pu that would give the same coincidence response as that observed from the actual measured item.

Clearly, if we know $^{240}\text{Pu}_{\text{eff}}$ mass from a coincidence counting measurement, we also need to know the isotopic distribution of the plutonium to determine the elemental plutonium mass. Therefore, we define the effective ^{240}Pu fraction in an analogous fashion by

$$\text{fract}^{240}\text{Pu}_{\text{eff}} = 2.52 * \text{fract}^{238}\text{Pu} + \text{fract}^{240}\text{Pu} + 1.68 * \text{fract}^{242}\text{Pu} . \quad (\text{I-6})$$

The isotopic fractions are obtained from either destructive analysis (mass spectrometry) or from nondestructive gamma-ray isotopic analysis. This yields the elemental plutonium mass in a fashion completely analogous to calorimetry as

$$M = \text{grams } ^{240}\text{Pu}_{\text{eff}} / \text{fract}^{240}\text{Pu}_{\text{eff}} \quad (\text{I-7})$$

where grams $^{240}\text{Pu}_{\text{eff}}$ comes from the neutron-coincidence counting measurement of the bulk item and $\text{fract}^{240}\text{Pu}_{\text{eff}}$ comes from the isotopic analysis measurement. In addition to the isotopic information required in computing $\text{fract}^{240}\text{Pu}_{\text{eff}}$, coincidence counting also requires knowledge of the complete isotopic distribution, including ^{241}Am , for computing sample (α, n) rates for multiplication corrections.

3. Other Bulk Measurement Techniques.

a. Active Well Coincidence Counter.

The active well coincidence counter (AWCC) uses AmLi neutron sources mounted above and below the assay chamber in a coincidence counter body to induce fissions in isotopes not having significant spontaneous fission activity. The induced-fission neutrons are quantified with standard coincidence counting techniques. The primary use of this detector is for measuring ^{235}U and, as with nearly all bulk NDA techniques, the AWCC is only sensitive to a particular isotope or isotopes, not the entire element. Thus, for application to ^{235}U in the AWCC, we require knowledge of the ^{235}U isotopic fraction. Nondestructive gamma-ray isotopic analysis can provide this information for most measured items. The FRAM software was the first gamma-ray isotopic analysis code to demonstrate measurements on uranium (Sampson 90) and today is the most versatile code, being able to analyze more types of uranium materials than any other software.

b. Segmented Gamma Scanner.

The segmented gamma scanner (SGS) uses transmission-corrected passive assay techniques (Parker 91) to quantify individual isotopes (usually ^{239}Pu or ^{235}U) in items of scrap and waste. Because only individual isotopes are measured, we require knowledge of the isotopic composition to convert the isotope measurement to elemental mass. The isotopic composition measurement is especially needed if the measured streams have variable isotopic composition. In other cases, such as streams of weapons-grade plutonium or highly enriched uranium (HEU), isotopic measurements can be avoided and the well-known stream average values can be used instead.

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The tomographic gamma scanner (TGS) (Prettyman 93, Mercer 02) is a three-dimensional analog to the SGS and requires the same type of isotopic information (Mercer 99) as does the SGS.

c. Solution Assay Instrument.

The solution assay instrument (SAI) also uses transmission-corrected passive assay techniques to quantify individual isotopes in solution samples. The use of the information provided by isotopic composition measurements is similar to that in the application of the SGS.

4. Process Control

There are numerous applications of gamma-ray isotopic analysis in providing information necessary for the control of various fabrication processes. Isotopic analysis may be required any time material from two different batches is mixed to produce a product that must meet designated specifications.

One example might be that of blending materials with different ^{240}Pu fractions to meet a given “weapons grade” specification. Another application is blending plutonium from different batches to produce mixed-oxide (MOX) fuel. In this case, the important parameter is usually the ^{239}Pu fraction. These operations are facilitated if the requisite isotopic analysis measurements can be made nondestructively. The accuracy and precision of the NDA measurement relative to alternative techniques such as mass spectrometry must be weighed against its convenience and the requirements of the blending specification.

5. Treaty Verification.

Arms control and plutonium disposition negotiations between the United States (US) and the Russian Federation (RF) are considering the disposition of plutonium from dismantled Russian nuclear weapons. The treaties and agreements arising from these negotiations contain requirements to verify the amount and isotopic composition of the plutonium declared as coming from dismantled weapons. A problem that arises is that in Russia the isotopic composition of the plutonium used in Russian weapons is classified. The US and the RF have agreed to declare plutonium with a $^{240}\text{Pu}/^{239}\text{Pu}$ ratio of less than 0.1 as “weapons grade.” Nondestructive gamma-ray isotopic analysis techniques are applied behind an information barrier to verify this ratio without revealing the detailed isotopic composition.

The Russian Weapons Plutonium Conversion Line will take plutonium from dismantled weapons, mix it with fuel grade plutonium and produce PuO_2 for MOX fuel with, again, a $^{240}\text{Pu}/^{239}\text{Pu}$ ratio of less than 0.1. Gamma-ray isotopic analysis will be used to determine the proper mixing ratios and also to verify the isotopic composition of the output PuO_2 .

6. Confirmation Measurements

The US DOE regulations often require confirmation measurements when materials are moved between material balance areas (MBAs) or between facilities. These measurements are not meant to quantify the SNM but to measure attributes of the item to confirm that it contains the type of material specified.

The isotopic composition of the plutonium in the item is one important attribute that is often measured. These measurements often place exacting requirements on the gamma-ray isotopic analysis software because most facilities want to do these measurements rapidly and without removing the items from the shipping container. This leads to requirements to measure items through the walls of various shipping containers. Fortunately, measurements of this type usually do not have to be as precise as accountability or verification measurements. Isotopic verification measurements are usually quite straightforward with the use of appropriate isotopic analysis software and an appropriate detector.

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A. Methods for Obtaining Isotopic Fractions Using Gamma Rays

Gamma-ray isotopic analysis methods rely on straightforward application of basic gamma-ray spectrometry principles by relating photopeak areas to isotope activity and hence to isotopic fractions. Early methods used absolute counting principles requiring strict control of the sample and measurement geometry. The next advance made use of ratio measurements of neighboring gamma-ray lines from different isotopes, reducing the requirement for sample and geometry control. The most modern techniques correct the isotopic ratios for efficiency differences between the energies of the peaks forming the isotopic ratio. The following sections in this chapter discuss each of these methods in more detail.

B. Calibrated Absolute Measurements

Some of the very first gamma-ray isotopic analysis measurements were developed starting in the mid-1970s at the Lawrence Livermore National Laboratory (LLNL) for application to solution samples. These measurements were made with small, approximately 1-cm³ planar high-purity germanium (HPGe) detectors with resolution of about 530–550 eV at 122 keV. The procedures developed by LLNL used a highly controlled geometry that placed a plutonium-bearing solution sample right in front of the detector. (Gunnink 74) The method used absolute counting techniques in the energy region from 40–60 keV for solutions separated from ²⁴¹Am and ²³⁷U and similar techniques in the 100-keV region for aged plutonium solutions.

The methods used to analyze the spectral data grew out of the computerized methods developed by Gunnink and coworkers in the early 70s for generalized radionuclide counting. (Gunnink 71). The solution-sample isotopic analysis work was one of the first applications of the response function fitting of x-rays in the 100-keV region (Gunnink 76). In general, these early methods were very successful for the specialized problem they were designed to solve. Their application was for in-line monitoring of solution isotopic composition with a short (10–15 minutes) measurement time. They also quantified ²⁴¹Am and exhibited ²⁴⁰Pu measurement precision and bias of under 1% [1 relative standard deviation (RSD)] for a 10-minute measurement.

This type of absolute measurement presented many challenges. Two types of calibrations were used on early applications (Gunnink 74). The first was a separate measurement to calibrate the peak shape required for the response function fitting in the 100-keV region. The second was an absolute efficiency calibration using solutions of known isotopic composition. For solution samples with a concentration differing from the calibration solutions, one must also make attenuation corrections to correct for self-absorption by the plutonium in the cell. The attenuation corrections are small for low concentrations of plutonium but had to be more carefully considered for concentrations in the 200-g/L range especially if the plutonium concentration is unknown. Finally, detector and electronic instabilities presented some difficulties. This is not surprising for the electronic systems of two to three decades ago.

These isotopic analysis techniques for solutions were fielded at the Savannah River Plant and also at the Tokai-mura reprocessing plant of the Power Reactor and Nuclear Fuel Development Corporation in Japan [Tokai Advanced Safeguards Exercise (TASTEX)] (Gunnink 81).

Gunnink's early work at LLNL pioneered the development of some of the isotopic analysis techniques, especially in the area of photopeak analysis, that are still used today both in FRAM and other isotopic analysis software.

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C. Ratio Measurements for the Arbitrary Sample—Without Efficiency Corrections

The measurement of the isotopic composition of plutonium in an arbitrary sample is an entirely different problem from the fixed-sample, fixed-geometry measurements just described. An “arbitrary sample” is the name given to items that have no constancy in their mass, chemical composition, physical composition, physical dimensions, packaging materials, and container characteristics. The lack of uniformity of the vast majority of items encountered in plutonium processing, makes it impractical and in many cases, impossible, to apply absolute counting techniques. The magnitude of the problem required a new approach to isotopic composition measurements.

A very simple expression can be developed for the ratio of the number of atoms of isotope i (N_i) to the number of atoms of a given isotope, assume ^{239}Pu , N_{239} using measured gamma-ray intensities.

The intensity of a gamma-ray peak from isotope i is given as a proportionality by

$$I_i \approx N_i * \lambda_i * B_i, \quad (\text{II-1})$$

where I_i is the intensity of the gamma-ray photopeak from isotope i in the recorded spectrum, λ_i is the decay constant of isotope i ($\lambda_i = \ln 2 / T_{1/2}$) with $T_{1/2}$ being the half life of isotope i , and B_i is the branching intensity of the recorded gamma ray. When the peak intensity of a gamma ray from isotope i is compared to the intensity of a gamma ray from ^{239}Pu , the expression for the atom number ratio of isotope i to ^{239}Pu can be simply written as

$$N_i / N_{239} = K * I_i / I_{239} \quad (\text{II-2})$$

where the constant K contains the known half lives of the of the two isotopes and the known branching intensities of the selected gamma rays.

This expression incorporates the important assumption that the two recorded gamma rays are close enough in energy that the differences in sample self-attenuation, absorption in the packaging materials, and detector efficiency can be neglected between the two gamma-ray energies. The early applications of this technique at the Mound Laboratory (Haas 74) recommended using gamma-ray pairs with energy spacing less than 10 keV. Earlier references to this technique dating back to 1970 are reported in Haas (Haas 74).

The assumption of equal detection efficiency for the two gamma rays limited the pairs of gamma rays that could be used for this method to those close in energy. Efficiency differences even with closely spaced peak pairs can be significant and were the cause of some of the biases observed with this early method. Table II-1 demonstrates the magnitude of the bias that can be caused by neglecting efficiency and absorption differences. In Table II-1 we document the combined efficiency differences for measurements on 454 g of PuO_2 when measured with a 16-mm-diam. by 13-mm-deep planar detector and a 25% relative-efficiency coaxial detector. The efficiency differences are tabulated for the energies of commonly used, “closely spaced” peak pairs. These biases will change with detector and sample and are meant to be illustrative, only.

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Table II-1. Bias Magnitude From Neglecting Efficiency Differences.

Peak Pairs Isotope1(keV)/Isotope2(keV)	Planar Detector	Coaxial Detector
²⁴⁰ Pu(160.3)/ ²⁴¹ Pu(148.6)	1.23	1.38
²⁴⁰ Pu(160.3)/ ²⁴¹ Pu(164.6)	0.94	0.90
²⁴¹ Pu(208.0)/ ²³⁹ Pu(203.5)	1.03	1.06

D. The Intrinsic Self-Calibration Technique

Parker and Reilly (Parker 74) at Los Alamos proposed the first practical method for measuring the isotopic composition of an arbitrary (size, shape, composition, and measurement geometry) plutonium sample via analysis of its gamma-ray spectrum. The key to their method was the incorporation of an internal or intrinsic self-determination of the relative efficiency curve from the gamma-ray spectrum of each unknown sample. No longer was it necessary to use closely spaced peak pairs or to assume equal detection efficiency. Their approach is developed below.

1. Isotopic Ratio Measurement

We can write an expression for the photopeak counts from a specific gamma ray, emitted from a given isotope in a sample of arbitrary configuration, as

$$C(E_j^i) = \lambda^i \times N^i \times BR_j^i \times \varepsilon(E_j), \quad (\text{II-3})$$

where

- $C(E_j^i)$ = photopeak area of gamma ray j with energy E_j emitted from isotope i ,
- λ^i = decay constant of isotope i , $\lambda^i = \ln 2 / T_{1/2}^i$ where $T_{1/2}^i$ is the half life of isotope i ,
- N^i = number of atoms of isotope i ,
- BR_j^i = branching ratio (gamma rays/disintegration) of gamma ray j from isotope i ,
- $\varepsilon(E_j)$ = total efficiency for photopeak detection of a gamma ray with energy E_j . This includes detector efficiency, geometry (solid angle), sample self-absorption, and attenuation in packaging and materials between the sample and the detector.

In an entirely analogous fashion, we can write the expression for the photopeak counts in terms of the mass of the isotope present as

$$C(E_j^i) = M^i \times \gamma_j^i \times \varepsilon(E_j) \quad (\text{II-4})$$

where

- M^i = mass of isotope i , and
- γ_j^i = photon emission rate of gamma ray j from isotope i (gammas/s·g isotope).

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Writing the expression for photopeak counts (Eq. II-3) for gamma ray l from isotope k and combining it with the expression for gamma ray j from isotope i gives the expression for the atom ratio of isotope i to isotope k from measurement of a gamma ray with energy E_j from isotope i and E_l from isotope k as

$$\frac{N^i}{N^k} = \frac{C(E_j^i)}{C(E_l^k)} \times \frac{T_{1/2}^i}{T_{1/2}^k} \times \frac{BR_l^k}{BR_j^i} \times \frac{RE(E_l)}{RE(E_j)} . \quad (\text{II-5})$$

Equation II-4 can also be cast in this form; however, we will use Eq. II-5 as the standard expression for obtaining isotopic ratios from a gamma-ray spectrum. We do this because the variables in Eq. II-5 are more commonly published and available than is the photon emission rate per gram in Eq. II-4.

In going from Eq. II-3 to Eq. II-5 the total efficiency has been rewritten in terms of the relative efficiency, RE. The geometric factors associated with the total efficiency cancel in the ratio in Eq. II-5. Also, now the RE includes the effects of sample self-absorption, attenuation in materials between the sample and the detector, and detector efficiency. The half lives, $T_{1/2}$, and the branching ratios, BR , are known nuclear data.

The $C(E)$ term is determined from the gamma-ray spectral data, leaving only the ratio of the relative detection efficiencies to be determined. The need for only an efficiency ratio removes the problems associated with the geometric and sample reproducibility associated with absolute measurements and makes the method applicable to samples of arbitrary size, shape, and composition.

For every sample, we can determine the ratio of the relative efficiency at the selected energies from the measured gamma-ray spectrum of that sample. From Eq. II-3, considering a series of gamma rays from a single isotope, we see that the quotient of the photopeak counts at energy E_j^i and the branching ratio BR_j^i is proportional to the efficiency at energy E_j :

$$\frac{C(E_j^i)}{BR_j^i} \propto \left[\frac{N^i \ln 2}{T_{1/2}^i} \right] \varepsilon(E_j) . \quad (\text{II-6})$$

Thus, this quotient defines the shape of the relative efficiency as a function of energy for that particular measurement. Because we use isotopic ratios, only the shape (variation with energy), not the absolute magnitude, of the relative efficiency curve is important. In practice, the values for $C(E_j^i)$ are obtained from analysis of the gamma-ray spectrum of the sample under study. The BR_j^i are tabulated nuclear constants. Gamma rays from several isotopes may be used to define the relative efficiency as long as all the isotopes used have the same physical distribution. The curves from different isotopes with the same physical distribution have the same shape and differ only in their amplitude, the term in brackets in Eq. II-6.

The development above of Parker and Reilly (Parker 74) forms the basis for nearly all isotopic analysis by gamma-ray spectrometry applications that are in use today, including the FRAM code.

2. Assumption of Isotopic Homogeneity

While the above development is very general, there is one very important assumption built into the formalism. This assumption is that all the measured isotopes in the sample are homogeneous with respect to each other. Another way of saying this is that gamma rays of the same energy from different isotopes must suffer the same average attenuation as they escape from the sample. This must not be confused with physical or chemical homogeneity. A sample may be highly heterogeneous physically and chemically and still satisfy the isotopic homogeneity assumption. Consider a plutonium-bearing solution with undissolved plutonium oxide and undissolved pieces of plutonium metal in it. If all of the plutonium

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(solution, oxide, metal) has the same isotopic content and same ^{241}Am concentration, then this technique works, regardless of the physical or chemical heterogeneity. However, if the plutonium metal has a different isotopic composition than the plutonium in solution, then the technique fails because the average attenuation of a gamma ray of energy E escaping from the metal is different than the average attenuation of a gamma ray of the same energy escaping from the solution. This situation is called isotopic heterogeneity.

a. Pyrochemical Residues

A very real example of isotopic heterogeneities occurs in pyrochemical plutonium processing applications. The pyrochemical process produces pure plutonium metal with americium and uranium removed. The waste americium and uranium that have been separated reside as a chloride salt along with small amounts of residual plutonium as metal fines in the salt residue stream. The proper quantification of the plutonium in this residue stream is complicated by the isotopic heterogeneity of the plutonium and americium present.

The calorimetric assay technique (section I. B. 1.) requires the accurate determination of the $^{241}\text{Am}/\text{Pu}$ ratio in the sample. The gamma rays from ^{241}Am suffer attenuation predominately in a low- Z chloride salt matrix while the plutonium gamma rays suffer attenuation characteristic of the high- Z plutonium metal fines. The relative efficiency curve for gamma rays from ^{241}Am is different than that from plutonium. The isotopic ratio expression of Eq. II-5 does not work in this instance. We will discuss later a method for improving the isotopic analysis results from these isotopically heterogeneous pyrochemical residues.

b. Waste Drums

Another application that often encounters isotopically heterogeneous items is that of analysis of 200-L drums of waste. Waste drums may contain several different smaller packages. Each of the smaller packages may have a different plutonium isotopic composition and ^{241}Am content. While the attenuations may be similar for gamma rays from the two elements (often not true), the different geometrical distributions, relative to the detector, of the individual, isotopically different, smaller packages will affect the relative contributions of the individual package contents. This is often more of a geometric problem, but the result is the same—the relative efficiencies are different for the individual packages and a single measurement cannot assure that they are weighted properly. Scanning and rotation are usually used to minimize this problem.

E. The Relative Efficiency Concept

The concept of the intrinsically determined self-calibration of the measurement's relative efficiency is the key feature of modern gamma-ray isotopic analysis methods. Equation II-6 is used to determine the relative efficiency at the gamma-ray energies used in the peak pair ratio expression of Eq. II-5.

The relative efficiency is viewed as a function of energy. Almost any variable that perturbs the absorption or relative intensity of gamma rays emitted from the sample can affect the shape or energy dependence of the relative efficiency curve. The following are examples:

- The size, configuration, and efficiency of the HPGe detector
- The mass of plutonium in the sample
- The areal density of plutonium in the sample
- The density and absorption properties of any matrix material
- Material properties and thickness of the container(s)
- Absorbers between the sample and the detector

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Figures II-1 and II-2 show the effects of some of these variables. Figure II-1 shows the overall effect seen as the sample gets larger, which also usually means thicker. The curves in Fig. II-1 are normalized to unity at their maximum value. The mean free path increases as energy increases, therefore, an isotopic measurement will “see” farther into the sample and hence more sample volume and mass at high energy than at low energy. This means that relative to low energies, more high-energy gamma rays than low-energy gamma rays escape from large samples and the relative efficiency tends to increase with increasing energy more strongly than for small samples. This is illustrated numerically in Table II-2 for plutonium at low density approximating that of PuO_2 . The “thickness” of the plutonium in a sample must be several mean free paths in magnitude to take full advantage of the intensity available at a specific measurement energy.

Table II-2. Mean Free Path for Various Gamma Rays in Plutonium of Density 3.0 g/cm^3 .

Pu238	λ (cm)	Pu239	λ (cm)	Pu240	λ (cm)
152 keV	0.13	129 keV	0.083	104 keV	0.19
766 keV	3.0	414 keV	1.2	160 keV	0.15
				642 keV	2.4

Figure II-1 shows that the user can get qualitative information on the plutonium areal density in comparably packaged samples just by examination of the shape of the relative efficiency curve.

Figure II-2 compares the relative efficiency for the same sample measured on two different detectors. The planar detector was a 16-mm-diam. by 13-mm-deep detector while the coaxial detector was small, (about 50 mm diam. by 40 mm thick). The two curves are normalized at 414 keV. The higher detection efficiency of the coaxial detector compared to the detection efficiency of the planar detector causes the relative efficiency of the coaxial detector above 250 keV to keep increasing where the planar efficiency falls off.

F. Relative Efficiency Models

After the relative efficiency has been determined for a specific measurement from Eq. II-6, we have a series of relative-efficiency energy points that might appear to look like Fig. II-3. We then need to find relative efficiency values for energies not defined by a specific relative efficiency point and also, sometimes, even outside the range defined by the relative efficiency points. This requirement has led to the development of several models to parameterize the relative efficiency curve.

1. Piecewise Linear

This simple model assumes that the efficiency is linear between any two adjacent points. It obviously works best where the efficiency itself is linear and requires closely spaced points for best results. This method was used in the early Los Alamos codes preceding FRAM (Sampson 80, Hsue 80, Sampson 82, Sampson 83).

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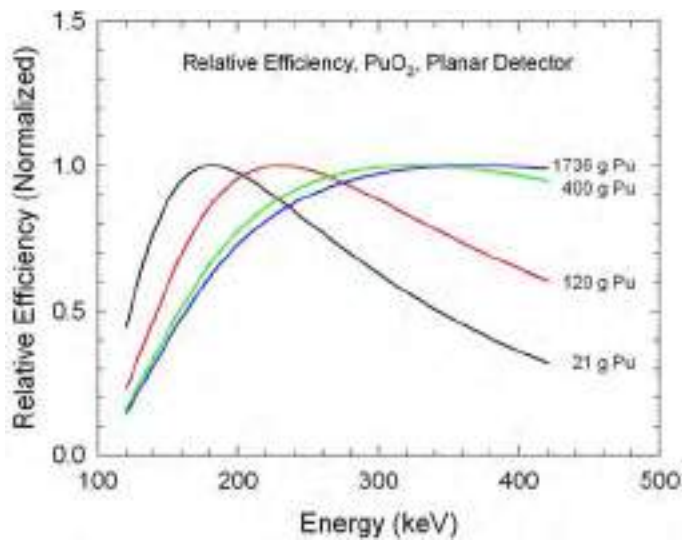


Fig. II-1. Relative efficiency variation for different size samples using the same 16-mm-diam. by 13-mm-deep planar detector. The curves are normalized at their maximum value.

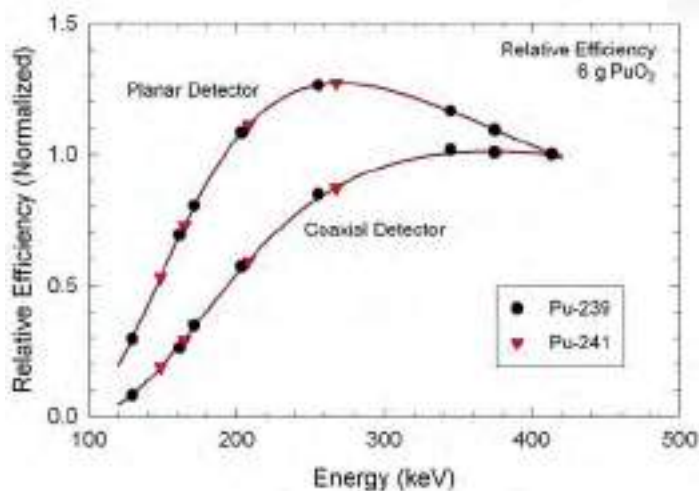


Fig. II-2. Relative efficiency variation for the same sample for a planar and coaxial HPGe detector. The curves are normalized at 414 keV.

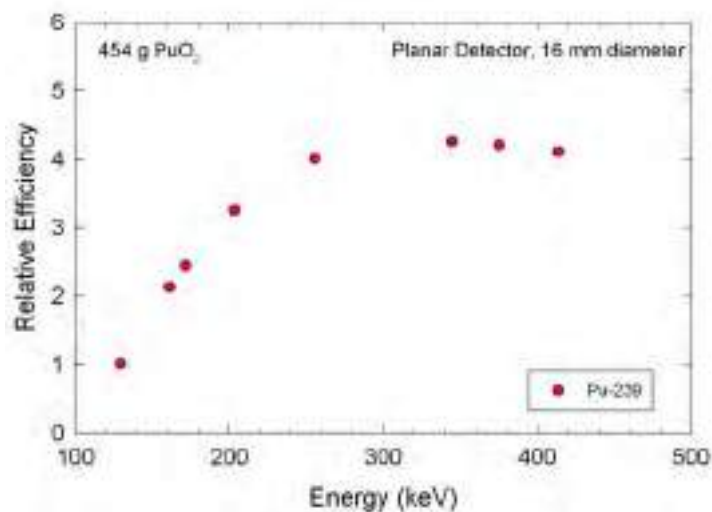


Fig. II-3. "Raw" relative efficiency points from ^{239}Pu for a specific measurement.

II. BASIC PRINCIPLES OF GAMMA-RAY ISOTOPIC ANALYSIS FOR THE ARBITRARY SAMPLE

Its advantage is computational simplicity and it worked very well in the framework of the early analysis software as long as it was applied within the range of definition of the data points.

2. Spline Fitting

Spline fitting could also be used to interpolate between the individual relative-efficiency points. This form would not extrapolate well outside the range of definition of the data points.

3. Polynomial Least-squares Fitting

Linear least-squares fitting of polynomial expressions in $\ln E$ were used by Fleissner (Fleissner 81) and Ruhter (Ruhter 84) in the early 1980s to parameterize the relative efficiency vs energy relationship.

Fleissner in his GRPAUT software (Fleissner 81a) used the form

$$\ln \varepsilon_i = a_0 + \sum_{j=1}^2 (a_j E_i^{-j}) + \sum_{j=1}^3 (a_{j+2} (\ln E_i)^j) + a_6 \delta_6 + a_7 \delta_7 \quad (\text{II-7})$$

in the energy range from 120 keV to above 450 keV, with points from ^{239}Pu , ^{241}Pu and ^{241}Am . The delta function terms, a_6 and a_7 , normalize the ^{241}Pu and ^{241}Am data points to the ^{239}Pu data points.

Ruhter's form (Eq. II-8) was similar and was used to fit from 120 keV to 210 keV if the data were limited to that range, or from 120 keV to 380 keV if the data included the 375-keV region. His expression was simpler because it was used on a system with limited computing resources:

$$\ln \varepsilon_i = a_0 + a_1 \delta_1 + \sum_{j=1}^{2 \text{ or } 3} (a_{j+1} (\ln E_i)^j) \quad (\text{II-8})$$

The delta function term, a_1 , normalizes the ^{241}Pu data points to the ^{239}Pu data points. Ruhter did not use any points from ^{241}Am to determine efficiency.

All versions of FRAM use or have available an empirical relative-efficiency curve of essentially the same polynomial form (Sampson 89). FRAM's empirical relative efficiency is

$$\ln \varepsilon_i = C_1 + C_2 E_i^{-2} + \sum_{j=1}^3 (C_{j+2} (\ln E_i)^j) + \sum_{k=1}^m C_{k+5} \delta_{k+5} + \sum_{l=1}^n C_{l+5+m} \delta_{l+5+m} E_i^{-1} \quad (\text{II-9})$$

where the k summation is the normalization for each isotope after the first and the l summation is the normalization for each additional relative-efficiency curve. The FRAM empirical relative-efficiency curve is not limited with regard to the number of isotopes, nor is it limited to the number of different relative-efficiency curves applied for isotopic heterogeneity (more on this later).

All applications of this empirical, polynomial-based relative-efficiency curve work very well over the range of definition but can run into trouble if extrapolated outside its range of definition or if the relative-efficiency data is statistically poor. In these cases, the cubic nature of most of the forms may give rise to unphysical behavior.

4. Physical Model (Gunnink)

A physics-based relative-efficiency model has been widely used by Gunnink and coworkers at the Lawrence Livermore National Laboratory (Gunnink 90).

II. BASIC PRINCIPLES OF GAMMA-RAY ISOTOPIC ANALYSIS FOR THE ARBITRARY SAMPLE

$$\varepsilon_j = \exp(-\mu_j^{Cd} * x_{Cd}) * \frac{1}{\mu_j^{Pu} * x_{Pu}} (1 - \exp(-\mu_j^{Pu} * x_{Pu})) * eff_j * (1 + bE_j + cE_j^2), \quad \text{II-10}$$

where

- μ_j^{Cd} = mass absorption coefficient of cadmium for peak j ,
- μ_j^{Pu} = mass absorption coefficient of plutonium for peak j ,
- x_{Cd} = thickness (g/cm²) of cadmium absorber,
- x_{Pu} = thickness (g/cm²) of plutonium in the sample,
- eff_j = detector efficiency for peak j from a “generic” efficiency curve,
- b, c , = coefficients in a quadratic function to account for small deviations in the efficiency from the generic value as well as other slowly varying effects, such as absorption from low Z matrix materials.

This model explicitly accounts for self-absorption in the plutonium in the sample, absorption in a cadmium filter between the sample and detector, and the intrinsic detector efficiency. It has been used very successfully in the region from 59 keV to 300 keV with a planar detector. The variables are determined by iterative nonlinear least-squares techniques. Because the model is based on physical principles, it can give valid results outside its range of definition in cases where empirical polynomials fail.

5. Physical Model (Vo)

Duc Vo at Los Alamos has implemented a very versatile physical model for relative efficiency that allows for multiple absorbers and multiple efficiency curves and uses a wide-ranging correction factor for slowly varying effects (Sampson 99):

$$\begin{aligned} \varepsilon = & \frac{1}{\mu_{Pu} * x_{Pu}} (1 - \exp(-\mu_{Pu} * x_{Pu})) \\ & * \exp(-\mu_{Cd} * x_{Cd}) * \exp(-\mu_{Fe} * x_{Fe}) * \exp(-\mu_{Pb} * x_{Pb}) \\ & * (I_i) * \exp\left(\frac{c_j}{E}\right) * (Det\ Eff) * (Correction\ Factor) \end{aligned} \quad \text{(II-11)}$$

The first term is self-absorption in the plutonium; the second line is the absorption in up to three different materials (out of a choice of seven—aluminum, iron, cadmium, erbium, lead, water, and concrete); I_i is the activity of isotope i ; $Det\ Eff$ is a generic detector efficiency parameterized in the software; and $Correction\ Factor$ corrects for variations of the actual detector efficiency, nuclear material, and matrix from those specified in the model. The *Correction Factor* is a modified Hoerl function.

$$Correction\ Factor = \left(E^b * c^{\frac{1}{E}} \right) \quad \text{(II-12)}$$

This physical efficiency function is available in FRAM version 4 and will be discussed later in this document.

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6. Heterogeneous Relative-Efficiency Models

Section II.D.2 discussed the basic assumption of isotopic homogeneity built into the fundamental isotopic ratio expression, Eq. II-5. We say we have isotopic heterogeneity whenever the isotopes are not physically distributed in the same manner; hence, gamma rays of the same energy from different isotopes suffer different attenuations. The two principal cases previously mentioned are those of pyrochemical separation residues and drums of scrap and waste.

Fleissner is credited with first applying a method to correct for isotopic heterogeneities in pyrochemical residues (Fleissner 83). He added an additional term to his relative-efficiency expression (Eq. II-7) to account for the different absorption in the isotopically heterogeneous isotope. This term was proportional to $\exp(\beta/E)$. The so-called “beta” term, fitted during the relative-efficiency determination, is a measure of the heterogeneity. The overall shape of the function modeled the difference in shape between the plutonium and americium relative-efficiency curves for pyrochemical residues. The heterogeneity term decreases as the energy E increases, allowing the correction to become smaller at higher energies. This models the observation that mass absorption coefficients of the elements decrease and tend to become independent of Z above 1000 keV.

Los Alamos adopted the Fleissner heterogeneous relative-efficiency correction for FRAM (Sampson 89), and this term is shown in the FRAM empirical relative-efficiency expression in Eq. II-9.

Testing of this heterogeneous model has involved comparison of isotopic measurements on heterogeneous pyrochemical residues with destructive chemical analysis of the entire item (Longmire 90, Fleissner 83, Sampson 89). These destructive chemical analysis studies are very lengthy and extremely expensive, so comparison data is limited. The most important parameter determined in the isotopic measurement is the effective specific power, P_{eff} in mW/gPu. This is used directly to convert a calorimetry measurement of total sample power to grams elemental plutonium. With the heterogeneous relative-efficiency model of Fleissner, both Fleissner’s GRPAUT code and the Los Alamos FRAM code determined P_{eff} with a bias that usually did not exceed 5%. Analysis of the same data without using the heterogeneous relative-efficiency correction yielded biases from 10% to 200%.

III. ISOTOPIC ANALYSIS DEVELOPMENT AT THE LOS ALAMOS NATIONAL LABORATORY

III. ISOTOPIC ANALYSIS DEVELOPMENT AT THE LOS ALAMOS NATIONAL LABORATORY

Several isotopic analysis systems, using a computerized implementation of the principles developed by Parker and Reilly, were completed at Los Alamos National Laboratory starting in 1980 (Sampson 80, Hsue 80, Sampson 82).

The computer systems used online control of data acquisition and analysis with PDP/11 computers and the RT-11 operating system. The analysis featured simple region-of-interest (ROI) summation to obtain peak areas (Reilly 91a). Small, planar (16-mm-diam. by 10–13-mm-deep), HPGe detectors were used for data collection with 4096 channels spanning the energy range from 10–420 keV. Detector resolution was typically approximately 500 eV at 122 keV. The specific peak ratios to be calculated in the 120–420 keV region were fixed in the code.

A system using multiple detectors to measure multiple samples simultaneously, with a single multichannel analyzer and computer, was implemented at the Los Alamos Plutonium Facility in 1981. The MUDPI (MULTiple Detector Plutonium Isotopic system) was used for all nondestructive isotopic measurements at Los Alamos until the late 1980s. The MUDPI system is pictured in Fig. III-1.



Fig. III-1. The MUDPI plutonium isotopic analysis system implemented at the Los Alamos TA-55 Plutonium Facility in the early 1980s.

A similar system with a single detector was fielded at the Savannah River site in 1981. This system, called LAPIS (Los Alamos Plutonium Isotopic System), is pictured in Fig. III-2. It was fielded in an air-conditioned instrument rack and the sample, placed on the platform above the up-looking detector, and surrounded with a shielding clamshell to reduce the radiation dose to the operator.

III. ISOTOPIC ANALYSIS DEVELOPMENT AT THE LOS ALAMOS NATIONAL LABORATORY



Fig. III-2. The LAPIS plutonium isotopic analysis system implemented at the Savannah River Plant.

Sampson (Sampson 83) describes both of these systems, including the data acquisition equipment, isotopic ratio algorithms, software user interface, and data from the initial operation of the systems. These systems used conventional analog nuclear instrumentation module (NIM) electronics with the amplifier time constant set at 3 μ s and a maximum recommended counting rate of 15 kHz. The measurement precision, or repeatability, for the effective specific power under these counting conditions was approximately 0.5% for a 2-hour count on a 500-g plutonium sample. The precision for ^{240}Pu for the same conditions fell into the range from 2%–4%, [1 relative standard deviation (RSD)].

The MUDPI system performed very well at Los Alamos throughout most of the 1980s. However, by the mid-1980s it became apparent that improvements were needed to address two measurement problems. The first problem was the presence of interference isotopes in some samples. Gamma rays from these interfering isotopes (^{235}U , ^{243}Am – ^{239}Np , ^{237}Np) were not accounted for in the simple ROI analysis leading to analysis error when gamma rays from these isotopes overlapped a peak or background ROI. A second problem arose from the analysis of residue samples from pyrochemical processes. These processes produce residues consisting of americium in low Z chloride matrix with plutonium metal fines suspended in the matrix. For these samples, gamma rays from americium suffer different attenuation than plutonium gamma rays of the same energy. This violated the isotopic homogeneity assumption of the analysis method and especially led to errors in the $^{241}\text{Am}/\text{Pu}$ measurement (see section II.D.2) and hence to errors in P_{eff} .

IV. FRAM DEVELOPMENT

IV. FRAM DEVELOPMENT

A. Factors Influencing Development

Starting in the mid-1980s, the development of FRAM was driven primarily by the needs and requirements for measurements at the Los Alamos Plutonium Facility. We have just discussed the general features of the first isotopic analysis codes implemented at Los Alamos. The details of the improvements are presented below.

1. Interferences

The MUDPI system (Sampson 83) used fixed ROIs to extract its peak areas. Some of the important regions for the analysis covered the energy ranges 140–165 keV, 203–208 keV, 330–345 keV, 375 keV, and 414 keV.

If ^{235}U is present it will produce interferences at 143, 163, 202, and 205 keV. Neptunium-237 will interfere at 375 and 415 keV while ^{243}Am – ^{239}Np has interferences at 209 and 334 keV. These interferences would invalidate a measurement when they were present in a spectrum because the simple ROI peak area extraction method was not designed to handle overlapping peaks. All three interferences can be present in the many materials processed at the Los Alamos Plutonium Facility. A peak area extraction method capable of handling multiple overlapping peaks was needed to solve this problem.

2. Heterogeneous Am/Pu

The previous sections, Assumption of Isotopic Homogeneity (II.D.2.a) and Heterogeneous Relative-Efficiency Models (II.F.6), have provided an introduction to this problem.

At the Los Alamos Plutonium Facility, a major isotopic analysis problem arose in the calorimetric assay of pyrochemical residues. This problem came about for several reasons involving the MUDPI software's inability to correctly determine ^{241}Am for these residues. Americium determination for pyrochemical residues is important for calorimetric assay because of americium's high specific power (114.2 mW/g compared to 1.9288 mW/g for ^{239}Pu), especially as it is concentrated in the residues, often at levels exceeding 5% or 50,000 ppm. This concentration of ^{241}Am in normal weapons grade plutonium produces over 70% of the total power produced by the sample.

The simple piecewise linear relative-efficiency model used in MUDPI used several "coenergetic" peaks (peaks with ^{241}Pu and ^{241}Am contributions at the same energy)—164, 208, and 267 keV—in its relative-efficiency determination. The correction for the ^{241}Am content of these peaks was made assuming isotopic homogeneity. The homogeneity assumption overestimated the actual concentration of the americium because gamma rays from the americium in a low-Z matrix were not absorbed as strongly as the gamma rays from the plutonium metal fines in the sample. Since americium was overestimated, P_{eff} was too large, and the total plutonium was underestimated. These errors could be 10%–100%.

3. Additional Versatility

The Los Alamos Plutonium Facility handled a very wide variety of plutonium-bearing materials in its research and development (R&D) and production missions. There were many special materials for which isotopic analysis was needed that could not be handled with MUDPI because the code was highly "hard-wired."

As an example, the first software implementation of the Parker and Reilly method involved software to determine isotopic ratios in research materials containing very high concentrations of ^{242}Pu . This measurement required a separate hard-wired program for this unique analysis, a program that could not be used for any other purpose (Sampson 80).

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4. Existing Approaches and Development

The requirement that isotopic analysis must have the capability to analyze a wider variety of materials was becoming apparent in the early 1980s. At that time there were two other implemented codes available that provided approaches to parts of the problem. The first was the LLNL “Blue Box” (Ruhter 84) and the second was GRPAUT (Fleissner 81, Fleissner 81a). Our overall approach was to use readily available developments when feasible and develop our own approaches in areas that needed new thinking.

The Blue Box software used the response function approach to determine peak areas while GRPAUT used iterative, nonlinear least-squares techniques for its peak area determination. The response function approach was appealing for several reasons:

- The Blue Box software used linear least-squares fitting techniques that were significantly faster than the nonlinear methods used in GRPAUT.
- The Blue Box software characterized all the energy variation of the peak shapes at the beginning of the analysis. Multiple peak parameters were predetermined before the analysis.
- Response function fitting is more robust for fitting multiple peaks, especially those containing peaks with large intensity ratios.

We chose response function analysis as the method for obtaining peak areas in FRAM.

At this time Fleissner had already developed a heterogeneous relative-efficiency model for analysis of pyrochemical residues (II.F.6). This proven model significantly improved the analysis of these residues. We adopted it for FRAM.

We also made a conscious choice to restrict the range of analysis to energies above 120 keV; that is, we chose not to pursue analysis of the 100-keV x-ray region that was being developed at Livermore (Gunnink 81a). The entire energy range above 120 keV provided more opportunities for analysis of the widest possible range of materials than did the narrower energy range from 100 keV to 300 keV. Also, at that time LANL did not have the experience in fitting the x-ray line shapes in the 100-keV region that LLNL had and we did not want to “reinvent the wheel.”

Over the years, the Los Alamos approach was very successful. Most recently, the approach has been expanded further to encompass analysis areas not previously used. The Los Alamos FRAM code now has the capability to analyze the 100-keV x-ray region for both uranium and plutonium, as well as the 40-keV region for plutonium.

B. VAX Version of FRAM

The first version of FRAM, running on Digital Equipment Corporation (DEC) MicroVAX computers, was fielded in 1988 at the Los Alamos Plutonium Facility. The FRAM code represented a major advance in measurement flexibility as it was designed to address the shortcomings of the MUDPI/LAPIS software and also included significant upgrades in the measurement and analysis hardware to the state of the art at that time. The features and characteristics of the FRAM code included the following:

- MicroVAX computer and VMS operating system with software written in FORTRAN 77
- The response function analysis for peak area determination allowed fitting of multiple overlapping peaks
- Heterogeneous Am/Pu analysis capability using separate relative-efficiency curves for heterogeneous isotopes
- Capability to select any or all spectral peaks to contribute to analysis via least-squares resolution of isotopic ratios

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- User-editable analysis parameters controlled all facets of the analysis allowing the user to cope with arbitrary interference peaks, variable energy calibrations, different detector types, and the widest possible variety of matrix conditions

The editable analysis parameters feature of the FRAM code is its most important characteristic, allowing FRAM to successfully analyze a wider range of materials than any other single code available. This characteristic is described in detail later in this document.

FRAM was installed at the Los Alamos Plutonium Facility at TA-55 in 1988 and was put into operation in 1989. Figure IV-1 shows the FRAM system that was in use until 1997. This system used two planar-HPGe-detectors allowing two samples to be measured simultaneously. The samples were placed on a scanning table in front of the detector and were rotated and translated vertically during the measurement. Scanning was performed primarily to improve measurements on the isotopically heterogeneous pyrochemical residues. The scanning mechanism was completely shielded to reduce operator exposure from the sample. The detector table and detector shield (hidden behind the shielded scanning mechanisms in Fig. IV-1) could be manually positioned to vary the sample-detector distance and hence the detector counting rate. Improvements in detectors and electronics permitted measurements at throughput rates significantly higher than those used with MUDPI/LAPIS. Triangular shaping with a 1 μ s time constant allowed a maximum recommended counting rate of 40 kHz.



Fig. IV-1. Testing a FRAM system before installation at TA-55.

In addition to implementing the capability improvements mentioned above, FRAM also allowed more rapid data collection that significantly improved precision in a shorter counting time.. Table IV-1 displays the summary results for Los Alamos from the DOE Calorimetry Exchange Program for the years 1988 to 2000, spanning the change over from MUDPI to FRAM. The DOE Calorimetry Exchange Program tabulates the results from the facility's measurements of a standard PuO_2 sample containing 400 g Pu with about 6% ^{240}Pu content. Each facility collects data in a manner suitable for their own operations. The Los Alamos data in Table IV-1 were collected in the same manner as routine unknown samples were

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measured and tabulates the precision or repeatability of a single measurement derived from the distribution of measurements over a period of a year. The data is tabulated for the ^{240}Pu isotope and the effective specific power (mW/gPu) derived from the entire isotopic distribution.

Table IV-1. Los Alamos Calorimetry Exchange Results: 454 g PuO_2 Calorimetry Exchange Standard, 5.86% ^{240}Pu , Measurement Repeatability.

Year	# of Meas.	% RSD Single Measurement		Code*	Ct. Time (h)
		^{240}Pu	P_{eff}		
1988	40	3.49	0.36	MP	2
1989	67	4.26	0.56	MP	2
1990	46	2.77	0.41	F	1
1991	42	2.07	0.28	F	1
1992	40	1.64	0.24	F	1
1993	44	1.73	0.20	F	1
1994	36	1.29	0.22	F	1
1995	51	1.58	0.25	F	1
1996	44	1.33	0.27	F	1
1997	68	1.60	0.25	F	1
1998	92	1.69	0.25	F	1
1999	65	1.92	0.23	F	1
2000	88	2.00	0.25	F	1

* MP = MUDPI, F = FRAM

Table IV-1 shows not only a decrease in the counting time from 2 hours to 1 hour but also a simultaneous improvement in precision of about a factor of two during the gradual switch over from MUDPI to FRAM. The precision continued to improve as the operators gained experience with the FRAM code. The improvement in precision arose from the following:

- The ability to use more gamma-ray peaks in the analysis; a typical FRAM analysis uses over 60 peaks while MUDPI used about 20
- Improved detectors and data acquisition electronics allowed data collection at higher count rates and shorter time constants yielding greater throughput

The average bias in these measurements was unchanged in moving from MUDPI to FRAM. The bias of less than 0.1% for P_{eff} and less than 0.3% for ^{240}Pu is about at the limit expected for the technique.

C. PC/FRAM Development

By the early 1990s computer hardware and software developments made the VAX/VMS-based FRAM system obsolete. The program was recoded in C to operate on a PC under Windows 3.1. This advance was necessary to open up the applications for the FRAM code (now called PC/FRAM) at other facilities that did not support the previous VAX system. This change has resulted in FRAM becoming commercially available through several vendors and now being used worldwide.

PC/FRAM has preserved all of the principal features of the VAX FRAM code while adding significant new capabilities (Sampson 95, Kelley 95).

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1. Single Detector System

Like all previous Los Alamos isotopic analysis systems, PC/FRAM uses only a single detector to acquire its data. We have made a conscious choice to keep FRAM a single detector system because single detector systems are inherently

- more versatile,
- easier to use,
- more reliable,
- less expensive, and
- occupy less facility space.

2. Choice of Detector Types

PC/FRAM is the only isotopic analysis system that can obtain a complete isotopic analysis using either a single planar-HPGe-detector, a single coaxial-HPGe-detector, or a single CdTe-detector with the same code. When using the traditional single planar-detector, PC/FRAM has most often been used to collect and analyze data in the 120–420 keV range, although it is not limited to this range. Indeed, PC/FRAM has been used with a single planar detector to measure uranium isotopic composition in the energy range from 120–1024 keV. The most widely used mode of operation for plutonium or uranium using a single coaxial detector is to acquire a single spectrum in the range from 0 to 1024 keV. Various analysis modes can then be used with this wide data range. If the region between 120 and 200 keV is available for plutonium, PC/FRAM often works best analyzing in an energy range from 120–450 keV. When sample shielding or thick-walled sample containers preclude analysis of plutonium below 200 keV, PC/FRAM can still obtain a complete isotopic analysis using only gamma rays above 200 keV from a single coaxial-detector spectrum. A complete analysis of plutonium (all measurable isotopes) using only gamma rays above 300 keV is also possible. Uranium analyses are carried out using the entire 0–1024 keV spectrum.

The optimum choice of planar or coaxial detectors is made only after all possible measurement applications are considered. The planar detector is usually the detector of choice if all measured items are unshielded or contained in “thin” containers. If shielded containers, thick-walled containers or a mixture of thin and thick/shielded containers are encountered, then a single coaxial detector system is optimum. PC/FRAM is the only available isotopic analysis method using a coaxial detector in the energy range from 120–300 keV.

The CdTe detector application is new as this report is being prepared (Vo 02). This detector collects data for analysis in the 125–414 keV range, just like a planar HPGe detector. The CdTe application is discussed in more detail in chapter XIII.

3. Shielded Samples

Most isotopic analysis codes (including the original FRAM) require the presence of spectral peaks in the region below 200 keV, regardless of whether they acquire data from one or two detectors. Some isotopic analysis codes may not function when the sample is shielded to lower radiation exposure or because the sample is inside a very heavy walled container precluding the use of the lower-energy gamma rays. PC/FRAM was the first code to demonstrate the ability to make measurements through thick walled containers or on shielded samples. Any software that obtains its results from gamma rays and x-rays in the region around 100 keV is easily defeated by as little as a few tenths of a millimeter of lead or approximately 10 mm of steel. FRAM measurements have been made through as much as 25 mm (1 in.) of lead and very easily through 25 mm of steel. These are examples only and do not exhaust the full range of capabilities in this area.

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4. Uranium Isotopic Analysis

Up until 1990 the isotopic analysis techniques originally proposed by Parker and Reilly were applied only to plutonium analysis. There was always the need for uranium isotopic analysis but the features of the uranium gamma-ray spectrum precluded the easy application of the “peak pair” ratio method that was used initially.

The uranium gamma-ray spectrum is essentially divided into two regions below 1 MeV. The low energy region up to about 200 keV contains gamma rays from ^{235}U with the major ^{235}U gamma rays at 143.76, 163.33, 185.72, 202.11, and 205.31 keV. The sole visible gamma ray from ^{234}U above 100 keV is at 120.90 keV and ^{236}U does not have any measurable gamma rays. Uranium-238 gamma rays arise from its $^{234\text{m}}\text{Pa}$ daughter with energies of 742.81, 766.36, 786.27, and 1001.03 keV (Sampson 72) for the most intense lines. The wide separation between ^{235}U and ^{238}U gamma rays stymied the application of the early arbitrary-sample isotopic analysis techniques to uranium.

The formalism of the FRAM software does not require closely spaced peak pairs for analysis. Thus, in the late 1980s we applied the original VAX version of FRAM to analysis of uranium. This required the use of a coaxial detector and data analysis in the 120–1200 keV region. We demonstrated FRAM’s ability to measure, *without any modifications to the code*, the $^{238}\text{U}/^{235}\text{U}$ ratio in samples of arbitrary physical and chemical composition, geometry, and mass, containing only uranium (Sampson 90).

In PC/FRAM uranium analysis was expanded to include ^{234}U and in the latest version we include a correlation to predict ^{236}U as well as a correction for cases where the $^{234\text{m}}\text{Pa}$ daughter is not in equilibrium.

D. Version/Feature History of PC/FRAM

1. Version 1

Version 1.0 of PC/FRAM was released in September of 1994 followed by version 1.1 in December of the same year. These versions were implemented at the Los Alamos Plutonium Facility and at the Atomic Weapons Establishment at Aldermaston, United Kingdom.

Parameter files were provided with version 1.1 for the following:

- Plutonium, planar detector, Am/Pu homogeneity, 10-420 keV
- Plutonium, planar detector, Am/Pu heterogeneity, 10-420 keV
- Plutonium, coaxial detector, Am/Pu homogeneity, 0-1024 keV
- Plutonium, shielded sample, coaxial detector, Am/Pu homogeneity, 200-1024 keV
- Uranium, $^{238}\text{U}/^{235}\text{U}$ ratio, coaxial detector, 0-1200 keV
- MOX, planar detector, $^{235}\text{U}/\text{Pu}$ ratio < 0.3, 10-420 keV

2. Version 2

Version 2 of PC/FRAM incorporated many changes, improvements, and capability enhancements. Versions 2.1, 2.2, and 2.3 were the first widely available versions with version 2.3 being customized for and licensed to ORTEC. Version 2 ran under either Windows 3.1 or Windows 95 and was first released in 1997. A computer with a 486-class processor was recommended. Over 20 major enhancements and new features are documented for versions 2.1 and 2.2 in the software user manual (Kelley 98). Some of these are highlighted below.

Version 2.1

- **Combined Acquisition and Analysis.** The Measure Sample option allowed the user to control the data acquisition in the MCA and automatically analyze the data after completion of the acquisition.
- **Plutonium-242 Correlation.** A general model for the ^{242}Pu correlation was introduced.

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$$^{242}\text{Pu} = A * (^{238}\text{Pu})^B * (^{239}\text{Pu})^C * (^{240}\text{Pu})^D * (^{241}\text{Pu} + ^{241}\text{Am})^E$$

- **Password Protection.** Password protection enabled for parameter changes.
- **ISOPOW.** A stand-alone plutonium decay correction program was incorporated as a menu option.
- **Plot Relative-Efficiency Curve.** A new option allows the user to view a plot of the relative-efficiency curve.
- **Display Analysis Results.** The analysis results can be viewed on the terminal in the same form they appear on the printed output.
- **Uranium Analysis Output.** A separate output is specifically formatted for uranium (only) isotopic results.
- **MCA Support.** Support for control of Canberra S100, ORTEC ADCAM, and LANL M³CA.
- **Plotting Spectral Data.** Spectral data can be plotted on the computer monitor with full zoom and scroll features from within FRAM. There is no need to have an MCA emulator present for detailed spectral viewing.
- **Plotting Fits.** The fits of the response functions to the data can be viewed with zoom and scroll control from within FRAM.
- **FWHM Calibration.** Improvements were made in the way the internal calibration of FWHM vs Energy is carried out.
- **Backgrounds.** Improvements in the calculation of the background underneath a peak region.
- **Dates.** Versatile date template allows display of date in all common formats.

Version 2.2

- **Acquire Data.** FRAM's built-in MCA emulator displays the spectrum on the screen as it is being accumulated in the MCA.
- **Plotting Response Functions.** The individual response functions for the fit of a multiplet can be viewed and plotted.
- **MCA Choice.** Control of ORTEC MCAs updated to use their universal multichannel buffer interface (UMCBI) routines.

Version 2.3 of FRAM, customized and licensed to ORTEC, was functionally the same as version 2.2. The only difference was that support for Canberra S100 MCA was not included.

3. Version 3

While the new features in version 3 are not numerous, they represent a very major upgrade to the overall capability and utility of PC/FRAM.

Version 3.2

- **32-bit Code.** Version 3 was upgraded to 32-bit code from the old 16-bit code of version 2. It is designed to run under Windows 95, Windows 98, and Windows NT.
- **New User Interface.** The user interface is new, having a three-dimensional (3-D) look and feel similar to that of Windows 95.

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- **New Measure Menu.** There is a new option under the Measure menu called Analyze Data. This combines and replaces the old **Analyze | Single Spectrum** and **Analyze | Autocycle** options.
- **Bi-lingual Support.** There is a new option called Language under the Options menu. It allows the user to choose one of two languages to be used when displaying information on the screen or printer. The character strings to be displayed are stored in one of two language files. Currently we support English and Russian as the two languages. This can be easily extended to other European languages.
- **New Database Format.** The analysis parameters are stored in a database using a new format. This format is not compatible with previous versions of FRAM. The distribution kit does not contain an “empty” database as it did for version 2.2. The new version of PC/FRAM creates the necessary files when it is first executed.

Version 3 exists in three variants. Version 3.2 is the standard version used at Los Alamos and contains MCA support for both ORTEC and Canberra MCAs. Version 3.3 is functionally equivalent and is licensed to ORTEC and ANTECH with only ORTEC MCA support. Version 3.4 is also functionally equivalent and is licensed to Canberra with only Canberra MCA support.

4. Version 4

The new features and upgrades in version 4 mainly concern enhancements to the physics algorithms, new measurement capabilities, and a new structure to make derivative applications easier to implement.

Version 4.2

- **Relative Efficiency.** This version incorporates a new physical model for calculating the relative-efficiency curve. See II.F.5.
- **Analysis Engine.** The analysis algorithms have been split out from FRAM proper and placed in their own library. This makes it easier for licensees and other users to adapt FRAM for their own applications.
- **New Menus for Uranium Analysis.** There are separate dialog boxes for measuring plutonium and uranium. There are separate dialog boxes for analyzing plutonium and uranium data files.
- **Intelligence.** There is a selectable capability of automatically switching, in a limited way, from one parameter set to another depending on the results of the analysis.
- **Canberra MCA Enhancements.** There is now support for the control of Canberra MCA's as well as the reading and writing of spectral data to and from their CAM files. This is done in conjunction with the Genie 2000 software package from Canberra.
- **Uranium Analysis Enhancements.** Enhancements for uranium analysis include 1) correction for ^{234}Th nonequilibrium, 2) isotopic correlation to predict ^{236}U , and 3) corrections for coincidence summing effects (Vo 99a).
- **Data Formats.** The MMCA and MCARS systems of the International Atomic Energy Agency (IAEA) and the Green Star SBS-60 systems are now supported.
- **CdTe.** FRAM now has the capability for complete plutonium analysis from spectra taken with a CdTe detector in the 120–414 keV energy range (Vo 02).
- **100-keV Region Analysis.** FRAM version 4 has complete capability for plutonium analysis in the 100-keV region (Vo 01, Vo 01a).

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- **40-keV Region Analysis.** FRAM version 4 has complete capability for plutonium analysis in the 40-keV region (Vo 99, Vo 01a).

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This section of the FRAM Application Guide describes the process by which FRAM obtains the isotopic composition from a gamma-ray spectrum.

A. Obtain Data

FRAM can analyze data from a number of sources. There are two basic types of sources of data for FRAM.

1) “Live” data from a multichannel analyzer (MCA) acquisition of a gamma-ray spectrum from a high-resolution detector (usually HPGe). FRAM can control the data acquisition from several commercially available multichannel analyzer families. The ORTEC line of multichannel buffers (MCB) operating with Maestro can all be controlled via FRAM. Canberra MCAs operating under Genie 2000 can be controlled from FRAM. Note that this control is limited to the basic functions of preset count time, start, stop, and readout to a disk file. The user must invoke the appropriate commercial MCA emulator, e.g., Maestro for ORTEC and Genie 2000 for Canberra, to perform functions involving MCA and data acquisition (high voltage, amplifier gain, etc.) setup.

The analysis of the data acquired in a “live” data acquisition under FRAM control proceeds automatically without operator intervention after the acquisition terminates.

2) Data from a disk file. FRAM can read and analyze data from disk files recorded in several different data formats. These data formats include, for version 4, the following formats:*

- NIS-5 standard
- Canberra S100
- Ortec ‘chn’
- Ortec ‘spc’
- Canberra CAM
- IAEA MCRS
- IAEA MMCA
- Green Star
- ASCII

B. Perform Analysis

The analysis of a gamma-ray pulse height spectrum by the PC/FRAM code can be described in two parts, 1) Internal Calibration, and 2) Analysis of the Spectral Data.

1. Internal Calibrations

The internal calibration uses selected peaks in the spectrum under analysis to provide a calibration of energy vs channel, full width at half maximum (FWHM) vs channel, and peak shape (tailing parameters) vs channel. These calibrations are done internally on the spectrum under analysis so the analysis does not depend on parameters determined from other measurements that may have been taken with different conditions of count rate, resolution, or electronic adjustment.

* Proprietary Information: If FRAM is purchased from a licensee it will not contain the full range of control and format features outlined above. Only the control and data formats appropriate to the vendor’s own products or that are publicly available are likely to be present. In a version of FRAM from Los Alamos, the user will have access to everything that was current at the version release date. The user will have to purchase and install the appropriate commercial MCA emulator to control the electronics setup of the MCA and to make full use of all the file formats.

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There may be cases where the spectral quality or type is such that there are insufficient peaks to be able to use the unknown spectrum for its own peak calibrations. In these cases one can fix the peak calibration parameters to their initial values in the parameter set. The appropriate portion of the internal calibration is bypassed in this case.

a. Energy Calibration

The first portion of the internal calibration procedure calibrates energy vs channel number from a list of peaks, usually strong single peaks, in the parameter set. A piecewise linear calibration between pairs of peaks is used for the energy calibration. The peaks are located using the default gain (keV/ch) and default zero (keV at channel 0) in the parameter set. The algorithm locates the peak at the maximum count found in a region of 10 channels on either side of the default peak position, which is located using the default gain and zero. With this algorithm FRAM is not constrained to any particular energy calibration. Within the general constraints of spectral quality, FRAM can analyze spectra at any gain, if the energy calibration is known a priori well enough to find the internal energy calibration peaks within a ± 10 channel window.

The peak centroid is found using a least-squares fit of a quadratic function to the logarithm of the counts. If there is an error in the calculation the peak is not used in the calibration. Calibration outside the range of peaks defined in the energy calibration list is extrapolated from the nearest two points.

b. Initial Background

A background is then calculated for all peak regions defined in the parameter set. The background is calculated using the specific background functional shape for each region as specified in the parameter set.

c. FWHM Calibration

The parameter set contains a user-editable list of peaks for use in the internal calibration of FWHM vs energy. The FWHM of the peaks in this list is calculated from the net data after a channel-by-channel subtraction of the initial background. The FWHM is calculated from a least-squares fit of a quadratic equation to the logarithm of the net counts. The fit is over a range of channels in which the counts exceed 75% of the peak maximum on the low-energy side and exceed 25% of the peak maximum on the high-energy side (for CdTe detectors, because of their larger tails, the fit starts from 85% on the low-energy side). This fit also yields the peak centroid, and if there is a match with an energy calibration peak (very likely) the centroid of the energy calibration peak is updated.

The FWHM as a function of energy that is used in calculating the response function for an arbitrary fitted peak is found from a least-squares fit to the function

$$FWHM(E) = SQRT \left[A_1 + (A_2 * E) + \left(\frac{A_3}{E} \right) \right] \quad (V-1)$$

The first two terms are physics-based and the third term is incorporated to account for the empirical observation that, for some detectors, the FWHM tends to “level out” at low energies.

d. Peak Shape/Tailing Calibration

The gamma-ray peak shape is described by a central Gaussian component with a single exponential tail on the low-energy side of the peak.

$$Y(J) = Ht * \exp[\alpha * (J - x_0)^2] + Tail(J) \quad (V-2)$$

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where

$Y(J)$ = Net counts in channel J
 Ht = Peak height at the peak centroid x_0
 $\alpha = 2.77259/FWHM^2$ is the peak width parameter

and the tailing parameter $Tail(J)$ is given by

$$Tail(J) = Ht * \exp[(T1 + T2 * E) + (T3 + T4 * E) * (J - x_0)] * [1 - \exp(-0.4 * \alpha * (J - x_0)^2)] . \quad (V-3)$$

Both the amplitude and slope of the tailing function are permitted to be a function of energy. However, in practice we set $T4$ to zero, reducing the number of unknowns to three. After subtracting the Gaussian portion of the peak (known because we have calibrations for energy and FWHM), we determine the slope and amplitude constants from a least-squares fit of the data from all the FWHM peaks (using the net channel contents on the low-energy side of the peak from 0.5 to 1.5 FWHMs from the peak center).

At this point we have completed the internal calibration and have all the parameters necessary to calculate the shape of a gamma-ray peak at any location in the spectrum.

2. Analysis of Spectral Data

After the internal calibration is complete the analysis proceeds on a region-by-region basis in the order that the regions are presented in the parameter set. The program makes three passes or iterations through all the regions. While the regions are generally analyzed in order of increasing energy, if a region has a peak fixed to a second peak outside of the region, it is desirable to analyze the second region before the first so all peaks fit in a given region use the most current data. This ordering is done when constructing the regions in the parameter set.

The analysis starts by subtracting the background to get the net counts in a region. The background for the first iteration is available from the initial background calculation, which was done during the calibration phase. Below we describe the steps taken during each iteration of the analysis.

a. Calculate Peak Areas Using Response Functions

For each of the regions defined in the parameter set, FRAM does the following:

- Establishes the start and end of the region and the number of peaks in the region.
- Subtracts background for the region using the most current information.
- Allocates dynamic memory for the least-squares fitting of the response functions. Sets the values of the output array to the net counts in the region.
- Constructs a set of response functions, one for each isotope with a free peak in the region. Each response function has the form

$$\sum_i f_i R_i(x), \quad (V-4)$$

where each R_i is a unit area function describing the shape of a photopeak and f_i is the associated area factor. One of the terms in this sum will correspond to a given free peak: its area factor is set to one. The other terms in the sum will correspond to peaks, which are fixed to this free peak. If peak i is fixed to peak j , the area factor will be

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$$f_i = \left(\frac{BR_i}{BR_j} \right) * \left(\frac{RE_i}{RE_j} \right) * \left(\frac{RA_i}{RA_j} \right) \quad (V-5)$$

where BR = branching ratio, RE = relative efficiency, and RA = relative activity. This defines the ratio of the area of peak i to the area of peak j . The relative activity is the ratio of the activity of the given isotope to that of the first isotope in the parameter set's isotope list. The relative activity ratio is set to unity for the first iteration.

If a peak in the region is fixed to another peak outside the region, its photopeak function $R_i(x)$ is multiplied by the product of the area factor and the previously determined area of the other peak. These values are then subtracted from the values in the output array. Thus, this peak is effectively stripped off or removed from the spectrum.

- Performs the weighted least-squares fitting of the response function for the free peaks to the adjusted (adjusted for stripped peaks) net counts. If the areas of any of the peaks turn out to be negative, perform another least-squares analysis, forcing them to be zero. The coefficients resulting from the analysis will be the areas of the free peaks.
- Calculates the predicted responses and saves them for display and output.
- Calculates the areas of all the peaks from the coefficients and determines appropriate values for their errors. If this is not the final iteration, use the results at this point to update the background offsets.

b. Calculate Relative Efficiencies

- Obtain the number of peaks to be used from the relative-efficiency peak list in the parameter set.
- Determine the number of isotopes, N , and the number of efficiency functions, M , represented by these peaks. The number of parameters used in the least-squares analysis for the empirical model relative-efficiency curve will be $5 + (N - 1) + (M - 1)$.
- The model for the empirical relative-efficiency curve is

$$\ln\left(\frac{Area}{BR}\right) = c_1 + \frac{c_2}{E^2} + c_3(\ln E) + c_4(\ln E)^2 + c_5(\ln E)^3 + c_i + \frac{c_j}{E} \quad (V-6)$$

where the energy E is in MeV. Each c_i is associated with isotopes beyond the first one, and i ranges in value from 6 to $5 + (N-1)$. Each c_j is associated with an efficiency function beyond the first one; j ranges in value from 6 to $5 + (N-1) + (M-1)$.

- Perform the least-squares analysis.
- Compute the relative efficiency for every peak in the relative-efficiency peak list using the first $5 + (N-1)$ terms in the above model. In addition, if a peak is associated with an isotope that is assigned an efficiency function other than one, compute its heterogeneity factor, $h = \exp(c_j/E)$, then multiply its relative efficiency by h .
- The model for the physical relative-efficiency curve is

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$$\varepsilon = \frac{1}{\mu_{Pu} * x_{Pu}} \left(1 - \exp(-\mu_{Pu} * x_{Pu}) \right) * \exp(-\mu_{Cd} * x_{Cd}) * \exp(-\mu_{Fe} * x_{Fe}) * \exp(-\mu_{Pb} * x_{Pb}) * (I_i) * \exp\left(\frac{c_j}{E}\right) * (Det\ Eff) * (Correction\ Factor) \quad (V-7)$$

This model has been discussed in II.F.5 above. The relative-efficiency function is fit to the selected relative-efficiency data points by nonlinear least-squares using the Levenberg-Marquardt method.

c. Calculate Relative Activities

The model used to calculate the relative activities is $Area_i = \sum_j A_j (BR_{ij})(RE_i)$ where A_j is the activity ratio for the j th isotope, BR_{ij} is the branching ratio for the gamma ray emitted by the j th isotope contributing to the area of the i th photopeak, and RE_i is the relative efficiency at the energy of the i th peak. In this formula, the sum ranges over the isotopes contributing to the area of the i th photopeak. The sum will have more than one term if a peak was “summed” with another peak.

The estimates for the relative activities can be calculated via a weighted linear least-squares algorithm, the weights being based on the errors involved with the peak areas. The problem is that there are significant errors associated with both the areas and the relative efficiencies, whereas this linear model assumes that the independent variables are known precisely. In addition, there is sometimes a wide range of weights assigned spanning many orders of magnitude, and this causes difficulties in the calculations.

So the calculation proceeds in two steps. First the data for each isotope, where none of its peaks are “summed” with any other peak, are extracted from the model. Suppose that the j th isotope can be

uncoupled from all the other isotopes. For each photopeak used, we calculate $Z_k = \frac{Area_k}{(BR_{kj})(RE_k)}$ and

propagate the error involved with the relative efficiency. The estimate for the relative activity of this isotope is computed as the weighted average $\frac{\sum_k Z_k w_k}{\sum_k w_k}$ where w_k is the reciprocal of the square of the

error associated with Z_k . In the second step, the remaining isotopes are collected into a smaller set of equations that is then subjected to a weighted least-squares calculation. The weights used in the calculations are the errors associated with the peak areas, but these are inflated according to the largest error associated with the relative efficiencies appearing in the sum.

The relative masses for each isotope are calculated from the relative activities, the half lives, and atomic masses of the isotopes.

d. Calculate Isotopic Fractions

After the third iteration is complete the final relative masses (relative to the first isotope in the isotope list) are combined to give the absolute isotopic fractions for the directly measured isotopes. The fractions are renormalized accounting for ^{242}Pu (^{236}U) computed by correlation or fixed by operator entry. Nonplutonium (uranium) isotopes are quantified relative to total plutonium (uranium). For samples containing no plutonium or uranium, the final results are the relative masses themselves.

Auxiliary results such as the effective specific power and effective ^{240}Pu fraction are computed from the plutonium isotopic fractions and the appropriate constants in the isotope list in the parameter set.

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Calculate Isotopic Correlation for ^{242}Pu and ^{236}U

Plutonium-242 and ^{236}U cannot be measured directly with gamma-ray spectroscopy techniques. It is customary to introduce an empirical isotopic correlation (Gunnink 80, Bignan 95) to predict their concentrations from the measured ratios for the other isotopes.

FRAM predicts the value for ^{242}Pu by

$$^{242}\text{Pu} = A \times \left[\left(^{238}\text{Pu} \right)^B \times \left(^{239}\text{Pu} \right)^C \times \left(^{240}\text{Pu} \right)^D \times \left(^{241}\text{Pu} + ^{241}\text{Am} \right)^E \right] \quad (\text{IV-4})$$

where the five constants, A–E are user-editable values in the parameter file.

In a similar manner, Vo has developed a correlation to predict ^{236}U in uranium-bearing samples (Sampson 95). It is of the form

$$^{236}\text{U} = A \times \left[\left(^{235}\text{U} \right)^B \times \left(^{238}\text{U} \right)^C \right] . \quad (\text{IV-5})$$

The constants in Eq. IV-5 have been determined from mass spectrometry values for US uranium produced by the gaseous diffusion process and are user-editable values in the parameter file.

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A. What are Parameter Files?

The FRAM code has been structured to give the user as much control as desired over the analysis to increase the versatility and applicability of FRAM. This is accomplished via the use of the Parameter File (or Parameter Set) mechanism. A Parameter File (or Parameter Set) contains all the parameters required to carry out an analysis on a gamma-ray spectrum. This includes information on the isotopes to be analyzed; the specific gamma-ray peaks to use; the nuclear data for the isotopes and gamma-ray peaks; data acquisition conditions such as gain, zero, number of channels, and regions of the spectrum for analysis; and diagnostic test parameters.

A complete group of these parameters resides in a single, custom-designed database within the FRAM program. The complete group of parameters in the database is called a Parameter Set. This database can accommodate multiple parameter sets (limited only by computer memory). A separate utility, called the Change Parameter Utility, accessed from the FRAM program, gives the user access to all the parameter sets. The Change Parameter Utility allows the user to augment the database with a new parameter set, delete a parameter set from the database, or modify the values in any parameter set. The utility also allows the user to export the information in a parameter set to a text file on disk and subsequently to import this information back into the database. This allows parameter sets to be shared among different FRAM systems. The text file on disk is called a Parameter File. Formally our terminology of a "parameter set" refers to the information residing in the database in computer memory. The terminology of a "parameter file" refers to the information in a text file residing on a disk. We often ignore this distinction when discussing this concept. The Change Parameter Utility is password protected.

The amount of accessible information in a parameter set can be daunting. "How am I ever going to be able to run this code?" is a question that occurs in many new users' minds. This question is easily answered in almost every case because FRAM is delivered with a variety of parameter sets suitable for nearly all routine analyses. These parameter sets usually do not need any editing or changes for first-time use. Routine FRAM analyses can be started with as few as three clicks of the mouse.

B. The Change Parameter Utility

The Change Parameter Utility is entered under password protection (valid User Name and Password required) from the FRAM main menu. The password protection option will be illustrated later in this document.

The Change Parameter Utility has two menu options, File and Edit, illustrated below in Fig. VI-1, which shows the options active after entering the utility.

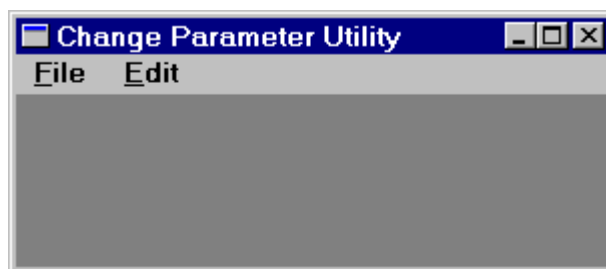


Fig. VI-1. The Change Parameter Utility window.

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The **File** menu governs the manipulation of parameter sets in the parameter database. The dropdown menu (see Fig. VI-2) shows the options available for manipulation of parameter sets in the parameter database. Greyed options become active after a parameter set has been opened.

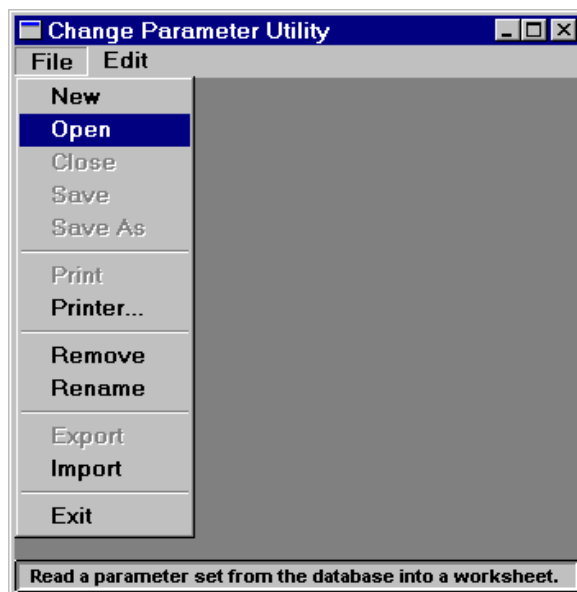


Fig. VI-2. Options under the File menu in the Change Parameter Utility.

A parameter set from the parameter database is read into a worksheet area in memory by invoking the **Open** option. The parameters may then be edited using the **Edit** menu. The **Edit** menu (see Fig. VI-3) allows the user to edit values in the parameter set in five main categories: 1) fitting parameter values and defaults, 2) peak information, 3) region information, 4) isotope information, and 5) application constants governing diagnostic tests. The **Postpone editing** option allows the user to experiment with new parameters without actually modifying the data in the database.

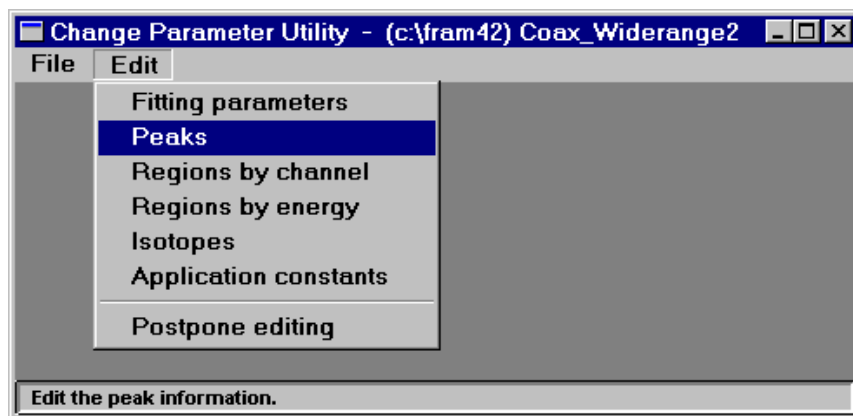


Fig. VI-3. Options under the Edit menu in the Change Parameter Utility.

The next section discusses the parameter groups that may be edited with the Edit option in the Change Parameter Utility.

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C. Analysis Parameters

1. Fitting Parameters

Selecting **Edit | Fitting Parameters** brings up the menu below (Fig. VI-4).

Edit Fitting Parameters - Coax Widerange2

OK Cancel

Default Energy Calibration
Gain (keV/ch) = 0.12500 Offset (keV) = 0.00500
☐ Fixed

Default FWHM constants
 $fwhm(ch) = \sqrt{A1 + A2*E + A3/E}$
A1 (ch²) = 15.0000 A2 (ch²/keV) = 0.18000 A3 (ch²*keV) = 2000.000
☐ Fixed

Default tailing constants
 $tail(ch) = H * \exp((T1 + T2*E) + (T3 + T4*E)*(ch-x0)) * [1 - \exp(-C*(ch-x0)^2)]$
T1 = -4.20000 T2 = 0.00300 T3 = 0.27000 T4 = 0.00000
☒ Fixed

Description: Coax .125 kev/ch, HomoAm/Pu, Equ., 3-25% Pu240, <450 keV

Last modified on 2001.08.30 15:17

Fig. VI-4. The Edit Fitting Parameters screen in the Change Parameters Utility.

The **Default Energy Calibration** allows the user to match the analysis to the actual energy calibration of the spectrum under study. Most other isotopic analysis codes require a single fixed energy calibration that the spectrum must match. FRAM has no limitations in this respect except the global requirement that the number of channels in the peak must not be so small (keV/ch so large) that peak fitting fails. Peak fitting becomes difficult for energies below 200 keV for coaxial HPGe detectors when the gain is above 0.5 keV/ch and above 0.25 keV/ch for planar HPGe because the photopeak contains too few data points. The FRAM code uses the **Default Energy Calibration** to find the position of the internal energy calibration peaks. It must be accurate enough to predict the actual peak position to within ± 10 channels. This is seldom a problem because one can always view the spectrum before setting this parameter. The internal energy calibration is bypassed if the **Fixed** box is checked, although we have not encountered a measurement situation where this has been necessary.

While FRAM can successfully operate using a wide range of energy calibration values, we have the most experience operating with standard **Default Energy Calibration** values delivered with each parameter set. Table VI-1 displays these standard values.

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Table VI-1. Customary/Recommended Default Energy Calibration Values for FRAM.

Detector	Gain (keV/ch)	Zero (keV at ch 0)	No. Channels
Coaxial	0.125	0.0	8192
Planar	0.100	10.0	4096
Planar	0.105	0.0	4096

The wide analysis range and gain range capability of FRAM can be seen in Table VI-2.

Table VI-2. Data Acquisition/Analysis Conditions Successfully Used with FRAM.

Isotope	Detector	Analysis Range	Gain (keV/ch)	Comment
Plutonium	Planar	120–420 keV	0.100	
		120–420 keV	0.105	
		120–307 keV	0.075	
		90–208 keV	0.075	
		38–208 keV	0.075	
		38–130 keV	0.075	
	Coaxial	120–460 keV	0.125	
		120–460 keV	0.115	
		120–460 keV	0.250	
		120–460 keV	0.500	Not recommended ¹
		120–800 keV	0.125	
		200–800 keV	0.125	
		300–800 keV	0.125	
Uranium	Coaxial	120–1024 keV	0.125	
		120–1024 keV	0.130	
		120–1300 keV	0.156	
		120–1024 keV	0.250	
	Planar	120–1024 keV	0.250	Not recommended ¹

¹Combination of energy range and keV/ch not recommended. Peaks are too narrow at low energies for reliable shape calibration.

One example of the utility of the **Default Energy Calibration** selection occurs in the analysis of uranium with a coaxial detector. Our standard parameter files for uranium are set up to analyze data from 120–1024 keV collected in 8192 channels at a gain of 0.125 keV/ch. Under these conditions, the important 1001-keV uranium daughter peak is located at channel 8008. However, some successive approximations-type analog-to-digital converters (ADC) cut off their data storage at the high end of the range resulting in incorrect storage of count information right around the 8008 channel location of the 1001-keV peak. FRAM easily handles this problem if the user adjusts the gain of the electronics to 0.130 keV/ch and then changes the **Default Energy Calibration** gain to 0.130 keV/ch to match. The 100-keV peak now occurs at

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channel 7700, well away from the ADC's spectral distortion area. With this one change in the appropriate FRAM parameter file, the analysis at the new gain proceeds without a hitch.

The **Default FWHM constants** govern the energy variation of the FWHM in the absence of the internal FWHM calibration (V.B.1.c), that is, when the **Fixed** box is checked. Each parameter file for FRAM is loaded with **Default FWHM constants** appropriate for a high-quality detector of the type characteristic of the parameter file values. These default constants may be obtained from a medium length printout of an analysis using the parameter file of interest with the FWHM constants free. We have little, if any, experience using fixed values of the **Default FWHM constants** as essentially all analyses provide enough internal peaks to carry out the internal FWHM calibration.

The **Default tailing constants** govern the default values of the slope and amplitude of the exponential tail on the low-energy side of the peak. The four constants T1 through T4 allow both the slope and amplitude to be parameterized as a linear function of energy. In practice we set T4 to zero, leaving the slope independent of energy and the amplitude with linear energy dependence. These parameters are determined during the internal calibrations by fitting the residuals on the low energy side of the peak after subtracting the central Gaussian component.

Most new detectors are of such high quality that the low-energy tail is essentially invisible. This will occasionally cause the internal shape calibration to fail and default to the Default tailing constants. The **Default tailing constants** with LANL-delivered parameter sets are characteristic of high-quality detectors that do not exhibit any neutron damage or enhanced tailing characteristics.

The best results for spectra with good statistics should be obtained by leaving the **Default tailing constants** "free." In this manner the tailing will adapt to the slow increase in tails that appear with age and neutron exposure in most HPGe detectors.

Spectra with poor counting statistics may not have strong enough internal shape-calibration peaks to enable FRAM to extract good values for the tailing constants if the Default tailing constants are "free." The danger is not that the shape calibration will fail completely (the Default tailing constants will be used in that case) but that it will actually calculate tail parameters with very poor data, yielding bad peak shapes. For this reason we recommend that analysis of spectra with poor statistics proceed with the **Default tailing constants** "Fixed" in the **Edit Fitting Parameters** window.

In a general measurement situation where both good and poor statistics spectra may be encountered, we recommend "Fixing" the Default tailing constants for all analyses.

We have also observed over many years the different factors that can affect the tailing parameters. The shaping electronics, analog or digital, have a subtle effect, even when properly adjusted. Detectors from different manufacturers also exhibit different tail characteristics, even when new. For any new system (electronics or detector) we recommend that the user characterize the Default tailing constants and replace those delivered with the parameter set with new constants most characteristic of the specific system in use. Analyzing several spectra with good statistics and the tailing parameters "Free" easily performs this characterization. The new tailing parameters are listed in the medium length printout. Averaged results from several measurements should be used as these parameters vary from run to run. This is a suggestion, not a requirement. The differences observed between optimum and nonoptimum tailing parameters are small and generally within the overall uncertainty of FRAM.

2. Gamma-Ray Peak Data

Selecting **Edit | Peaks** in the Change Parameter Utility brings up a window (see Fig. VI-5) allowing the user to specify information about the peaks to be used in the analysis. This window allows the user to customize the analysis for nearly any conceivable application.

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	isotope	peak energy	line width	branching ratio	fix area to	sum area with	used for eff	used for act	used for ecal	used for fcal	used for scal
24	Pu239	171.372	0.00	1.13000e-006	0	0	☐	☒	☐	☐	☐
25	U235	185.718	0.00	5.73000e-001	0	0	☐	☒	☐	☐	☐
26	U235	202.130	0.00	1.08000e-002	25	0	☐	☐	☐	☐	☐
27	Pu239	203.545	0.00	5.72700e-006	0	0	☒	☒	☐	☐	☐
28	U235	205.311	0.00	5.05000e-002	25	0	☐	☐	☐	☐	☐
29	Pu241	208.000	0.00	5.39200e-006	0	0	☒	☒	☒	☒	☒
30	Am241	208.000	0.00	7.95400e-006	3	0	☐	☐	☐	☐	☐
31	Am243	209.750	0.00	3.42000e-002	34	0	☐	☐	☐	☐	☐

Fig. VI-5. The Edit Peak information screen in the Change Parameter Utility allows the user to customize the analysis.

a. Isotope

The first column is the peak index number. The second column lists the isotope assigned to the peak. The isotope name must be listed in the Isotopes list if it is to be used for activity, efficiency, or for “stripping” outside its region of definition.

b. Peak Energy

The second column lists the peak energy in keV.

c. Line Width

The third column lists the line width in eV of any x-ray peak used in the analysis. This is used only for x-ray fitting in the 100 keV region.

d. Branching Ratio

The branching intensity or branching ratio (photons/disintegration) is listed in the fifth column. Primary sources for this information are the Table of Isotopes (Firestone 96) and the 1976 publication by Gunnink (Gunnink 76a) that is reproduced in Appendix D. Some of the branching ratio values used in a FRAM parameter file are fine tuned from their published values.

e. Uses in Analysis

The last seven columns detail how each peak is to be used in the analysis.

fix area to This column contains the number of the free peak that will be used to determine the peak area by use of the known activity, relative efficiency, and branching ratio of the two peaks in question. The ratio of the area A_i of peak i to the area A_j of peak j is given by

$$\frac{A_i}{A_j} = \frac{BR_i}{BR_j} \times \frac{RE_i}{RE_j} \times \frac{RA_i}{RA_j} \quad (\text{VI-1})$$

where BR = branching ratio, RE = relative efficiency, and RA = relative activity.

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sum area with This column contains the number of the free peak that the listed peak area will be summed with before the least-squares fitting is used to resolve the activities. Summing can be used to unravel very close or even coenergetic peaks that are too close together to be accurately resolved with the response function fitting.

used for eff A check placed in this column denotes that the peak will be used for the relative-efficiency determination.

used for act A check placed in this column denotes that the peak will be used for the activity determination.

used for ecal A check placed in this column denotes that the peak will be used in the internal energy calibration.

used for fcal A check placed in this column denotes that the peak will be used in the internal calibration of full width at half maximum.

used for scal A check placed in this column denotes that the peak will be used in the internal calibration of the peak shape tailing parameters.

3. Analysis Region Definition

Selecting **Edit | Regions by energy** or **Edit | Regions by channel** in the **Change Parameter Utility** brings up the window allowing the user to edit the regions of interest selected for analysis (see Fig. VI-6). The windows allow editing either by energy (illustrated below) or channel. The actual setup in the software is in energy units (keV). The default energy calibration is used for the energy/channel conversion. The code works in energy units, therefore the region information is independent of the energy calibration of the spectral data.

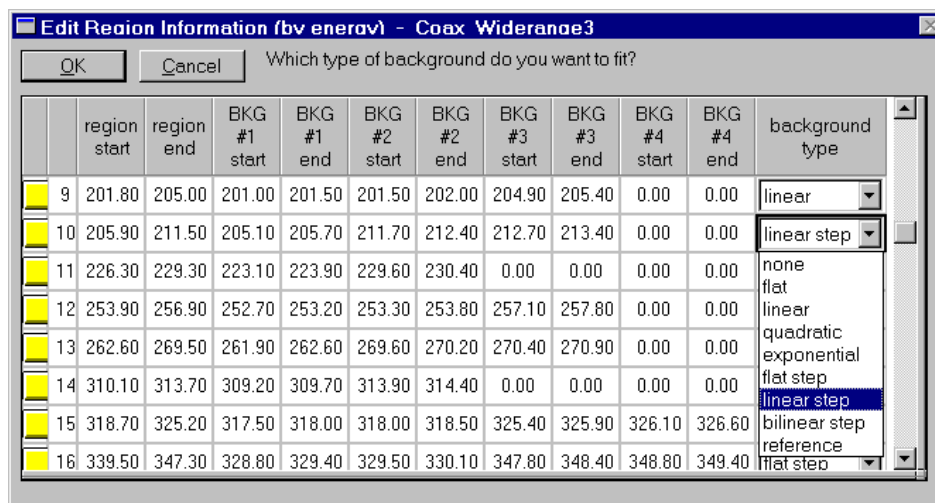


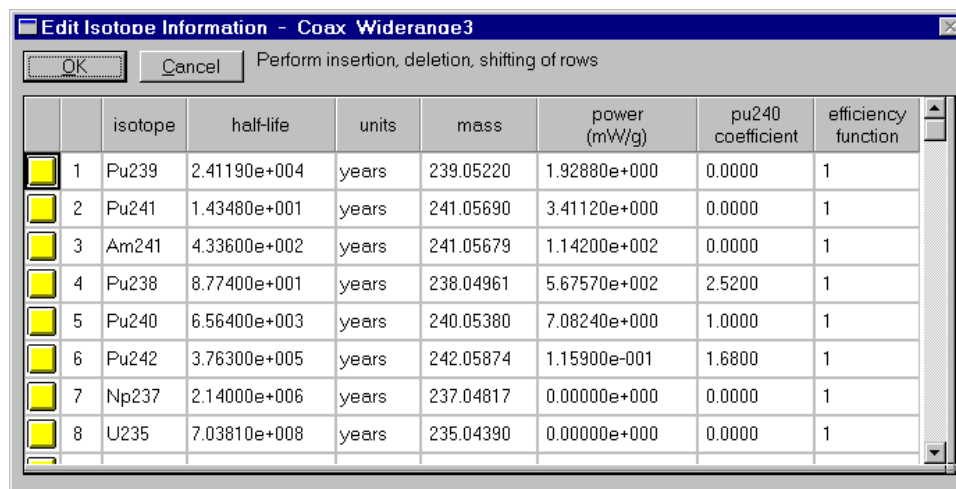
Fig. VI-6. The Edit Region Information window in the change Parameter Utility allows the user to set up or change analysis regions.

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The **Edit Region Information** window allows the user to specify the boundaries of a peak region and the boundaries of up to four background regions used to define the background continuum underneath the peak region. There are no limitations on the size and location of the background regions. Also, the peak region may contain multiple peaks. The user selects a **background type** from a choice of seven shapes from the drop down menu as shown above. The regions are analyzed in the order listed in the worksheet.

4. Isotope Information

Selecting **Edit | Isotopes** in the **Change Parameter Utility** brings up the window allowing the user to edit the names and data for the isotopes quantified in the analysis (see Fig. VI-7).



	isotope	half-life	units	mass	power (mW/g)	pu240 coefficient	efficiency function
1	Pu239	2.41190e+004	years	239.05220	1.92880e+000	0.0000	1
2	Pu241	1.43480e+001	years	241.05690	3.41120e+000	0.0000	1
3	Am241	4.33600e+002	years	241.05679	1.14200e+002	0.0000	1
4	Pu238	8.77400e+001	years	238.04961	5.67570e+002	2.5200	1
5	Pu240	6.56400e+003	years	240.05380	7.08240e+000	1.0000	1
6	Pu242	3.76300e+005	years	242.05874	1.15900e-001	1.6800	1
7	Np237	2.14000e+006	years	237.04817	0.00000e+000	0.0000	1
8	U235	7.03810e+008	years	235.04390	0.00000e+000	0.0000	1

Fig. VI-7. The Edit Isotope Information screen in the Change Parameter Utility allows the user to specify the parameters of the isotopes to be analyzed.

The first isotope in the list has special significance. All other isotopes are ratioed to the first isotope in the list. The first isotope in the list is usually the isotope that principally defines the relative-efficiency curve although it does not have to be. After the first isotope, the order of the remaining isotopes is not important.

The efficiency function is defined to be “1” for the first isotope in the isotope list. All isotopes that have the same spatial distribution as the first isotope will also have an efficiency function of “1.” Any isotope that is known to have a different spatial distribution should be assigned an efficiency function of 2 or higher. Any isotope with a different efficiency function must have enough gamma rays to fully define its efficiency function.

In principle, FRAM can have an unlimited number of efficiency functions. In practice, we only have experience using two functions. This experience is primarily with pyrochemical residues with the plutonium being present as metal fines or metal shot dispersed in a low-Z chloride matrix containing the americium. We define two efficiency curves for this case: number 1 for all the plutonium isotopes and number 2 for ²⁴¹Am (see sections II.D.2.a and II.F.6).

5. Application Constants

Selecting **Edit | Application constants** in the **Change Parameter Utility** brings up the window allowing the user to assign and edit the values for the Application Constants in the program (see Fig. VI-8).

VI. PARAMETER FILES, THE KEY TO FRAM'S VERSATILITY

Grouping a wide variety of user-editable constants into this single option has proved to be of great advantage in allowing the user to adapt FRAM to specific facility/user needs. The **Edit Application constants** window contains a two column listing in the form of *Variable Name* | *Variable Value*. These variable-constant pairs control many options in the FRAM program, and the presence/absence of any given pair turns that option on/off. The use of these constants is discussed in detail in the FRAM Software User Manual (Kelley 97, Sampson 99a, Kelley 02). A short discussion of the classes of constants, their uses, and illustration of the user interface follows.

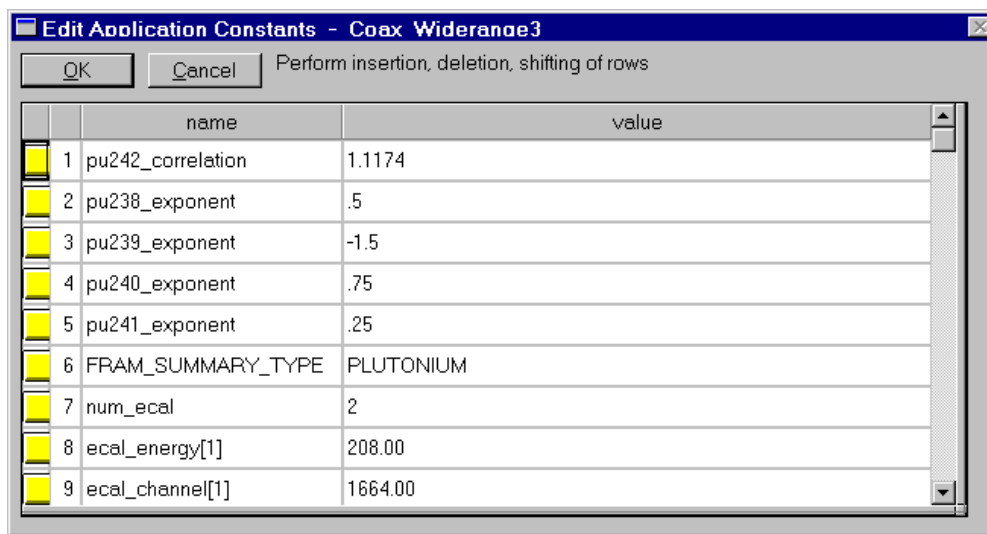


Fig. VI-8. Example of the Edit Application Constants window.

The Application Constants can appear in any order, even within a group of constants for the same application. Many of the tests, where appropriate, can be performed on as many peaks as the user desires.

The first grouping of constants 1–5 above, govern the calculation of the correlation to predict ^{242}Pu .

$$^{242}\text{Pu} = A \times \left[\left(^{238}\text{Pu} \right)^B \times \left(^{239}\text{Pu} \right)^C \times \left(^{240}\text{Pu} \right)^D \times \left(^{241}\text{Pu} + ^{241}\text{Am} \right)^E \right] \quad (\text{VI-2})$$

The first five application constants correspond to the constants A through E in Eq. VI-2.

The constant FRAM_SUMMARY_TYPE governs whether the output is formatted for uranium or plutonium.

The application constants govern customized diagnostic tests on detector performance. FRAM can test the peak position against a centroid $\pm$ a channel limit, peak FWHM against an upper limit in eV, and peak tailing against a peak area percentage underneath the tail, all on a user-selectable number of peaks tested against user-established limits. Rows 7–9 above and 11–19 below (see Figs. VI-8 and VI-9) and show the interface for these tests.

As an example, row 7 defines that an energy calibration test is to be performed on 2 peaks. The second of these two peaks (line 11) has an energy of 662.456 keV. The 662.456-keV peak is expected to fall in channel 5299.40 (line 12) within a limit of ± 4 channels (line 13). Line 14 defines a FWHM test on a single peak with an energy (line 15) of 413.714 keV. The FWHM of the peak at 413.714 keV should be less than 1500 eV (line 16) for the test to pass.

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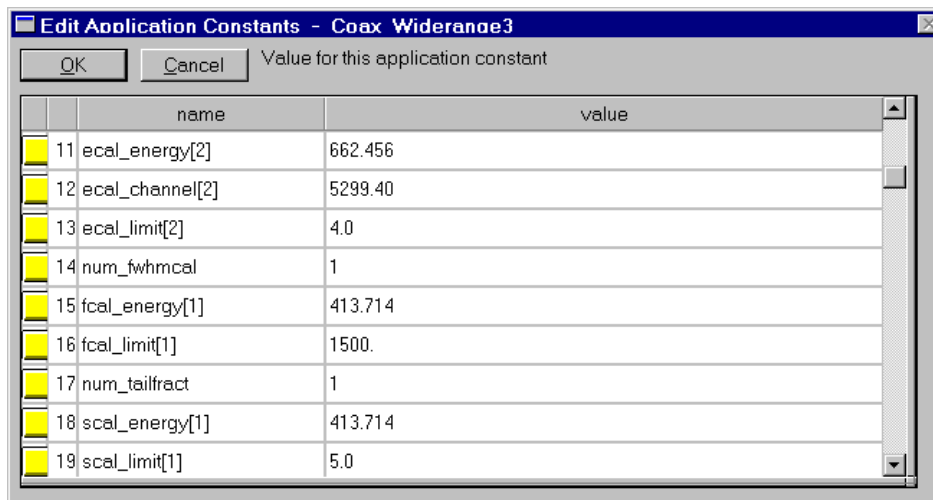


Fig. VI-9. Example of the Edit Application Constants window.

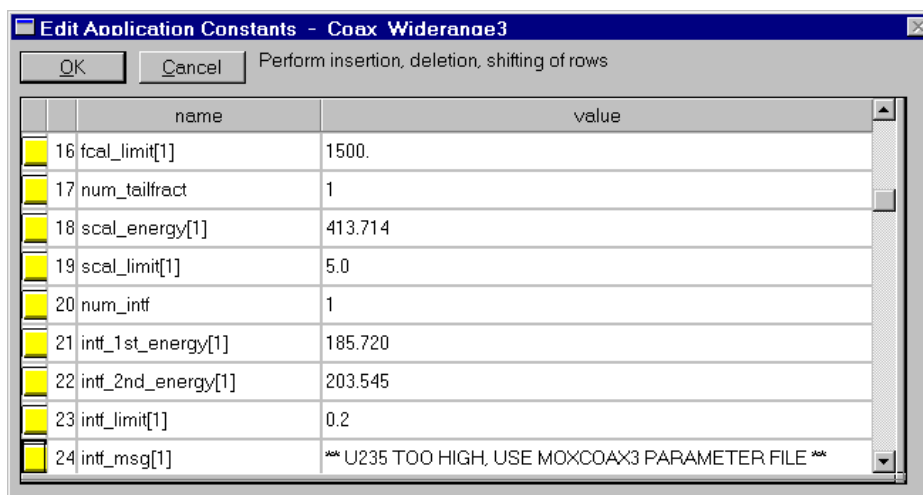


Fig. VI-10. Example of the Edit Application Constants window.

The user can test for the presence of any number of interference peaks that may appear rarely in the spectrum and are unaccounted for in the analysis. The presence of an interference peak above a certain magnitude may disrupt the analysis. The magnitude of an interference peak is determined by a ratio of the interference peak area to the area of a peak from a major isotope in the sample. A user editable message can direct the user to another analysis path. This test is illustrated in lines 20–24 above where the interference peak is at 185.72 keV and the denominator of the ratio is the area of the peak at 203.545 keV.

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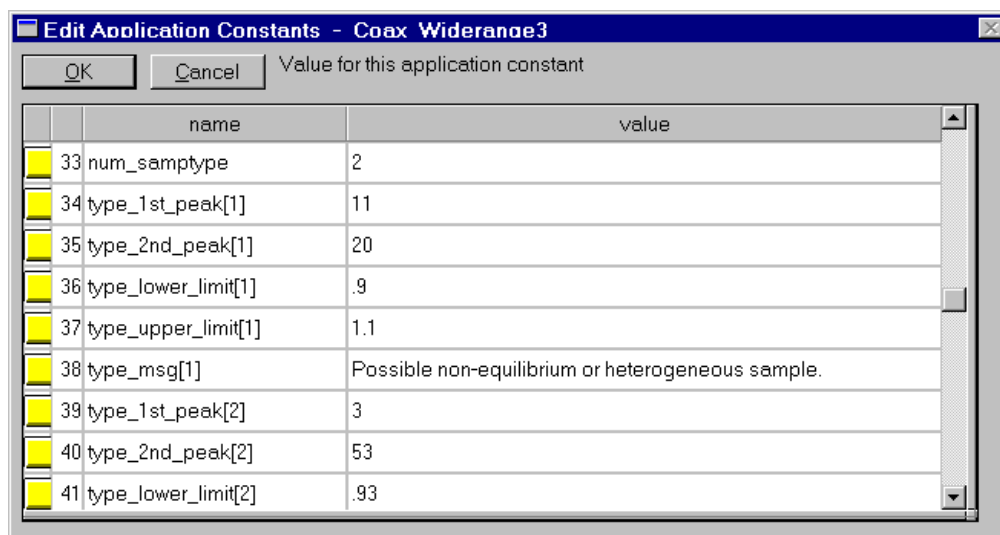


Fig. VI-11. Example of the Edit Application Constants window.

Tests called “sample type” tests check for Am/Pu heterogeneity and ^{241}Pu - ^{237}U nonequilibrium. This test is illustrated in lines 33–38 (Fig. VI-11). The “sample type” tests compare the ratio of two peak areas against upper and lower limits. A message is printed when the test ratio falls outside the designated limits. This test uses the peak index numbers in the Peaks list (section VI.C.2).

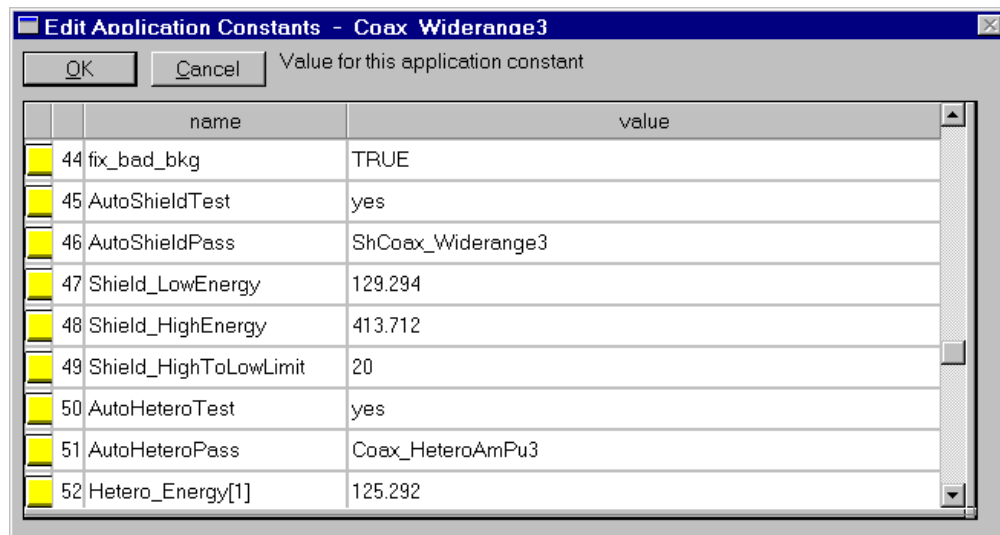


Fig. VI-12. Example of the Edit Application Constants window.

The fix_bad_bkg test (line 44, shown in Fig. VI-12) allows the code to default the selected region background type (VI.C.3) to a more simple shape if the code senses a poor background fit.

There are a number of Application Constants that direct the “Intelligent Isotopic Analysis” that is implemented in version 4.2. These constants direct tests to detect conditions that could affect the optimum choice of the parameter set. If these conditions are present, the Application Constants automatically direct FRAM to reanalyze the spectrum with a different parameter set. The conditions that FRAM looks for are 1) shielding that removes gamma-ray peaks below approximately 200 keV, 2)

VI. PARAMETER FILES, THE KEY TO FRAM'S VERSATILITY

heterogeneous Am/Pu, and 3) very high $^{241}\text{Am}/\text{Pu}$. These tests are described further in section XIV.A.1. and in the manual for version 4 of FRAM (Kelly 02). Some of the constants governing these tests are shown starting in row 45.

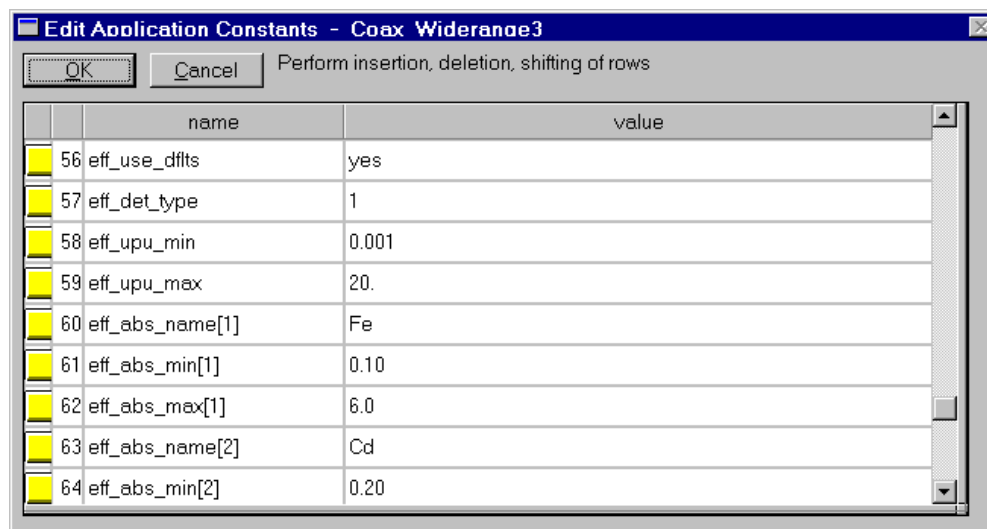


Fig. VI-13. Example of the Edit Application Constants window.

The final set of Application Constants, new in version 4.2, sets up default values for the parameters used in the fitting of the physical relative-efficiency curve (section II.F.5) (see Fig. VI-13). These include default ranges for the thickness of the plutonium (uranium) and thickness ranges for the chosen absorbers.

The entire category of Application Constants can appear quite formidable to a new user. However, the specific parameters and values have been carefully chosen and tested for appropriateness for each parameter file. The use of this option is usually completely transparent to the user.

VII. FRAM USER INTERFACE

VII. FRAM USER INTERFACE

A. FRAM Main Menu

The main menu of FRAM (see Fig. VII-1) appears with four major options, **F**ile, **E**dit, **M**easure, and **O**ptions.

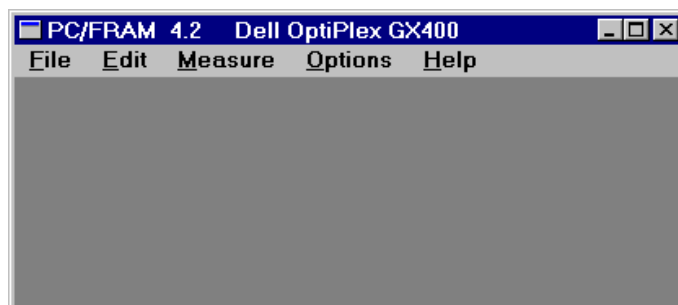


Fig. VII-1. The main menu of FRAM.

B. Main Menu Options

1. F ile

The **F**ile option (see Fig. VII-2) allows the user to open a spectral data file and view it under **O**ptions. The file can also be saved in any of the supported data formats (section V.A). Saving the file in the ASCII text format makes it easy to plot the data in many graphical applications.

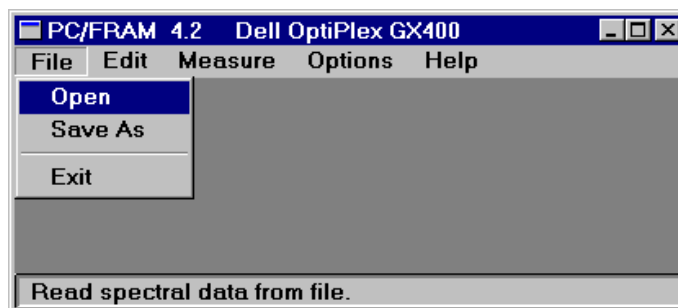


Fig. VII-2. Options under the File menu.

2. E dit

The **E**dit menu (see Fig. VII-3) has three groups of options. **P**arameters have been discussed in chapter VI. **G**eneral Defaults, shown below in Fig. VII-4, allows the user to set up global parameters that govern the data handling in the system, such as default paths for accessing FRAM, storing the spectral data and results files, and access to supported MCAs.

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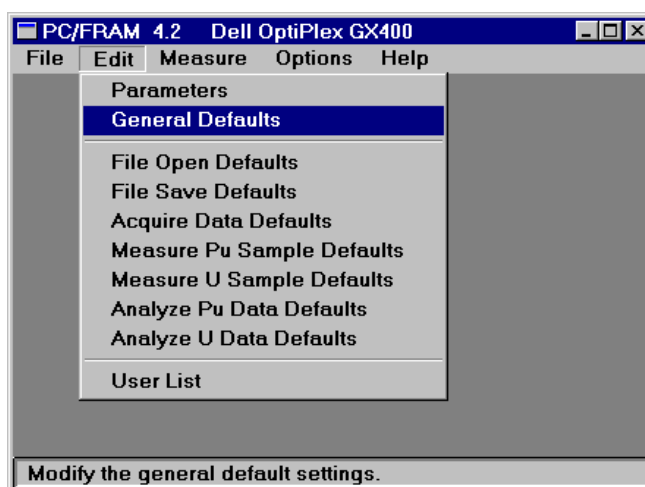


Fig. VII-3. Options under the Edit menu.

The second group of parameters under the **Edit** menu allows the user to set up default entries in many of the application windows. Some of these will be illustrated later in the discussion of those windows.

The third group is the password-protected **User List**. The User List controls access at three levels of password protection to all of the password-protected options.

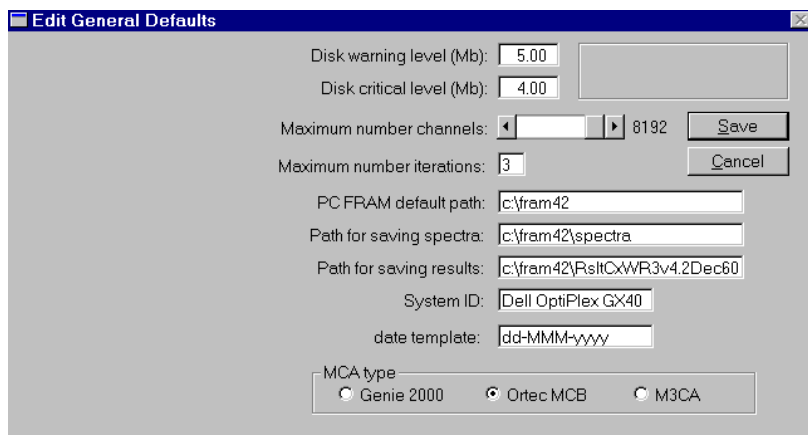


Fig. VII-4. The screen for setting General Default values.

3. Measure

The **Measure** menu (see Fig. VII-5) governs the acquisition and analysis of data from both "live" MCA sources and disk files.

VII. FRAM USER INTERFACE

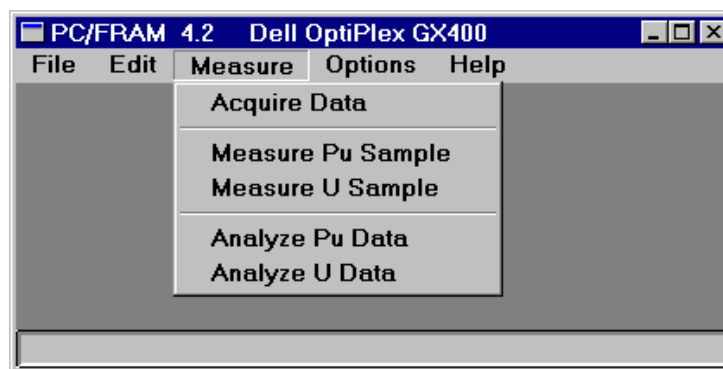


Fig. VII-5. Options under the Measure menu.

The **Acquire Data** option controls acquisition of data from a supported MCA and the storage of the data (without analysis) in a disk file. The **Measure Pu (U) Sample** options follow the data acquisition with an immediate analysis of the acquired spectrum, producing the measurement result seconds after completion of the data acquisition. **Analyze Pu (U) Data** analyzes the spectral data from an existing disk file. We show the **Measure Pu Sample** window below as an example.

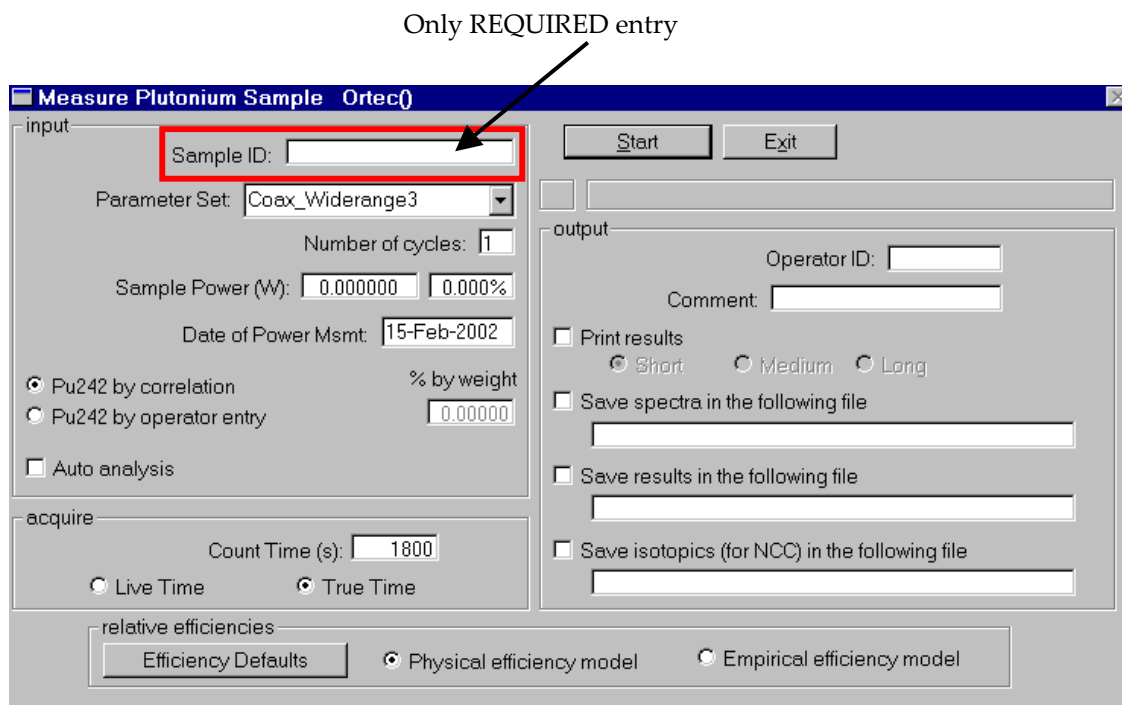


Fig. VII-6. The Measure Plutonium Sample window.

The **Measure Plutonium Sample** window (Fig. VII-6 above) is shown with some of the entries defaulted from the **Edit | Measure Pu Sample Defaults** option. At this point the only entry *required* to start the measurement and complete the analysis displaying results on the terminal is the entry of the Sample ID. With the use of defaults successive measurements may be completed with only identification of the sample and clicking the **Start** button. In many cases the user will also want to utilize some of the optional

VII. FRAM USER INTERFACE

output options. To further make this easier, the entered **Sample ID** is defaulted as the filename for data storage purposes.

4. Options

The **Options** menu allows the user several ways to display and view the spectral data and the results of the analysis. The entire spectrum can be displayed and manipulated from the **Plot Spectrum** option with versatility similar to that of a commercial MCA emulator. The user can also display the peak fits and view the relative-efficiency curve. These options are invaluable when troubleshooting a suspect analysis. The results of selecting **Plot Efficiencies** and **Display Fits** are shown in Fig. VII-9 below with fits being displayed showing only the fit envelope (left) or with the individual components (right).

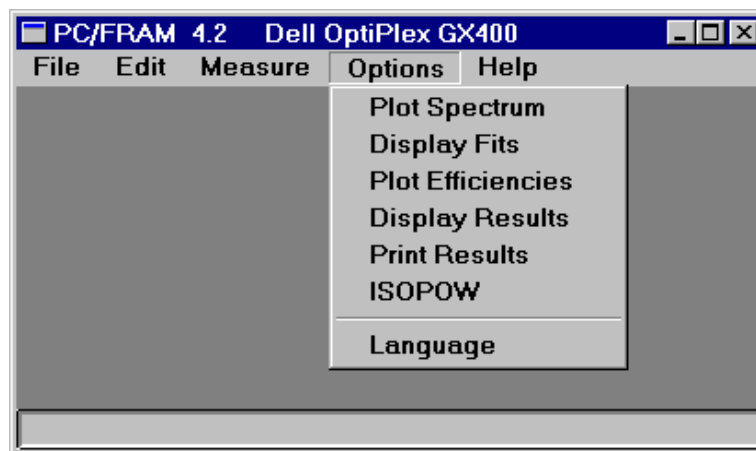


Fig. VII-7. Options under the Options menu.

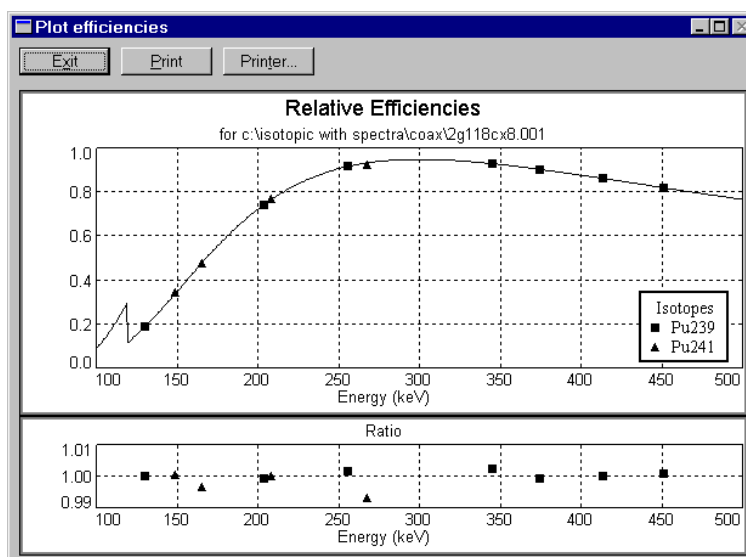


Fig. VII-8. Screen displaying fitting of relative-efficiency curve.

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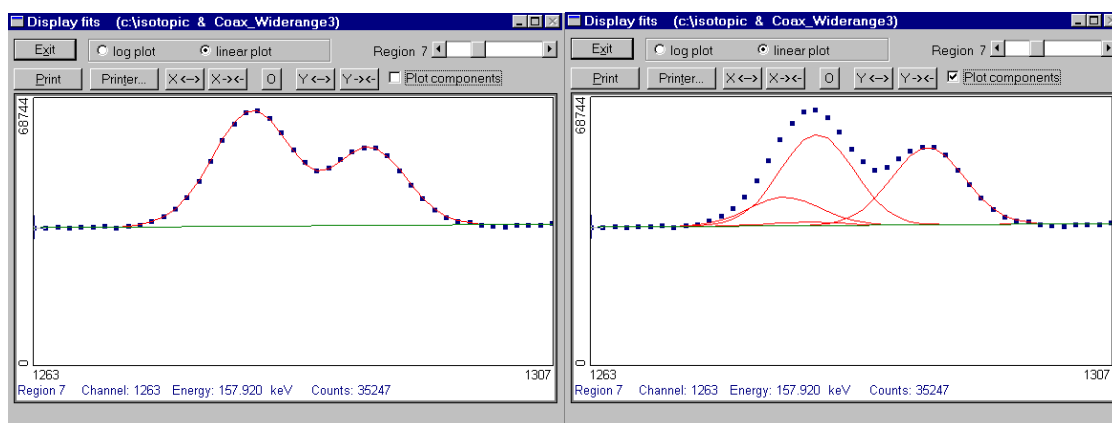


Fig. VII-9. Screens displaying peak fitting; fit envelope on left and individual components on right.

The ISOPOW option gives access to a plutonium and americium decay correction program (Sampson 86). The input values are defaulted to the results of the most recent analysis or the program can be used “off line” with arbitrary operator control of the input parameters.

5. Help

The Help option on the main menu lists copyright and contact information.

C. Password Protection

Several options are password protected. The **Edit | Parameters**, **Edit | General Defaults**, and **Edit | User List** all require the entry of a valid user name and a valid password. Passwords are established at three levels for operator, supervisor, and manager, with manager being the highest level. Only the manager has access to the User List and only the manager can change the access levels of other users. A person with supervisor level privileges can edit the parameters and general defaults.

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D. Dual Language Capability

The option **Language** under the **Options** menu allows the user to display the operator interface, FRAM program messages, and results in a language other than English. The language strings are kept in a text file allowing any European language to be used as the second language merely by editing the second language text file. The current second language used with FRAM is Russian. The main menu in Russian with “Options” pulled down is shown in Fig. VII-10. The user can switch between the two languages at will by clicking on the **Language** option.

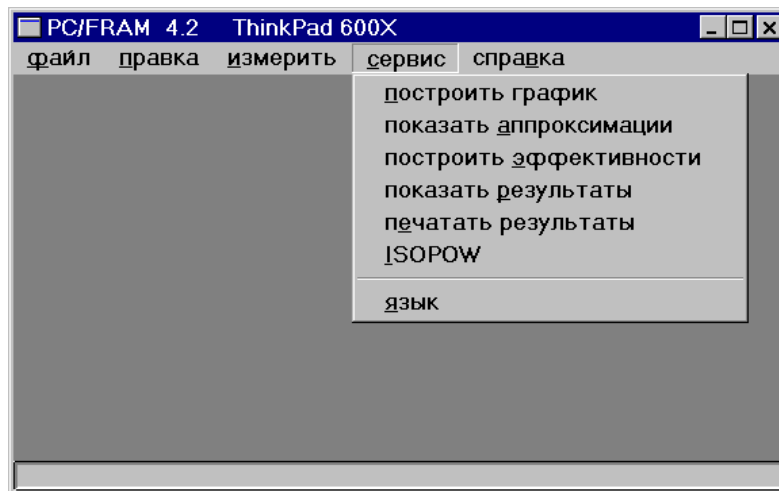


Fig. VII-10. The menu screen appearance when Russian is selected under Options/Language.

VIII. FRAM COMPUTER REQUIREMENTS

VIII. FRAM COMPUTER REQUIREMENTS

Current FRAM software, versions 3 and 4, should be run on PCs with Pentium III or Pentium 4 processors. Processor speed should be at least 200 MHz. When the physical relative-efficiency option is selected, version 4 runs slowly on a 200-MHz machine (approximately 1 minute analysis time).

Memory should be at least 128 MB. Both version 3 and version 4 have run under Windows 95, Windows 98, Windows NT, and Windows 2000. The choice of operating system does affect the ease with which the code can be set up to use Russian as the second language. Windows 2000 is particularly difficult to "Russify."

Analysis time is almost never an issue with modern PCs but nevertheless is of interest. As FRAM has developed the code has gotten more complex, leading to longer analysis times, which have then been reduced by corresponding advances in computing power. As a benchmark, the first FRAM software running on a DEC MicroVAX (chapter IV.B) performed the analysis of a plutonium spectrum in the 120–420 keV range in about 30 s. Current analysis times tabulated in Table VIII-1 vary as much as a factor of 10, depending upon the specifics of the parameter file. The number of peaks analyzed may vary from 30 for a typical uranium parameter file to over 80 for a plutonium parameter file. In version 4 of FRAM the analysis time using the physical model relative-efficiency curve may be 4–5 times greater than using the empirical relative-efficiency curve because of the iterative analysis involved in the physical model calculation.

Table VIII-1 shows the analysis times for some typical conditions for two versions of FRAM.

Table VIII-1. Typical FRAM Analysis Times for Plutonium on a Dell Optiplex 400, Pentium 4, 1.4 Ghz.

FRAM Version	Analysis Range (keV)	Efficiency Model	Analysis Time (s) for 10 Spectra
3.2	120-420	Empirical	5
3.2	200-800	Empirical	7
4.2	120-420	Physical	22
4.2	200-800	Physical	48
4.2	120-420	Empirical	6
4.2	200-800	Empirical	10

IX. FRAM PERFORMANCE

IX. FRAM PERFORMANCE

A. Measurement Precision or Repeatability

1. Definitions

In this section we will describe the many interrelated factors that govern the statistical precision of an isotopic measurement. In this context the terms precision or repeatability refer to counting statistics and are usually denoted by the relative standard deviation (RSD) expressed as a percentage.

$$\%RSD = 100 \times \frac{\text{sigma}}{\text{measured value}} \quad . \quad (\text{IX-1})$$

Here *sigma* is the absolute standard deviation, arising from counting statistics, of the *measured value*.

Sigma can be determined in at least two ways. First, the sigma from counting statistics is estimated within FRAM using standard error propagation techniques. This process is difficult given the amount of mathematical analysis involved, the presence of correlated variables, and the wide range of the magnitude of the measured values. However, this method gives an estimate or prediction of sigma for every measurement and is invaluable when one has only a single measurement. The second method of determining sigma is by repeated measurements. From *n*, repeated measurements of the variable *x*, we determine *s*, the standard deviation of the sample and use it as an estimate of the standard deviation of the population.

$$(s^2) = \frac{1}{n-1} \sum_1^n (x_i - \bar{x})^2 \quad (\text{IX-2})$$

Sigma estimated in this fashion is also a random variable. That is, if the series of *n* measurements of *x* is repeated, *s* will be different. The mean value of *s* will be the population sigma. The relative standard deviation of *s* values is given by the formula

$$RSD(s) = \frac{1}{\sqrt{2(n-1)}} \quad . \quad (\text{IX-3})$$

This expression is useful when comparing the standard deviation estimated in FRAM with the standard deviation (Eq. IX-2) observed from repeated measurements. One has to perform many repeated measurements to verify propagated error estimates accurately, as Table IX-1 illustrates.

Table IX-1. The RSD of Sigma (Error of the Error).

Number of Measurements	RSD of Sigma
10	0.235
15	0.189
25	0.144
50	0.101

IX. FRAM PERFORMANCE

This table should be kept in mind later on when we compare the sigmas from repeated measurements with FRAM's estimated sigmas.

One caveat should be mentioned before we proceed to the detailed discussion of measurement precision. For isotopic measurements of plutonium we usually express results in terms of weight percent (wt %) relative to total plutonium. The uncertainties are usually expressed as % RSD. Both the measured value and its error can be expressed as percentages. When the measured value and its uncertainty are both expressed as percentages, the reader may not know the units of the “% error.” Is the % error an absolute error in units of wt % or is the % error a relative error being expressed as a % RSD? In FRAM outputs we try to be very clear about the units of the uncertainties. Uncertainties labeled as *sigma* are absolute uncertainties in the same units as the measured value. Uncertainties labeled as % are % RSD and have no units. One way we write this in FRAM output is

(Measured value $\pm$ sigma) (% RSD)

where % RSD is as defined in Eq. IX-1.

2. Influencing Factors

In this section we will discuss some of the many factors that influence the precision or repeatability of the isotopic measurement. These factors are often interrelated and result in a general inability to estimate a priori the precision of a given measurement system unless all variables affecting this parameter are specified.

a. Count Rate and Throughput

The net counts in the photopeaks of the analyzed spectrum are the primary factors determining the measurement precision. The counting rate directly influences the net photopeak counts. While the counting rate in the detector is the parameter that is often observed, it is the actual data storage rate in the MCA that is of direct importance. The data storage rate depends upon the settings of the electronics, including shaping times and the use of pulse pileup rejection. Measurement systems are usually optimized by measuring a throughput vs incoming count rate curve along with system resolution vs incoming count rate and choosing the compromise settings best for the application at hand. An excellent discussion of these compromises may be found in Parker (Parker 91a).

These throughput curves show that higher counting rates do not always produce better measurement precision. Indeed, there is a maximum throughput rate beyond which throughput decreases and counting precision worsens. The best compromise for throughput and resolution is usually chosen to be at a counting rate significantly below the throughput maximum. Operating at input counting rates that are 50%–60% of the count rate at the throughput maximum usually yields throughput values that are 80%–90% of maximum while simultaneously preserving detector resolution.

Figure IX-1 shows the throughput and resolution measured with a 25% relative-efficiency coaxial HPGe detector coupled with first generation digital signal processing electronics (an ORTEC DSpec) operated with a rise time of 4 μ s (equivalent to a 2- μ s shaping time in an analog amplifier). The sample is 965 g PuO₂ with 16.85-wt % ²⁴⁰Pu.

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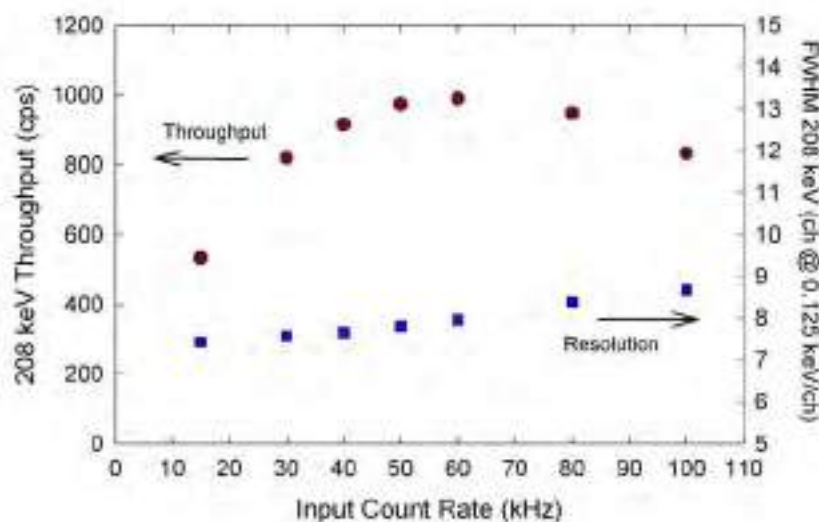


Fig. IX-1. Throughput and resolution for the 208-keV peak of ^{241}Pu - ^{237}U with 965 g PuO_2 with 16.85% ^{240}Pu , a 25% relative-efficiency HPGe detector, and an ORTEC DSPEC operated at 4- μs rise time.

Here the throughput maximum occurs at an input count rate of 60 kHz, but we usually choose to operate at a maximum input rate of around 40 kHz, where the resolution is better.

Optimizations performed in this manner affect the primary results of a FRAM isotopic analysis measurement. Figure IX-2 shows how the precision of the FRAM result for ^{240}Pu and P_{eff} varies for the same data set presented in Fig. IX-1. Collection of spectral data at an input rate of 40 kHz gives essentially the same precision as operating at the 60-kHz peak of the throughput curve. The precision does not change very rapidly in a broad range about the throughput maximum, but it does change significantly above that at low count rates. In the range where the throughput curve is linear at rates below 15 kHz, the precision varies with the square root of the counting rate.

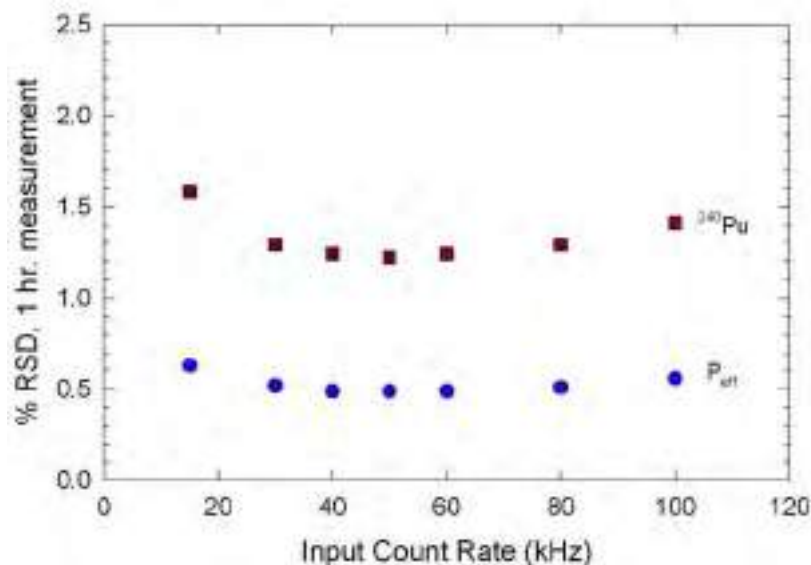


Fig. IX-2. % RSD of FRAM measurement of ^{240}Pu and P_{eff} for 965 g PuO_2 with 16.85% ^{240}Pu , a 25% relative-efficiency HPGe detector, and an ORTEC DSPEC operated at 4- μs rise time with analysis in the 120–450 keV region.

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b. Electronic Settings

The amplifier shaping time is the single most influential electronic setting affecting system performance. The shaping time-resolution tradeoff is well known and is discussed in detail by Parker (Parker 91a). The term “rise time” is usually used in characterizing digital spectroscopy systems with the rise time being about twice the customary analog shaping time. Throughput generally varies inversely with the shaping time. A shorter or lower shaping time improves throughput.

Longer shaping times usually correspond to better resolution and lower throughput although for any specific system the user will find that the resolution-shaping time curve goes through a broad minimum that is dependent upon the type of detector being characterized. One always operates on the low or shorter shaping time side of this minimum. We most often find that it is best to give up a little resolution in order to improve throughput. Fortunately the minimum is broad and resolution does not have to suffer too much.

For the relatively small coaxial detectors (25%–30% relative efficiency) often used with FRAM, we obtain good results with analog systems using 2- μ s Gaussian or triangular shaping. This corresponds to a rise time setting of 4 μ s for digital systems. With these settings good resolution is obtained at maximum counting rates of approximately 30 kHz (analog) and 40 kHz (digital).

For the planar detectors most often used with FRAM (16–25 mm diam. by 13–15 mm deep) we currently recommend a 1- μ s triangular shaping with an analog system or a 2- μ s rise time with digital system. The historical evolution of this setting for planar detectors parallels the development of improved amplifiers and pulse-processing methods. The first Los Alamos isotopic systems in the early 1980s (Chapter III) used 16-mm by 13-mm planar detectors, analog electronics, 100-MHz Wilkinson ADCs, and an analog amplifier shaping time of 3 μ s. Amplifier and ADC improvements in the late 1980s led to approximately 500-MHz Wilkinson ADCs and analog amplifiers with improved triangular shaping. With these systems we operated with an analog amplifier shaping time of 2 μ s and later changed to 1- μ s triangular shaping. These changes, coupled with the increase in counting rate allowed by the shorter time constants, gave a total improvement of about a factor of 3 in the precision for ^{240}Pu or P_{eff} .

Pileup rejection is the other principal electronic setting that the user usually controls. Pileup rejection should always be used, if available, for isotopic measurements. Pileup rejection will prevent most of the distorted, time-overlapping events from being stored in the MCA. Pileup events, if stored, will distort the spectrum, especially the spectrum continuum, making it more difficult to extract accurate peak areas. Note, however, that pileup rejection will not prevent the storage of true coincidence events nor will it prevent the storage of random events separated in time by less than the typical pulse-pair resolution of the pileup rejector (0.5–1.0 μ s).

c. Count Time

Poisson counting statistics are an appropriate model to represent the influence of counting time on the precision of FRAM isotopic analysis measurements. That is, the % RSD of the measurement of an isotopic fraction varies inversely with the square root of the counting time, T .

$$\%RSD \approx \frac{1}{\sqrt{T}} \quad (\text{IX-4})$$

Increasing the counting time by a factor of 2 improves (decreases) the % RSD by a factor of 1.4.

d. Energy Range

The energy range used in the analysis is often the single largest factor in determining the precision or repeatability of a FRAM isotopic measurement. Several factors contribute to precision differences among the different energy ranges.

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The foremost factor contributing to the precision of the isotopic measurement is the intrinsic intensity of the gamma rays used in the analysis. Table IX-2 displays these intensities for the principal gamma rays from each of the four energy regions that have been historically used for isotopic analysis. It is of interest to note the intensity variation of the even isotopes ^{238}Pu and ^{240}Pu as one moves from lower energies to higher energies. The intensities drop by roughly an order of magnitude as one moves to each successively higher energy region. This leads to the conclusion that the best precision measurements, at least for the important ^{240}Pu and ^{238}Pu isotopes, come from the regions of lowest energy.

The 40–60 keV energy region is used only in the special case of freshly reprocessed (^{241}Am and ^{237}U removed) plutonium-bearing solutions, mainly in reprocessing plants. This region is not used widely, if at all, in mainstream isotopic analysis applications for two reasons. First, the Compton continuum from the 59.5-keV ^{241}Am peak swamps the other plutonium peaks in the 40-keV region for materials more than 45 days from a chemical separation, and second, these low-energy gamma rays are easily absorbed precluding their easy escape from many types of containers. For example, the mean free path of the 45-keV ^{240}Pu gamma ray is about 0.5 mm in steel.

In contrast, the 90–105 keV region has widely been used for isotopic analysis and offers, in many cases, the best available precision for the measurement of ^{240}Pu . Strong attenuation of these low-energy gamma rays does preclude the use of this region for samples in thick-walled or shielded containers. An absorber of 10 mm of steel is usually enough to defeat plutonium isotopic analysis measurements in this region.

Table IX-2. Intrinsic Gamma-Ray Intensities of Major Gamma Rays in Principal Energy Regions.

Region (keV)	^{238}Pu		^{239}Pu		^{240}Pu		$^{241}\text{Pu}, ^{237}\text{U} (*)$		^{241}Am	
	(keV)	$\gamma/\text{s/g}$	(keV)	$\gamma/\text{s/g}$	(keV)	$\gamma/\text{s/g}$	(keV)	$\gamma/\text{s/g}$	(keV)	$\gamma/\text{s/g}$
40–60	43.5	2.5 e8	51.6	6.2 e5	45.2	3.8 e6			59.5	4.5 e10
90–105	99.9	4.6 e7	98.8	2.8 e4	104.2	5.9 e5	103.7	3.9 e6	98.9	2.6 e7
									103.0	2.5 e7
120–450	152.7	6.1 e6	129.3	1.4 e5	160.3	3.4 e4	148.6	7.2 e6	125.3	5.2 e6
			375.0	3.6 e4			*208.0	2.0 e7	335.4	6.3 e5
			413.7	3.4 e4			*332.4	1.1 e6		
450–800	766.4	1.4 e5	646.0	3.4 e2	642.5	1.0 e3			662.4	4.6 e5
									722.0	2.5 e5

The 120–450 keV region is the most versatile single region for plutonium isotopic analysis measurements and has historically been the region addressed by isotopic measurements at Los Alamos. Measurements in this region can easily be performed through as much as 12 mm of steel and have also been carried out through 0.3 mm of lead shielding (Sampson 97). This small amount of lead shielding precludes any analysis in the 100-keV region.

FRAM was the first isotopic analysis code to carry out a complete plutonium isotopic analysis using gamma rays in the 200–800 keV region (Kelley 95, Sampson 95). This capability allows measurements in heavy-walled containers or containers whose internal shielding prevents gamma rays with energies below 200 keV from reaching the detector. Variants of this analysis allow a complete plutonium isotopic analysis through shielding of up to 25 mm of lead (Hypes 00). Figure IX-3 shows the low energy region of the gamma-ray spectrum from a plutonium oxide sample, with and without 1.6 mm of lead shielding.

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The ability to analyze the energy region from 200-800 keV for the complete plutonium isotopic distribution gives the FRAM user several more options for the analysis of large samples. The inherent advantage of the 100-keV energy region for ^{240}Pu and ^{238}Pu analysis is reduced for large samples analyzed at high energy because of the increased penetrability of the higher-energy gamma rays in the 600–800 keV range relative to the penetrability of 100-keV gamma rays. In effect, the higher-energy gamma rays sample a larger volume of the measured item because they can escape from deeper into the measured item. This effect of increased penetrability is apparent principally for items with larger areal plutonium densities. Table IX-3 shows the parameters that affect penetrability for the three ^{240}Pu gamma rays at 104, 160, and 642 keV. This is the effect causing the relative-efficiency curves for large items to increase in magnitude as one moves to higher energies (see Fig. II-1).

Table IX-3 shows the somewhat unexpected result that the self-absorption at 160 keV is actually greater than at 104 keV. This arises because the plutonium K edge falls at 121.8 keV, between the two energies. The mean free path (mfp) at 642 keV is about 15 times greater than at 160 keV. Samples with a thickness greater than three mfp at 642 keV will have an emission rate increase at 642 keV over that at 160 keV that nearly compensates for the intrinsic intensity ($\gamma/\text{s/g}$) difference (Table IX-2) at the two energies. When this is coupled with the lower background continuum present at higher energies, one often obtains better precision for measurement of ^{240}Pu at 642 keV than at 160 keV.

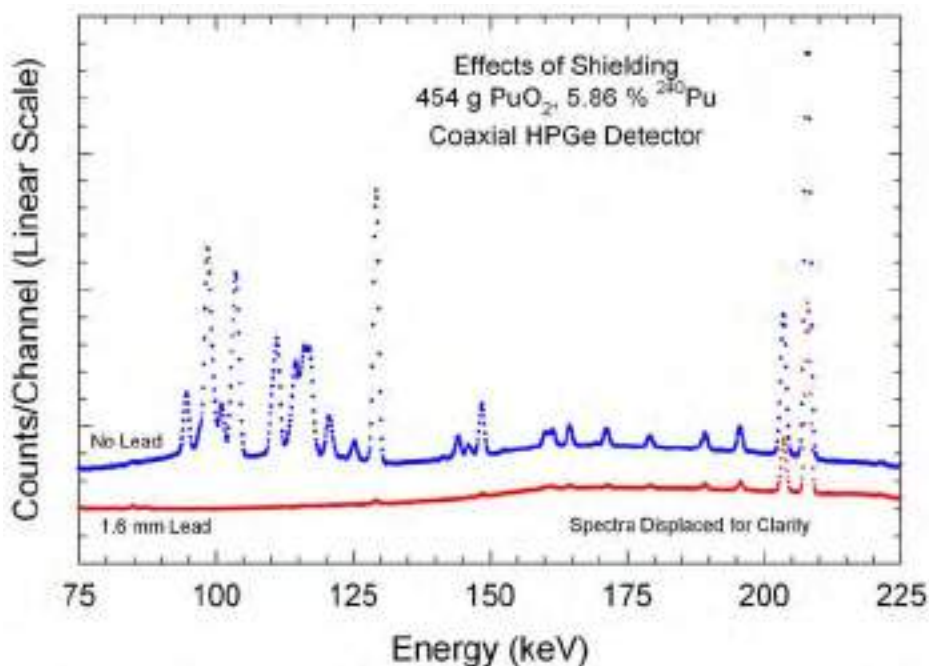


Fig. IX-3. Effect of sample shielding on the gamma-ray spectrum of 454 g PuO_2 with 5.86% ^{240}Pu taken with a 25% relative-efficiency HPGe detector. The sample is bare in the spectrum on top and shielded with 1.6 mm of lead in the bottom graph.

Table IX-3. Absorption Properties for PuO_2 at $\rho = 3\text{g/cm}^3$ for Gamma Rays from ^{240}Pu .

Energy (keV)	μ/ρ (cm^2/g)	μ (cm^{-1})	Mean Free Path (cm)
104	1.62	4.9	0.21
160	2.01	6.0	0.17
642	0.131	0.39	2.5

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Another consideration for the use of the 200–800 keV analysis range for larger samples is that one is often able to improve the precision still further by filtering the detector with additional lead. While this may seem strange, what happens is the additional lead filter removes the gamma rays below 200 keV that do not contribute to the 200–800 keV analysis. The sample counts at a constant input counting rate are shifted preferentially to higher energies and a greater fraction of the incoming count rate will fall into the 600-keV region compared to an unfiltered sample.

Table IX-4 summarizes the precision for all isotopes for a variety of samples with masses greater than 60 g plutonium. For nearly all measurements the counting rate is constant at 30 kHz and the precisions are given for a 1-hour count time. The precisions are those estimated by the FRAM software so the dependence on analysis range and filtering is not masked by the variability inherent in using the precision from repeated measurements. The table lists the precision from the bare sample analyzed in the 120–450 keV range, the precision from the same bare sample spectra analyzed in the 200–800 keV range, and also the precision from a lead-filtered spectrum. The lead filter thickness, with one exception, is 1.6 mm or 3 mm.

Table IX-4. Coaxial Detector Analysis With and Without Lead Filters, at 120–450 keV and 200–800 keV Analysis. Count rate = 30 kHz, Count time = 1 hour

Sample	Shielding	Analysis Range (keV)	238 % rsd	239 % rsd	240 % rsd	241 % rsd	Am % rsd	Peff % rsd	Pu Mass (g)	wt% Pu240	Ct. Rate kHz
CALEX	Bare	120–450	12.40	0.16	2.54	0.24	0.49	0.52	398	5.86	30
CALEX	Bare	200–800	5.15	0.11	1.69	0.23	0.31	0.32	398	5.86	30
CALEX	1.6 mm Pb	200–800	4.24	0.09	1.41	0.30	0.28	0.26	398	5.86	30
PUEU7	Bare	120–450	6.98	0.14	2.30	0.22	0.92	0.48	2000	5.86	30
PUEU7	Bare	200–800	3.49	0.10	1.62	0.21	0.43	0.32	2000	5.86	30
PUEU7	1.6 mm Pb	200–800	2.79	0.08	1.31	0.28	0.36	0.26	2000	5.86	30
JOO1325	Bare	120–450	11.40	0.17	2.62	0.28	0.57	0.55	500	5.90	30
JOO1325	Bare	200–800	3.90	0.10	1.61	0.26	0.32	0.31	500	5.90	30
JOO1325	0.8 mm Pb	200–800	3.43	0.09	1.37	0.31	0.29	0.26	500	5.90	30
JOO1325	2.4 mm Pb	200–800	3.15	0.08	1.25	0.53	0.29	0.24	500	5.90	30
STD8	Bare	120–450	7.62	0.11	1.66	0.22	0.51	0.36	239	6.30	30
STD8	Bare	200–800	6.66	0.14	2.06	0.27	0.38	0.42	239	6.30	30
STD8	1.6 mm Pb	200–800	5.31	0.11	1.65	0.36	0.34	0.33	239	6.30	30
SD4030	Bare	120–450	1.89	0.18	1.31	0.22	0.27	0.39	869	11.79	30
SD4030	Bare	200–800	1.48	0.16	1.23	0.22	0.25	0.35	869	11.79	30
SD4030	1.6 mm Pb	200–800	1.13	0.13	0.94	0.20	0.21	0.27	869	11.79	30
LAO225	Bare	120–450	1.83	0.16	0.82	0.19	0.24	0.33	869	16.53	30
LAO225	Bare	200–800	1.28	0.16	0.79	0.20	0.22	0.30	869	16.53	30
LAO225	1.6 mm Pb	200–800	1.00	0.13	0.65	0.18	0.19	0.25	869	16.53	30
LAO250	Bare	120–450	2.51	0.19	0.97	0.23	0.27	0.39	60	16.27	28
LAO250	Bare	200–800	1.89	0.20	1.05	0.25	0.27	0.40	60	16.27	28
LAO250	3 mm Pb	200–800	1.64	0.20	1.00	0.32	0.31	0.38	60	16.27	11

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Table IX-4 (Continued)

Sample	Shielding	Analysis Range (keV)	238 % rsd	239 % rsd	240 % rsd	241 % rsd	Am % rsd	Peff % rsd	Pu Mass (g)	wt% Pu240	Ct. Rate kHz
LAO251	Bare	120–450	3.21	0.24	1.20	0.27	0.31	0.49	172	16.45	30
LAO251	Bare	200–800	1.73	0.20	0.99	0.24	0.27	0.37	172	16.45	30
LAO251	3 mm Pb	200–800	1.26	0.16	0.80	0.34	0.29	0.30	172	16.45	25
LAO252	Bare	120–450	3.43	0.26	1.33	0.30	0.34	0.54	322	16.31	32
LAO252	Bare	200–800	1.62	0.19	0.96	0.24	0.26	0.36	322	16.31	32
LAO252	3 mm Pb	200–800	1.23	0.16	0.81	0.27	0.24	0.30	322	16.31	32
LAO253	Bare	120–450	3.28	0.25	1.27	0.29	0.33	0.51	613	16.47	34
LAO253	Bare	200–800	1.54	0.18	0.90	0.23	0.25	0.34	613	16.47	34
LAO253	3 mm Pb	200–800	1.12	0.14	0.72	0.32	0.26	0.27	613	16.47	34
LAO255	Bare	120–450	3.21	0.25	1.25	0.28	0.32	0.50	544	16.35	30
LAO255	Bare	200–800	1.61	0.18	0.93	0.24	0.26	0.35	544	16.35	30
LAO255	3 mm Pb	200–800	1.13	0.14	0.71	0.26	0.23	0.27	544	16.35	30
LAO256	Bare	120–450	3.63	0.27	1.37	0.31	0.35	0.56	385	16.35	30
LAO256	Bare	200–800	1.65	0.19	0.94	0.24	0.26	0.36	385	16.35	30
LAO256	3 mm Pb	200–800	1.12	0.14	0.69	0.27	0.22	0.26	385	16.35	30
LAO261	Bare	120–450	3.56	0.26	1.31	0.30	0.34	0.54	849	16.45	30
LAO261	Bare	200–800	1.58	0.18	0.91	0.24	0.26	0.35	849	16.45	30
LAO261	3 mm Pb	200–800	1.15	0.14	0.70	0.27	0.23	0.27	849	16.45	30
PEO381	Bare	120–450	4.97	0.18	1.55	0.23	0.25	0.43	614	10.36	30
PEO381	Bare	200–800	2.06	0.12	1.07	0.19	0.19	0.27	614	10.36	30
PEO381	3 mm Pb	200–800	1.86	0.12	1.05	0.35	0.23	0.27	614	10.36	30
PEO382D	Bare	120–450	7.07	0.23	2.07	0.29	0.33	0.56	300	9.70	30
PEO382D	Bare	200–800	3.06	0.16	1.47	0.26	0.26	0.37	300	9.70	30
PEO382D	3 mm Pb	200–800	2.12	0.12	1.08	0.37	0.23	0.27	300	9.70	30
PEO385	Bare	120–450	7.24	0.21	2.05	0.28	0.34	0.56	459	9.28	30
PEO385	Bare	200–800	3.07	0.14	1.38	0.25	0.25	0.34	459	9.28	30
PEO385	3 mm Pb	200–800	2.21	0.11	1.05	0.41	0.23	0.26	459	9.28	30
PEO447	Bare	120–450	5.15	0.24	2.07	0.30	0.33	0.57	778	10.16	30
PEO447	Bare	200–800	2.14	0.15	1.35	0.24	0.24	0.34	778	10.16	30
PEO447	3 mm Pb	200–800	1.56	0.12	1.04	0.36	0.23	0.26	778	10.16	30
SRP12-1	Bare	120–450	3.58	0.27	1.94	0.31	0.38	0.62	875	11.85	30
SRP12-1	Bare	200–800	1.52	0.16	1.16	0.23	0.26	0.35	875	11.85	30
SRP12-1	3 mm Pb	200–800	1.07	0.12	0.88	0.29	0.23	0.26	875	11.85	30

The trend is very clear for these larger samples. Measurement precision improves as the analysis moves into the 200–800 keV range and improves further when the spectrum is filtered. Plutonium-241 does not improve in every case because its analysis is carried out at the lowest energies (200–340 keV) of the analysis range.

e. Detector Type

The influence of the detector type is directly related to the energy range used in the analysis. Two principle types of HPGe detectors have been most often used for isotopic analysis with the FRAM code.

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Planar Detectors Planar detectors of dimensions 16 mm diam. by 13 mm thick and 25 mm diam. by 15 mm thick are commonly used for FRAM measurements. These detectors have historically been used in the 120–420 keV energy range and with the advent of version 4 of FRAM, can now be used in the 100-keV region. For most measurements on samples in thin containers, analysis of the spectrum in the 100-keV region will provide better precision for all of the isotopes than the analysis of the spectrum in the 120–420 keV region. For samples in containers with steel wall thicknesses in the range of 5–10 mm, the optimum analysis region for a planar detector becomes less clear. Above a wall thickness of approximately 10 mm of steel, the 100-keV region analysis may fail leaving analysis in the 120–420 keV region as the only viable option.

Coaxial Detectors Coaxial detectors of approximately 25%–30% relative efficiency (relative to a 3-in.-diam. by 3-in.-thick NaI(Tl) detector for ^{60}Co at a distance of 25 cm) have been most often used with FRAM. The precision of a coaxial detector's measurements depends upon the energy range and shielding, as discussed previously. It is not always possible to predetermine which detector, planar or coaxial, will have the better precision in the 120–420 keV region. Suffice to say that the measurement precision in this energy range is often similar for the two detector types, and the choice is often made empirically with measurements under realistic conditions. When samples are shielded, planar detectors will not be viable and the coaxial detector choice often comes down to whether or not to use additional filters.

CdTe Detectors Although version 4 of FRAM can also analyze spectra from CdTe detectors, the precision of CdTe detector results is not as good as with HPGe detectors. This is because of the small size of the CdTe detectors (dimensions of a few millimeters) giving volumes over a thousand times smaller than a coaxial HPGe detector (Vo 02). detectors are discussed further in Chapter XIII.

f. Sample Characteristics

Characteristics of the measured item, such as mass, density, and shape, affect measurement precision in conjunction with other variables. While we have seen the effect of larger mass samples on the analysis energy range (Table IX-4) the effect of the combination of density and shape at a constant mass is less apparent.

Compare a sample with a large area presented to the detector, but with a low areal density (g/cm^2) of plutonium, to a sample of the same mass with less surface area and higher areal density. In the large-area, low areal density case, the lower-energy gamma rays will be enhanced relative to those at higher energy and analysis in the 120–450 keV region may produce the best precision. Conversely, the sample with the greater areal density will have an enhanced high-energy region relative to the low areal density sample. These characteristics can often be observed in the shape of the relative-efficiency curve (see Fig. II-1). The relative-efficiency curve tends to fall off with increasing energy more rapidly for low areal density samples while samples with a greater areal density tend to have a higher relative efficiency continuing to higher energies.

3. Prediction of Precision in the FRAM Code

The output of every FRAM measurement includes a predicted value for *sigma*, the absolute error in the measured mass %, where *sigma* is obtained from the propagation of counting statistics uncertainties in the photopeak areas used in the analysis. These fundamental values are seen in the “boxed” portion of the FRAM output displayed in Fig. IX-4. This predicted counting statistics error is also reported as a % RSD where % RSD has been defined in Eq. IX-1. These fundamental errors are further propagated to produce the absolute and relative errors in the other parameters in the output.

We purposely do not include any systematic error components (such as errors in branching ratios, half lives, or fitting errors described by a reduced Chi squared value) in the *sigma* or % RSD values so we may check our purely statistical error prediction with repeated measurements.

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```

*****
PC FRAM (4.2) Isotopic Analysis 17-Jun-2002 16:01:19
(Fixed energy Response function Analysis with Multiple efficiencies)
System ID: Demonstration

spectrum source: c:\fram42\testspec.chn\70coax8k.chn
spectrum date: 11-Oct-1993 15:08:14
live time: 5778 s
true time: 7200 s
num channels: 8192

parameter set: Coax_Wliderange3 (2002.06.10 18:25)
Coax .125 kev/ch, HomoAm/Pu, Equ., 3-25% Pu240,<450 keV
*****
*****
diagnostics passed.

                                (By Corr)      (ug/gPu)

      Pu238      Pu239      Pu240      Pu241      Pu242      Am241
mass% 0.8303      74.7812      18.1917      3.9603      2.2366      28036.9
sigma 0.0032      0.1914      0.2081      0.0107      0.0238      80.4
%RSD  0.39%      0.26%      1.14%      0.27%      1.06%      0.29%
-----
%TotPwr 43.70      13.38      11.95      1.25      0.02      29.69

Specific Power (W/gPu): ( 10.7827 +/- 0.0229)e-003 ( 0.21%)

Effective Pu240 fraction: ( 24.0414 +/- 0.2121)e-002 ( 0.88%)

Time since chemical separation: 4077.7 +/- 4.3 days ( 0.11%)

Relative mass (Np237 / Pu): 2.949e-004 ( 0.52%)
Relative mass ( U235 / Pu): 1.713e-003 ( 65.74%)
Relative mass (Am243 / Pu): 3.524e-008 ( 69.67%)
*****

```

Fig. IX-4. FRAM output showing the absolute statistical error (sigma) and the relative error (% RSD) propagated from counting statistics.

We confirm the correctness of the error propagation within the FRAM code by analyzing many sets of repeated measurements on many different types of samples. We compare the sigma predicted by the FRAM software with the sigma calculated from the distribution of the repeated measurements (see section IX.A.1). The ratio of the propagated sigma to the sigma observed from repeated measurements should be near unity within the uncertainty of the observed sigma (Eq. IX-3).

These comparisons are made with a database containing over 40 repeat measurement data sets, with each data set containing from 10 to 25 repeat measurements. Table IX-4 displays the average ratio over many data sets of the FRAM-propagated sigma to the estimate of sigma observed from repeated measurements on plutonium samples. Table IX-5 displays the same information for repeated measurements on uranium.

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Table IX-4. Comparison of Predicted and Observed Statistical Uncertainties for Plutonium Analysis Using FRAM version 4.

Detector	Region (keV)	No. Data Sets	No. Meas.	Average Ratio: Predicted/Observed					
				²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴¹ Am	P _{eff}
Coaxial	120–450	46	751	0.97	0.97	0.98	0.65	0.74	1.28
Coaxial	200–800	53	828	0.73	0.94	0.94	0.59	0.82	1.18

Table IX-5. Comparison of Predicted and Observed Statistical Uncertainties for Uranium Analysis Using FRAM version 4.

Detector	Region (keV)	No. Data Sets	No. Meas.	Average Ratio: Predicted/Observed		
				²³⁴ U	²³⁵ U	²³⁸ U
Coaxial	120–1001	33	415	1.35	0.84	0.80

We predict the statistical uncertainty very well for ²³⁸Pu, ²³⁹Pu, and ²⁴⁰Pu. FRAM underestimates the statistical error by about 25% (relative) for ²⁴¹Pu and ²⁴¹Am. This likely arises from the difficulty in correctly apportioning the uncertainties for the coenergetic peaks that contain contributions from both ²⁴¹Pu (and daughter ²³⁷U) and ²⁴¹Am. The statistical error in P_{eff} is overestimated in FRAM, probably because of the correlations resulting from the normalization condition that all isotopic fractions must sum to unity.

On the average, the statistical predictions for uranium are reasonably good. When displayed as a function of ²³⁵U enrichment (Fig. IX-5), we do see some ²³⁵U dependence. The error bars in Fig. IX-5 show the uncertainty from the finite number of measurements (Eq. IX-3) for the observed uncertainty in each data set.

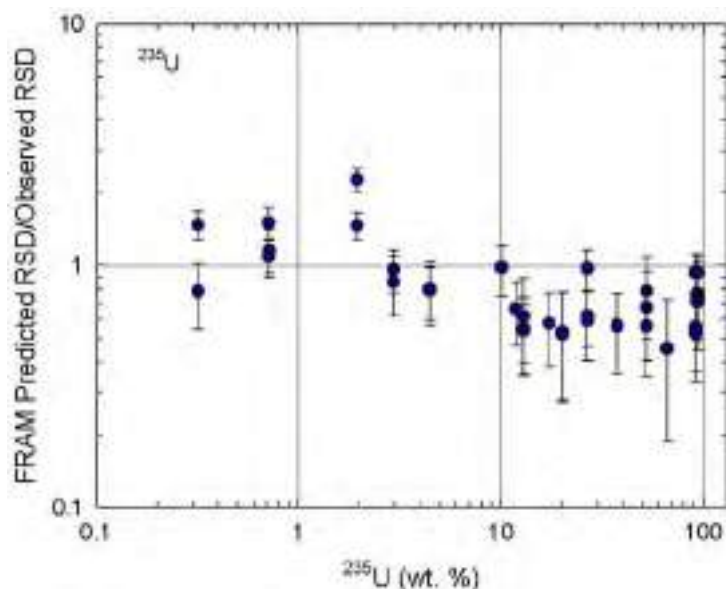


Fig. IX-5. Uranium-235 dependence of FRAM estimate of ²³⁵U statistical uncertainty.

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4. Examples of FRAM's Statistical Precision

In this section we present examples of FRAM's statistical precision taken from the precision observed from archival data sets of repeated measurements. In Fig. IX-6 we display the precision for plutonium observed from repeated measurements plotted vs sample mass for P_{eff} . Figure IX-7 displays the same data plotted for ^{240}Pu percentage.

These data represent not only different samples, different sample masses, and different isotopic compositions, but also different detectors, counting times, counting rates, and data acquisition electronics. Counting times for most data sets are 1 hour, but some data sets have 30-minute or 2-hour count times. As such, the data display the wide range of precisions that one might expect to obtain under the many different measurement conditions applicable to FRAM analysis.

One should also note that these are laboratory measurements, in most cases, where one was able to attain an optimum counting rate from the sample. In many field applications detector-to-sample distance constraints prevent this and lead to poorer measurement precision.

The coax and planar data in the 120–450 (420) keV region show similar results, at least at lower masses. We do see a definite trend [precision becomes poorer (larger) as mass decreases] in the precision vs mass for the 200–800 keV analysis region. This precision is worse than that in the 120–450 (420) keV region for small masses but can be, in many cases, the best choice for large mass samples.

Figures IX-8 and IX-9 display the same data plotted as a function of ^{240}Pu percentage.

Figure IX-10 extracts data for a single-analysis-method-coaxial-detector data analyzed in the 120–450 keV region. Each sample's data set is analyzed for precision of ^{240}Pu and P_{eff} . The P_{eff} precision is better in every case as shown by the ratio [% RSD ^{240}Pu /% RSD P_{eff}] being greater than 1 for all samples.

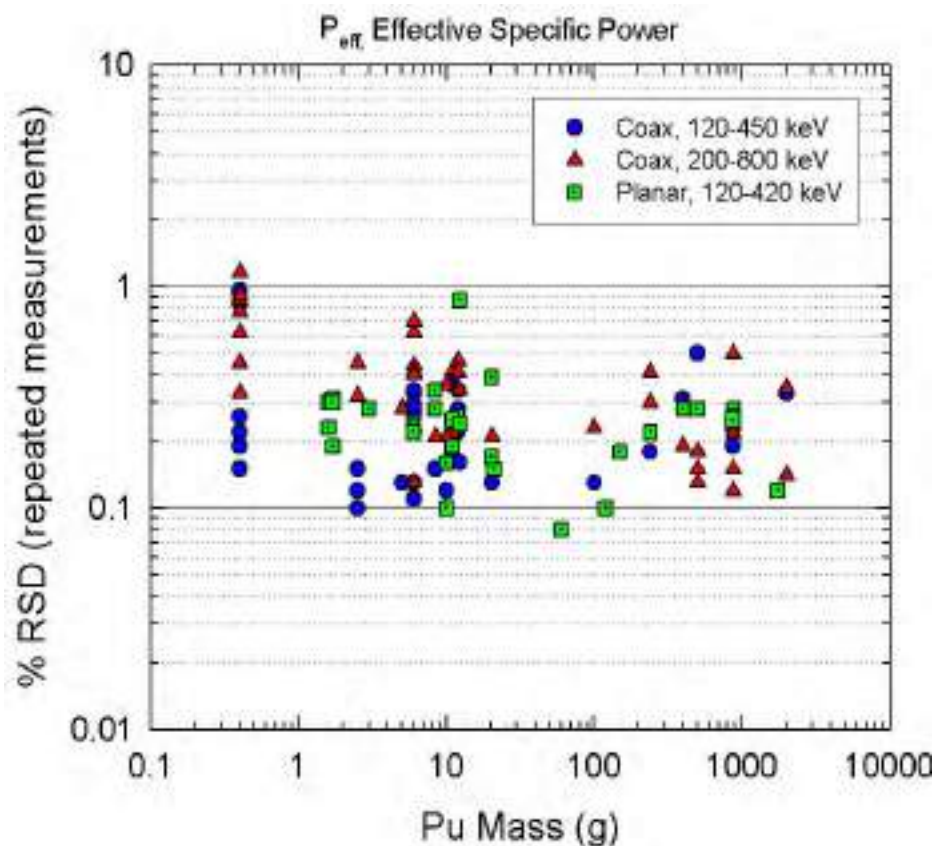


Fig. IX-6. Observed precision for P_{eff} for different detectors, different isotopic compositions, different count times, and different analysis regions as a function of plutonium mass.

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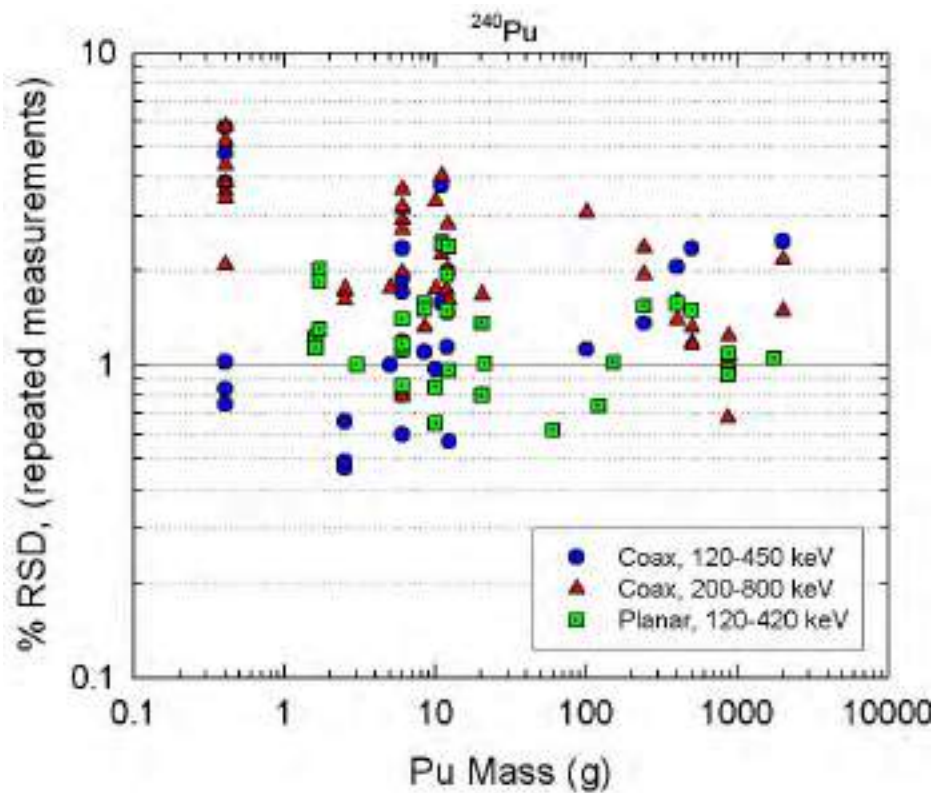


Fig.IX-7. Observed precision for ^{240}Pu for different detectors, different isotopic compositions, different count times, and different analysis regions as a function of plutonium mass.

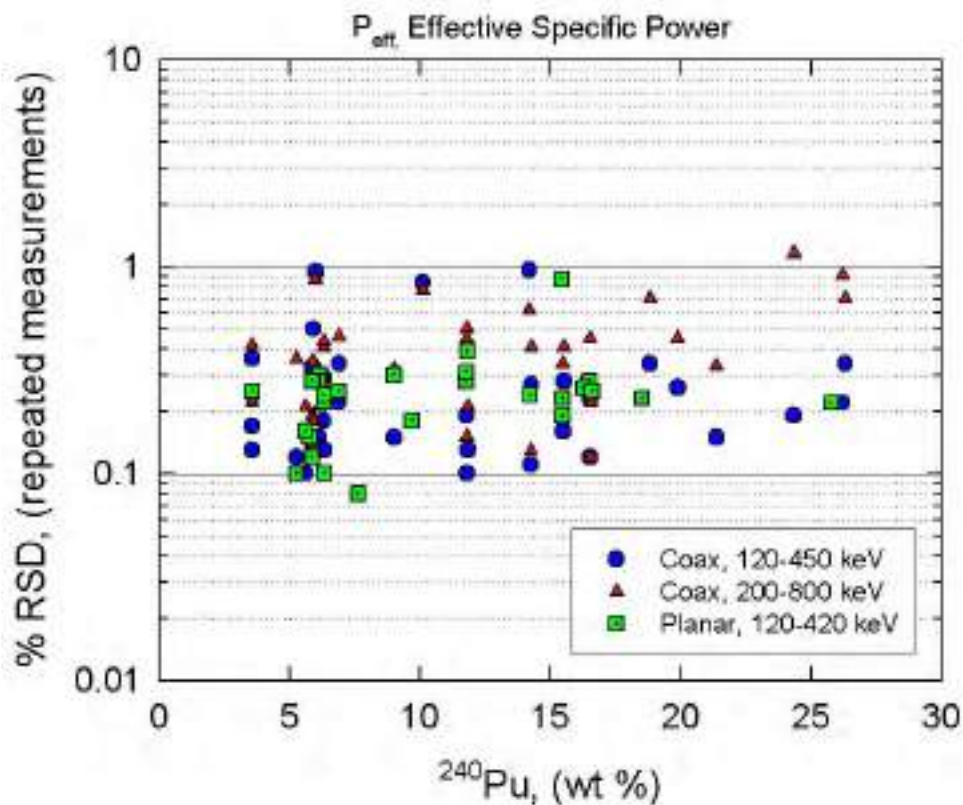


Fig.IX-8. Observed precision for P_{eff} for different detectors, different isotopic compositions, different count times, and different analysis regions as a function of ^{240}Pu percentage.

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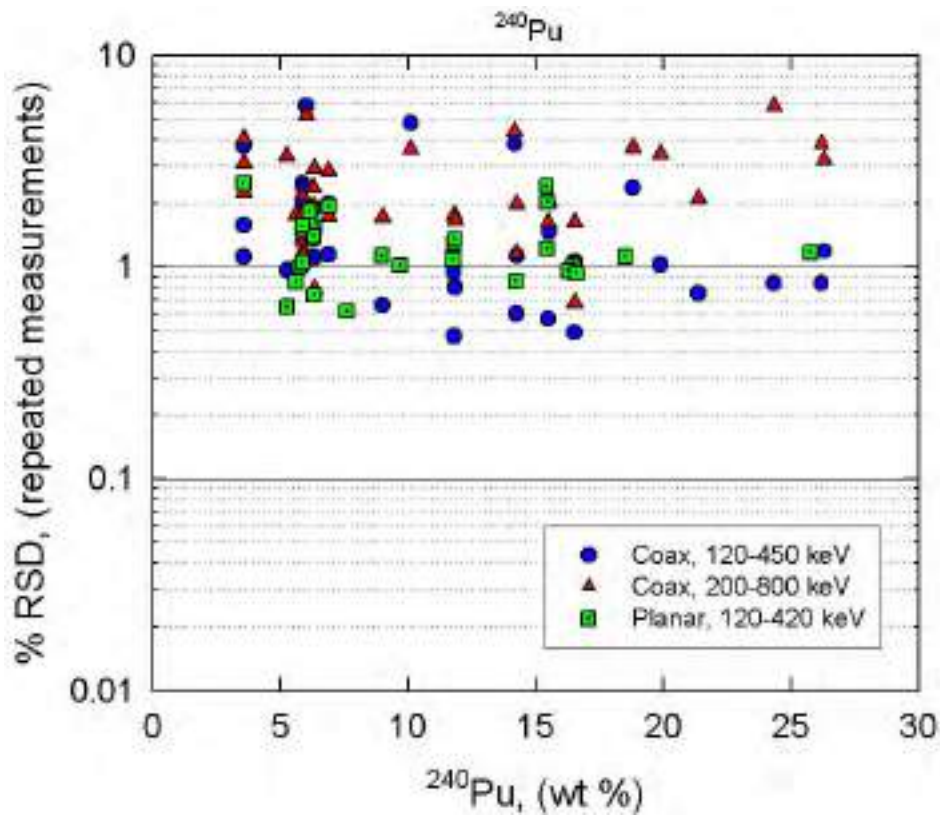


Fig.IX-9. Observed precision for ^{240}Pu for different detectors, different isotopic compositions, different count times, and different analysis regions as a function of ^{240}Pu percentage.

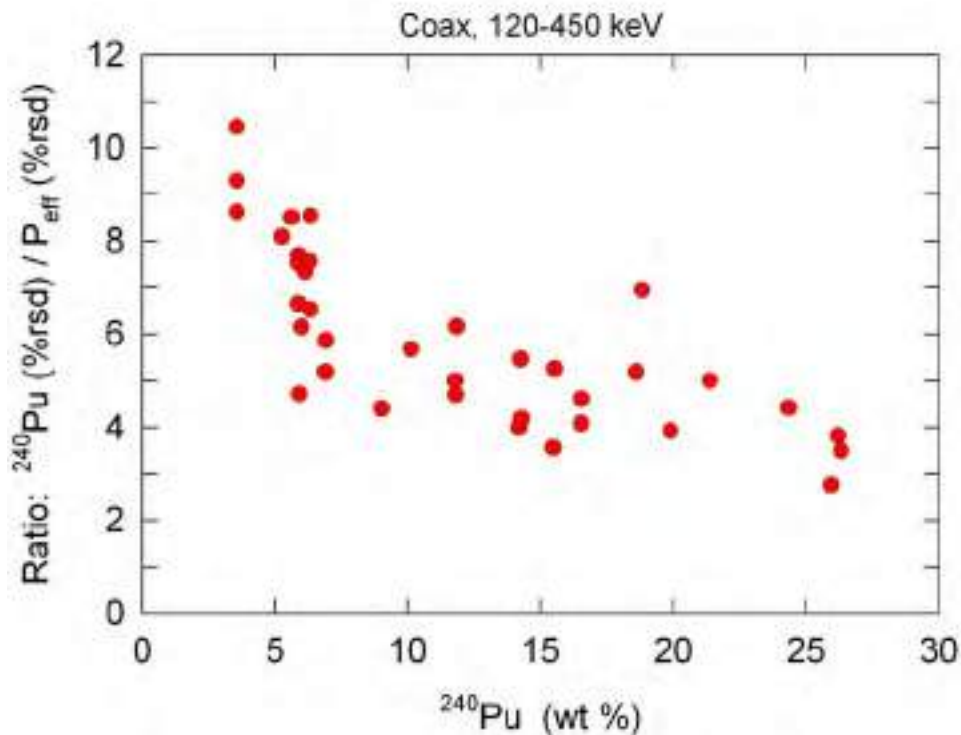


Fig. IX-10. The ratio of the observed precision for ^{240}Pu to that for P_{eff} for a coaxial detector with analysis in the 120-450 keV region is plotted vs the percentage of ^{240}Pu in the sample. Every sample shows better precision for P_{eff} than for ^{240}Pu (ratio > 1) for the same data.

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We also document the performance of FRAM for analysis in the 100-keV region, as this is one of the newest features of version 4 of FRAM. The available data are less extensive than those shown for the analyses above 120 keV. It does demonstrate, however, that FRAM analyses in this energy region can be more precise than other analyses for unshielded samples in thin-walled containers.

Table IX-6 compares the 100-keV region precision from planar detector data to planar detector analyses in the 120–420 keV region and also to a coaxial detector analysis in the 120–450 keV

Table IX-6. 100 keV Region Planar Detector Precision Compared With 120-420(450) keV Analysis.Thirty-Minute Count Time at Indicated Counting Rate.

Sample Name	Detector Energy Range	Pu-240 % RSD	Spec Pow % RSD	Pu Mass (g)	Ct. Rate (kHz)	Pu-240 wt %
CBNM93	Planar 100 keV	1.74	0.30	6.0	26	6.314
	Planar 120–420	2.11	0.31	6.0	10	6.314
	Coax 120–450	1.93	0.30	6.0	40	6.314
CBNM84	Planar 100 keV	0.53	0.21	6.0	31	14.270
	Planar 120–420	1.24	0.35	6.0	10	14.234
	Coax 120–450	1.02	0.25	6.0	40	14.269
CBNM70	Planar 100 keV	0.96	0.37	6.0	38	18.828
	Planar 120–420	1.57	0.31	6.0	25	18.509
	Coax 120–450	2.25	0.34	6.0	40	18.819
CBNM61	Planar 100 keV	0.78	0.37	6.0	38	26.330
	Planar 120–420	1.63	0.31	6.0	25	25.776
	Coax 120–450	1.20	0.38	6.0	40	26.314
STDEUPU7	Planar 100 keV	0.61	0.14	5.0	24	5.864
	Coax 120–450	1.25	0.19	5.0	30	5.864
STDISO3	Planar 100 keV	2.06	0.17	11.0	27	3.560
	Planar 120–420	4.47	0.45	11.0	8	3.562
	Coax 120–450	2.17	0.18	11.0	40	3.560
STDISO6	Planar 100 keV	0.92	0.15	8.4	26	6.131
	Planar 120–420	2.15	0.33	8.4	7	6.130
	Coax 120–450	1.40	0.25	8.4	40	6.131
STDISO9	Planar 100 keV	1.15	0.20	11.9	30	6.896
	Planar 120–420	2.79	0.33	11.9	9	6.891
	Coax 120–450	1.44	0.29	11.9	40	6.896
STDISO12	Planar 100 keV	0.55	0.19	20.2	38	11.854
	Planar 120–420	1.97	0.52	20.2	11	11.821
	Coax 120–450	1.42	0.33	20.2	40	11.854
STDISO15	Planar 100 keV	0.40	0.22	12.3	38	15.523
	Planar 120–420	3.34	1.17	12.3	11	15.437
	Coax 120–450	1.25	0.24	12.3	40	15.523
PIDIE6-1	Planar 100 keV	2.05	0.30	0.4	5	5.990
	Coax 120–450	1.43	0.21	0.4	12	5.990
PIDIE6-3	Planar 100 keV	0.70	0.31	0.4	8	14.200
	Coax 120–450	1.04	0.20	0.4	17	14.200
PIDIE6-5	Planar 100 keV	0.53	0.20	0.4	12	21.415
	Coax 120–450	0.84	0.19	0.4	26	21.415
PIDIE6-7	Planar 100 keV	0.53	0.19	0.4	28	26.433
	Coax 120–450	0.99	0.29	0.4	40	26.433

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region. Note that the measurements are not at a constant counting rate. The precisions are those observed from repeated measurements with most data sets having $n > 20$. Also, the 100-keV region data are not optimum as they were acquired with more cadmium filtering than necessary. Even so, Table IX-6 shows that measurements in the 100-keV region are more precise than measurements at higher energies, especially for small samples. This is, of course, as expected from the branching ratio values discussed earlier and has been well demonstrated in other isotopic analysis codes (Gunnink 90).

Figure IX-11 displays the precision of the measurement of the ^{235}U isotopic fraction in pure uranium samples. The precisions are those from repeated measurements and the data sets represent both 30-minute and 1-hour data. The detectors used are 25%–30% relative-efficiency coaxial detectors. The measurement precision (counting statistics) is pretty much constant for ^{235}U enrichments below approximately 10%. In this case the measurement precision is driven by the intensity of the 258-keV ^{238}U daughter peak that effectively controls the normalization of the relative-efficiency curve. The intensity of this peak does not change very much for enrichments below 10 wt %.

The precision of the measurement of ^{234}U is also of interest for higher enrichment samples as this isotope provides the overwhelming majority of the heat produced for calorimetry measurements. Figure IX-12 displays the ^{234}U precision for all ^{235}U enrichments for which you can measure ^{234}U . Only the enrichments above approximately 90% ^{235}U coupled with kilogram-sized samples can currently be measured by calorimetry. For these samples, measurement precision can be in the 1%–2% range for ^{234}U .

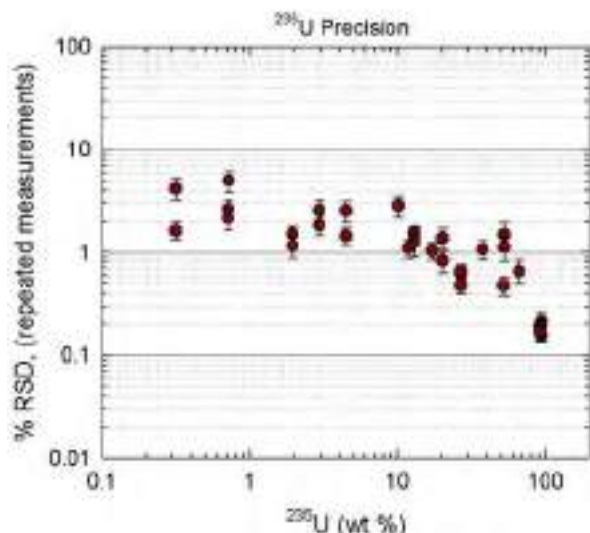


Fig. IX-11. Uranium-235 measurement precision.

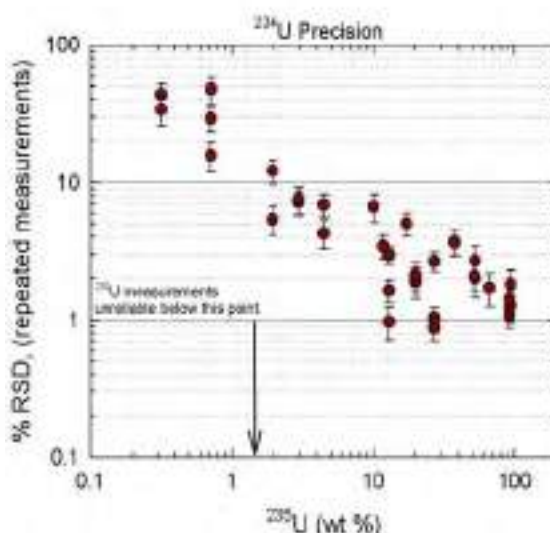


Fig. IX-12. Uranium-234 measurement precision.

B. Measurement Bias

1. Introduction

Bias is defined as the difference between the measured value and the true value. For all examples we estimate the true value by using the best available value for the isotopic composition and ^{241}Am content of the measured item. The best available values almost always are derived from mass spectrometry measurements, sometimes supplemented with alpha counting for ^{238}Pu and/or ^{241}Am . In this document bias is expressed as a ratio of the measured value divided by the best available or “accepted value.”

NDA practitioners at Los Alamos have access to a large number of well-characterized plutonium, uranium, and MOX-bearing items having well-known isotopic distributions and ^{241}Am content. Several

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of the items are certified reference materials (CRM) traceable to the national measurement system and are national and international standards. Most of the remaining items have well-documented mass spectrometry values from routine analytical characterizations. Still others have mass spectrometry values determined by several different laboratories or with extensive measurements at a single laboratory. We find that routine mass spectrometer measurements on modern instruments are nearly always adequate for characterization of the bias of a gamma-ray isotopic composition measurement. Nevertheless, we always examine the mass spectrometer and gamma-ray measurements closely. We especially look for problems with ^{238}Pu , ^{241}Pu , and ^{241}Am .

Plutonium-238 This isotope is one of the most difficult to measure by mass spectrometry. First of all, its low concentration, in the range of 0.01% for weapons grade plutonium, approaches the sensitivity limit for mass spectrometry. Second, it has the same mass as ^{238}U . The most careful procedures are necessary to keep the plutonium sample (typically nanograms of plutonium) from being contaminated with environmental uranium. Any such contamination will result in too large a value for the ^{238}Pu isotopic fraction from the mass spectrometer. We have observed these biases from old (20–30 years) mass spectrometer measurements of plutonium. Alpha counting can obviate these problems. Typical analytical uncertainties for ^{238}Pu fall in the 1%–3% (relative) range and can be the limiting factor in characterizing the ^{238}Pu bias for gamma-ray isotopic composition measurements.

Plutonium-241 The measurement of ^{241}Pu by mass spectrometry requires a chemical separation of the mass spectrometry sample to remove isobaric ^{241}Am . If this chemical separation is not complete, the mass spectrometer measurement of the ^{241}Pu isotopic fraction may be biased high.

Americium-241 There are no CRMs for characterizing the concentration of ^{241}Am in plutonium. This limits the ability of the analytical chemists to make traceable ^{241}Am measurements. Typical characterizations may be biased by several percent.

We discover these problems by comparing gamma-ray measurements of the sample in question with gamma-ray measurements on another sample of similar isotopic composition that is known to have a bias-free analytical characterization. We have not observed any problems with mass spectrometry measurements on uranium.

2. Plutonium Measurement Bias

Los Alamos has a large archive of spectral data from plutonium going back to 1988. These data encompass many different detectors and varying electronic configurations including NIM, portable MCA, and digital spectroscopy systems. Some of the samples have been measured on different dates, separated in some cases by eight or more years. This has proven invaluable for verifying the proper analysis for $^{241}\text{Am}/^{241}\text{Pu}$.

One such archival data set of over 800 measurements for plutonium using coaxial HPGe detectors is shown in Table F-1 in Appendix F. Similar, though less extensive, data sets exist for plutonium measurements with planar HPGe detectors as well as coaxial and planar detector measurements on uranium. Analysis consists of averaging results for the multiple runs for each sample and then averaging the averages for all samples to obtain an overall bias for the entire data set. The results of this analysis for the data set of Table F-3 (analysis of all data sets in Table F-3 in the 200–800 keV region) are displayed in Table IX-7. We manually enter the accepted value for ^{242}Pu so the correlation does not affect the results. We have omitted the averages for ^{238}Pu for samples known to have incorrect accepted values or have measurements so statistically poor as to be unreliable. In these cases we also omitted the value for P_{eff} that can depend strongly on ^{238}Pu .

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Table IX-7. Bias Analysis of Archival Coaxial Data, 200–800 keV Analysis

File Name	Ratio: [Average Measured/Accepted]								Pu Mass (g)	No. runs	Ct. Rate (kHz)	Ct time (h)	Data Date
	238	239	240	241	242	241 Am	Spec Pow	Pu240 Eff					
ISO03CX-2001	1.0629	1.0010	0.9721	1.0147	1.0001	0.9991	0.9986	0.9727	10.97	20	40	0.5	10-Aug-2001
stdiso03_01	0.9894	1.0005	0.9863	1.0137	1.0001	0.9979	0.9986	0.9864	11	20	40	0.5	23-Mar-2001
ISO3CX8K	1.0384	1.0007	0.9820	1.0093	1.0000	1.0101	0.9994	0.9824	10.97	10	30	2	10-May-1994
SGCOAX8K	1.0632	1.0003	0.9923	1.0071	1.0000	1.0169	1.0008	0.9927	100	10	30	2	21-Oct-1993
92COAX8K		1.0006	0.9889	0.9987	1.0000	0.9959		0.9891	10	10	30	2	18-Oct-1993
86COAX8K		1.0009	0.9849	0.9983	1.0000	1.0223		0.9847	10	10	30	2	20-Oct-1993
CALX30	0.9129	0.9998	1.0032	0.9995	1.0000	0.9948	0.9981	1.0028	398.2	10	30	1	2-Nov-1994
CALX30PB	0.8995	1.0003	0.9962	0.9916	1.0000	0.9930	0.9968	0.9959	398.2	11	30	1	6-Dec-1994
EUPU7CX8	1.0652	0.9988	1.0180	1.0081	1.0000	1.0115	1.0048	1.0180	5	10	30	2	22-Oct-1993
PUEU730	0.9639	0.9997	1.0050	0.9943	1.0000	1.0033	0.9996	1.0046	2000	11	30	1	3-Nov-1994
PUEU7PB	0.9136	1.0005	0.9930	0.9917	1.0000	1.0017	0.9964	0.9926	2000	11	30	1	8-Nov-1994
STDEUPU7-2001	0.9896	0.9992	1.0119	1.0139	0.9999	0.9983	1.0010	1.0116	5	30	30	0.5	18-Sep-2001
JOO1325	1.1419	0.9997	1.0047	0.9893	1.0000	1.0130	0.9994	1.0052	499.6	11	30	1	22-Dec-1994
J1325PB1	0.9341	1.0002	0.9977	0.9848	1.0000	0.9981	0.9980	0.9975	499.6	11	30	1	20-Dec-1994
J1325PB2	0.8667	1.0003	0.9957	0.9754	1.0000	1.0014	0.9963	0.9952	499.6	11	30	1	17-Dec-1994
PIDIE6-1-2001		1.0004	0.9943	1.0124	0.9999	0.9898		0.9934	0.4	21	40	0.5	8-Aug-2001
PID6_1		1.0027	0.9578	1.0041	1.0000	0.9891		0.9570	0.4	21	2.9	1	2-Oct-1996
ISO6CX8K	1.0618	0.9994	1.0089	1.0015	1.0000	1.0078	1.0035	1.0090	8.45	10	30	2	6-May-1994
ISO06CX-2001	1.0285	0.9991	1.0141	1.0111	1.0000	0.9984	1.0025	1.0140	8.4	21	40	0.5	8-Aug-2001
STD830	1.0084	0.9999	1.0011	0.9981	1.0000	0.9977	1.0001	1.0011	239.5	11	30	1	10-Jan-1995
STD8PB	0.9839	1.0006	0.9920	0.9863	1.0000	0.9942	0.9981	0.9920	239.5	11	30	1	23-Dec-1994
cbnm93_01	1.1285	0.9999	1.0011	1.0026	1.0000	0.9920	1.0023	1.0016	0.6	20	40	0.5	19-Mar-2001
93COAX8K	1.1781	1.0001	0.9983	0.9987	1.0000	0.9963	1.0039	0.9991	6	10	30	2	9-Oct-1993
ISO9CX8K	1.0269	0.9992	1.0109	0.9998	1.0000	1.0045	1.0030	1.0109	11.9	10	30	2	7-May-1994
stdiso09_01	1.0205	0.9985	1.0193	1.0049	1.0001	0.9930	1.0027	1.0190	12	20	40	0.5	26-Mar-2001
ISO09CX-2001	1.0347	0.9989	1.0143	1.0049	1.0000	0.9971	1.0030	1.0142	11.9	29	40	0.5	8-Aug-2001
2G118CX8	0.9192	0.9992	1.0078	0.9989	1.0000	1.0022	0.9977	1.0071	2.5		30	2	23-Oct-1993
PID6_2	0.8973	1.0008	0.9930	1.0025	1.0000	0.9743	0.9908	0.9926	0.4	21	3.2	1	4-Oct-1996
SD4030	1.0576	0.9987	1.0092	0.9992	1.0000	0.9995	1.0070	1.0096	869	11	30	1	9-Nov-1994
SD4030PB	0.9980	0.9989	1.0078	1.0000	1.0000	0.9938	0.9998	1.0075	869	11	30	1	21-Nov-1994
2G119CX8	0.9792	1.0008	0.9940	1.0020	1.0000	1.0035	0.9984	0.9940	2.5	10	30	2	24-Oct-1993
ISO12C8K	0.9910	0.9973	1.0196	0.9998	1.0000	1.0003	1.0028	1.0187	20.2	10	30	2	8-May-1994
ISO12CX-2001	1.0222	0.9975	1.0184	1.0021	1.0000	0.9979	1.0046	1.0179	20.2	20	40	0.5	9-Aug-2001
PID6_3	1.0044	1.0019	0.9883	1.0012	1.0000	0.9855	0.9942	0.9887	0.4	21	3.2	1	3-Oct-1996
PIDIE6-3-2001	0.9915	0.9995	1.0029	1.0090	1.0000	0.9855	0.9957	1.0027	0.4	26	17	0.5	6-Aug-2001
84COAX8K	1.0248	0.9983	1.0100	0.9971	1.0000	0.9977	1.0042	1.0098	6	10	30	2	10-Oct-1993
cbnm84_01	1.0163	0.9951	1.0291	0.9984	1.0000	0.9925	1.0054	1.0278	0.6	20	40	0.5	21-Mar-2001
ISO15C8K	1.0014	0.9964	1.0192	0.9964	1.0000	0.9992	1.0037	1.0175	12.3	10	30	2	9-May-1994
stdiso15_01	1.0043	0.9987	1.0069	1.0021	1.0000	0.9969	1.0013	1.0063	12	20	40	0.5	27-Mar-2001
ISO15CX-2001	1.0050	0.9955	1.0239	0.9994	1.0000	0.9971	1.0044	1.0218	12.3	26	40	0.5	9-Aug-2001
2G121CX8	0.9960	1.0001	0.9993	1.0042	1.0000	1.0104	1.0018	0.9993	2.5	10	30	2	3-Nov-1993
LAO225PB	1.0284	0.9970	1.0147	1.0027	1.0000	0.9951	1.0043	1.0143	868.8	11	30	1	15-Dec-1994
LAO22530	1.0315	0.9976	1.0119	1.0009	1.0000	0.9966	1.0043	1.0117	868.8	10	30	1	20-Dec-1994
70COAX8K	0.9887	1.0038	0.9849	1.0022	1.0000	0.9919	0.9914	0.9874	6	10	30	2	10-Oct-1989
cbnm70_01	0.9911	0.9952	1.0202	0.9952	1.0000	0.9861	0.9930	1.0149	0.6	20	40	0.5	22-Mar-2001
PID6_4	1.0188	1.0016	0.9937	1.0006	1.0000	0.9955	0.9988	0.9943	0.4	21	6.5	1	4-Dec-1996
PIDIE65	1.0125	0.9998	1.0007	0.9982	1.0000	0.9971	1.0002	1.0008	0.4	21	15	1	29-Nov-1996
PIDIE6-5-2001	1.0321	0.9976	1.0083	1.0044	1.0000	0.9962	1.0028	1.0082	0.4	21	26	0.5	7-Aug-2001
PIDIE66	0.9792	1.0107	0.9701	1.0074	1.0000	0.9984	0.9896	0.9763	0.4	21	28	1	30-Nov-1996
61COAX8K	0.9816	1.0052	0.9870	1.0054	1.0000	0.9984	0.9896	0.9892	6	10	30	2	11-Oct-1989
PIDIE67	0.9715	1.0169	0.9582	1.0121	1.0000	1.0026	0.9862	0.9683	0.4	21	29	1	1-Dec-1996
cbnm61_01	0.9941	0.9997	1.0012	0.9978	1.0000	0.9911	0.9944	1.0004	0.6	20	40	0.5	20-Mar-2001
PIDIE6-7-2001	0.9917	1.0116	0.9705	1.0123	1.0000	1.0015	0.9953	0.9786	0.4	26	40	0.5	7-Aug-2001
Average	1.0049	1.0003	0.9999	1.0013	1.0000	0.9982	0.9994	1.0002					
Std. Dev.	0.0586	0.0037	0.0158	0.0076	0.0000	0.0081	0.0047	0.0145					
% RSD	5.83	0.37	1.58	0.76	0.00	0.81	0.47	1.45					

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The standard deviation of the individual averages (second line from bottom in Table IX-7) is a parameter that captures the fluctuations in the measurements caused by different sample characteristics (size and isotopic composition), container characteristics, detector and data acquisition conditions, and errors in the accepted values. This becomes the minimum error or uncertainty that could be quoted a priori for an arbitrary measurement on an arbitrary sample and is the limiting uncertainty or minimum bias that should be assigned to an arbitrary measurement. This parameter is similar in interpretation to the between-sample variance from an analysis of variance calculation. The plutonium bias data for P_{eff} and ^{240}Pu from Table IX-7 are plotted in Figs. IX-13 and IX-14.

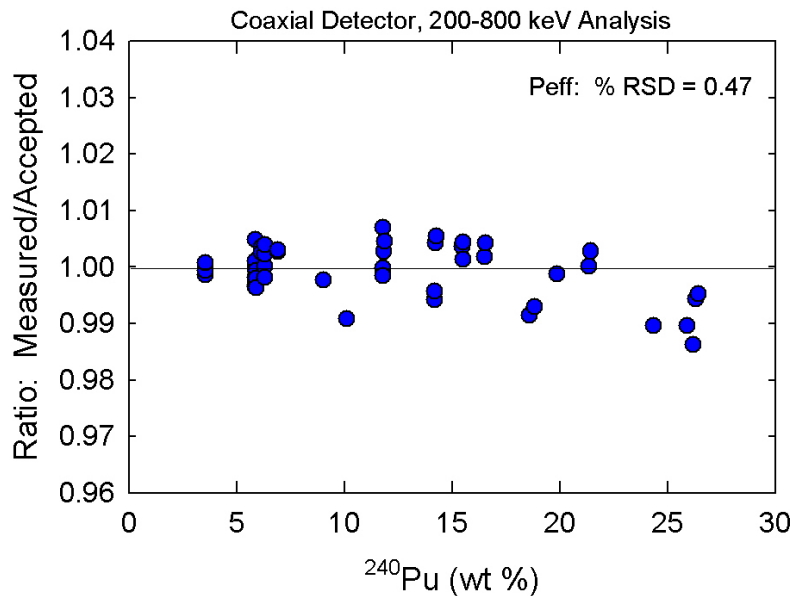


Fig.IX-13. Plutonium measurement bias for P_{eff} , 200–800 keV analysis on coaxial detectors.

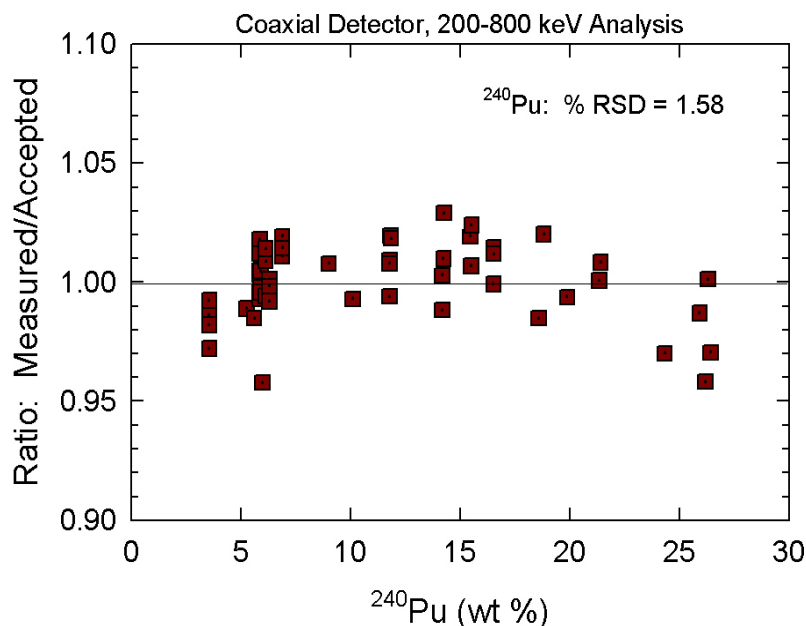


Fig.IX-14. Plutonium measurement bias for ^{240}Pu , 200–800 keV analysis on coaxial detectors.

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This same type of data is available for the 120–450 keV analysis with coaxial detectors and also for planar detector analysis in the 120–420 keV region. The bias analysis for all three data sets is summarized in Table IX-8 for all isotopes.

Table IX-8. FRAM Version 4, Bias for Plutonium.

		²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴¹ Am	P _{eff}
Coax 200–800 keV	Bias	1.0049	1.0003	0.9999	1.0013	0.9982	0.9994
	% RSD	5.83	0.37	1.58	0.76	0.81	0.47
Coax 120–450 keV	Bias	0.9958	1.0001	1.0000	0.9999	0.9955	0.9993
	% RSD	1.81	0.12	0.82	0.59	0.93	0.21
Planar 120–420 keV	Bias	1.0002	1.0002	0.9995	0.9979	0.9965	0.9995
	% RSD	1.91	0.12	0.77	0.61	1.30	0.24

3. Uranium Measurement Bias

Just as for plutonium, NDA personnel at Los Alamos have a large number of well-characterized uranium-bearing items used routinely for standards. The extent of these standards and the quality of their characterization is unique in the DOE complex (Parker 88).

The isotopic characteristics of the uranium standards used in characterizing FRAM's performance are given in Table F-2 in Appendix F.

For comparison with standards, we use an operator-entered accepted value for ²³⁶U since it does not have detectable gamma rays and is determined by isotopic correlation in FRAM. This is analogous to the method used to analyze plutonium standards for ²⁴²Pu.

The bias for uranium measurements is displayed in Table IX-9. This table contains individual measurement data from many samples and multiple data sets for several samples. The data sets encompass data from different detectors, different data acquisition systems, and different measurement geometries. The latter is particularly important to note. It demonstrates that version 4 of FRAM does indeed correct properly for the coincidence summing effects that affected earlier uranium measurements (Vo 99a). The values for individual items come from the average of repeated measurements of typically 30-minute or 1-hour duration. One sees for the important ²³⁵U isotope that the average bias for all samples, over the enrichment range from 0.3%–93% is 0.25%. The % RSD, in the same fashion as discussed for plutonium, is just under 1% for ²³⁵U. Recall that the interpretation of this parameter is the a priori measurement uncertainty for an arbitrary sample attributed to sample specific and measurement specific conditions.

The measurement bias data of Table IX-9 is plotted in Fig. IX-15.

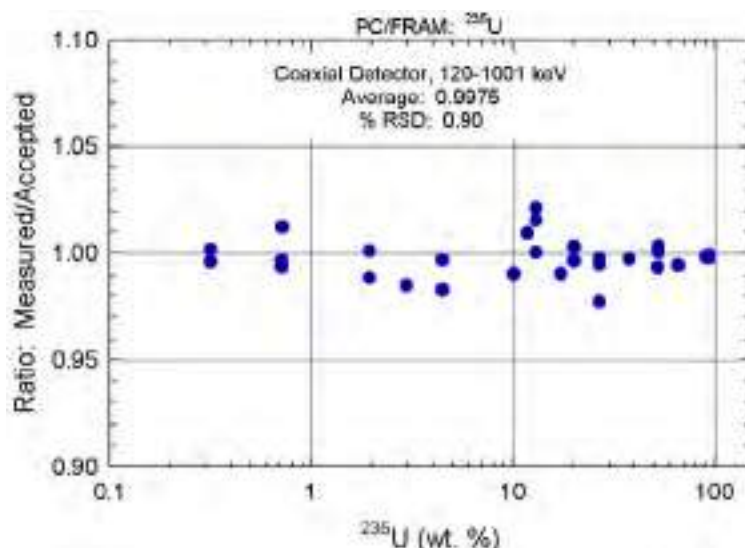
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Table IX-9. Uranium Bias for Version 4 of FRAM.

Filename	Accepted Wt % ²³⁵ U	Measured/Accepted		
		²³⁴ U	²³⁵ U	²³⁸ U
NBL93_03	93.1703	0.99495	0.99953	1.00875
NBL93_00	93.1703	1.00583	0.99777	1.03636
C2080001	93.1700		0.99901	
U91C2G20	91.3356	0.98896	0.99890	1.01493
U91C2T30	91.3356	0.97910	0.99823	1.02431
UIISO91_N	91.3356	1.01151	0.99819	1.02087
U66C2G20	66.0405	1.00983	0.99437	1.01106
NBL53_10	52.4880	0.99612	1.00049	0.99948
NBL53_03	52.4880	1.01046	1.00351	0.99598
U52C2G20	52.1174	1.02696	0.99345	1.00704
U38C2G15	37.5518	1.01110	0.99733	1.00157
UIISO_27	26.7519	1.02056	0.99782	1.00074
UIISO27PS	26.7519	1.01997	0.99494	1.00180
UIISO27	26.7519	0.99837	0.97735	1.00833
NBL20_01	20.1070	1.00905	0.99662	1.00084
NBL20_05	20.1070	0.99096	1.00318	0.99921
U17C2T10	17.2386	1.02646	0.99036	1.00197
UIISO_13	12.9543	1.04940	1.02127	0.99678
UIISO13_P	12.9543	1.04751	1.01551	0.99764
UIISO13	12.9543	1.02076	1.00058	0.99989
UIISO1212	11.7974	1.00117	1.00961	0.99871
A1324PS	10.0863	1.00801	0.99039	1.00107
NBS44612	4.4623	0.98043	0.99669	1.00016
NBS446PS	4.4623	1.00557	0.98285	1.00080
NBS29512	2.9491	0.96287	0.98473	1.00047
NBS295PS	2.9491	0.96205	0.98514	1.00046
NBS19412	1.9421	1.03156	1.00125	0.99997
NBS194PS	1.9421	0.97662	0.98849	1.00023
A11127PS	0.7167	1.29268	1.01235	0.99990
NBS07112	0.7119	1.07897	0.99649	1.00002
NBS071PS	0.7119	1.02303	0.99389	1.00004
NBS03112	0.3166	1.43220	0.99606	1.00000
NBS031PS	0.3166	1.03553	1.00190	0.99999
Average		1.0054 *	0.9975	1.0040
Std. Dev.		0.0221	0.0089	0.0088
% RSD		2.20	0.90	0.88

*Uranium-234 Average and Std. Dev. exclude enrichments with ²³⁵U < 1.9%. This enrichment value is at the sensitivity limit of FRAM for ²³⁴U.

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Fig. IX-15. FRAM Version 4 Measurement Bias for ^{235}U .

4. MOX Measurement Bias

Version 4 of FRAM can analyze the gamma spectra from MOX samples giving results, in many cases, for the complete plutonium isotopic distribution, the $^{235}\text{U}/\text{Pu}$ ratio, and the $^{238}\text{U}/\text{Pu}$ ratio.

MOX samples can be measured in several ways by FRAM depending upon the energy region analyzed and the amount of shielding surrounding the sample. Uranium-235 is always analyzed at 185.7 keV. This gamma ray may not be present in a shielded sample and is not visible above the continuum for $^{235}\text{U}/\text{Pu}$ ratios below approximately 0.005. If the sample is lightly shielded, FRAM can obtain both the $^{235}\text{U}/\text{Pu}$ ratio at 185.7 keV and the $^{238}\text{U}/\text{Pu}$ ratio at 1001 keV. For heavily shielded samples, the $^{238}\text{U}/\text{Pu}$ ratio at 1001 keV may be the only uranium measurement available.

Los Alamos has a limited number of MOX samples. The "HUA" series is described in Table F-3 in Appendix F. Results from unshielded sample measurements analyzed in the 120–450 keV range with version 4 of FRAM are given in Table IX-10. In the 120–450 keV analysis range we only have access to ^{235}U at 185.7 keV. The % RSD of the $^{235}\text{U}/\text{Pu}$ ratio, calculated from the distribution of the individual bias values, is about 4%. Some of the variation in the bias may arise from a different distribution of particle sizes between the uranium and the plutonium in the different samples.

Table IX-10. Unshielded Measurements, 120–450 keV Analysis.

	Ratio: Measured/Accepted							
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{241}Am	Spec. Pow	$^{240}\text{Pu}_{\text{eff}}$	$^{235}\text{U}/\text{Pu}$
HUA5062	0.97219	0.99813	1.01382	1.00258	1.01133	1.00411	1.01295	1.05023
HUA5065	0.98209	0.99661	1.02495	1.00382	1.00085	1.00226	1.02380	1.03559
HUA5069	0.98625	0.99680	1.02417	0.99727	0.99518	1.00058	1.02310	1.01876
HUA5301	0.96699	0.99754	1.01842	1.00526	0.96656	0.99228	1.01745	0.95162
HUA8971	0.97511	0.99410	1.04362	1.00208	0.99487	1.00339	1.04159	0.98511
Average	0.9765	0.9966	1.0250	1.0022	0.9938	1.0005	1.0238	1.0083
Std. Dev.	0.0077	0.0015	0.0114	0.0030	0.0166	0.0048	0.0109	0.0399
% RSD	0.79	0.15	1.11	0.30	1.67	0.48	1.06	3.96

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In Table IX-11 we show the results from the analysis of the unshielded samples using data in the 200–800 keV energy range. With this analysis we are still able to analyze for ^{235}U at 185.7 keV as well as for ^{238}U at 1001 keV. (Note: The designation of an energy range for analysis refers to the main plutonium analysis. Other gamma rays outside of that range may also be used for analysis, i.e., 185.7 and 1001 keV for uranium analysis, if they are present. The standard data collection range for coaxial detectors is 0–1024 keV.)

Table IX-11. Unshielded Measurements, 200–800 keV Analysis.

	Ratio: Measured/Accepted								
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{241}Am	Spec. Pow	$^{240}\text{Pu}_{\text{eff}}$	$^{235}\text{U}/\text{Pu}$	$^{238}\text{U}/\text{Pu}$
HUA5062	0.99196	0.99831	1.01240	1.00265	1.01013	1.00493	1.01184	1.05627	1.00610
HUA5065	0.97503	0.99858	1.01038	1.00576	1.00053	0.99973	1.00967	1.03709	1.00829
HUA5069	1.10796	0.99836	1.01164	1.00273	0.99419	1.00717	1.01244	1.02364	1.02691
HUA5301	1.03498	0.99935	1.00448	1.00633	0.96630	0.99475	1.00466	0.96645	1.03412
HUA8971	1.05086	0.99836	1.01146	1.01007	0.99776	1.00521	1.01157	0.98461	1.00068
Average	1.0322	0.9986	1.0101	1.0055	0.9938	1.0024	1.0100	1.0136	1.0152
Std. Dev.	0.0524	0.0004	0.0032	0.0031	0.0165	0.0051	0.0032	0.0372	0.0145
% RSD	5.08	0.04	0.32	0.30	1.66	0.51	0.31	3.67	1.42

In Table IX-12 we show results from the third possible method of analyzing MOX data from coaxial detectors. Here the samples are shielded with 3 mm of lead, making the 185.7-keV ^{235}U gamma ray undetectable. We can only analyze for $^{238}\text{U}/\text{Pu}$.

Table IX-12. Shielded Measurements, 3 mm Lead, 200–800 keV Analysis.

	Ratio: Measured/Accepted								
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{241}Am	Spec. Pow	$^{240}\text{Pu}_{\text{eff}}$	$^{235}\text{U}/\text{Pu}$	$^{238}\text{U}/\text{Pu}$
HUA5062	0.96534	1.00071	0.99475	1.00478	1.00929	1.00034	0.99450		1.04017
HUA5065	0.97299	1.00159	0.98809	1.00759	1.00089	0.99685	0.98819		1.04377
HUA5069	1.07305	1.00051	0.99548	1.00881	0.99510	1.00281	0.99648		1.04978
HUA5301	0.99139	1.00048	0.99609	1.00940	0.96484	0.98996	0.99614		1.05726
HUA8971	1.00948	1.00059	0.99515	1.01022	0.99855	0.99961	0.99544		1.03340
Average	1.00245	1.00077	0.99391	1.00816	0.99373	0.99792	0.99415		1.04488
Stdev	0.04301	0.00046	0.00329	0.00212	0.01698	0.00493	0.00342		0.00912
% RSD	4.29	0.05	0.33	0.21	1.71	0.49	0.34		0.87

All of the MOX measurements tabulated in Tables IX-13–IX-15 were made for a 1-hour counting time at counting rates between 30 and 40 kHz. We typically made 12–15 repeated measurements. The % RSD is calculated from the distribution of the five individual averages of the repeated measurements.

The details of how MOX measurements are set up in FRAM have been described previously in some detail (Sampson 99b). The FRAM Technical Note, “Measurement of MOX with PC/FRAM” is reproduced in its entirety in Appendix A of this Application Guide. Appendix A describes the application of MOX

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measurements in version 3.2 of FRAM, which does not include ^{238}U analysis. The results above are from version 4.2 and include analysis for ^{238}U .

C. Intercomparison Exercises

1. The PIDIE Exercise

The Plutonium Isotopic Determination Intercomparison Exercise (PIDIE) was the first exercise designed to characterize gamma-ray isotopic analysis measurements and analysis on a worldwide basis. This exercise was organized in Europe and was notable in that the organizers provided to each participant seven identical sets of nominal 0.4 g plutonium as PuO_2 samples. The international shipment of the sample sets containing plutonium proved to be extraordinarily difficult because of shipping regulation and compliance issues.

These samples came to Los Alamos around 1980 at the time when we were developing our first isotopic analysis software (see section III). Los Alamos submitted measurement results with a “preproduction” version of our first RT-11 based analysis software. The Los Alamos measurement results were comparable to other measurements that were submitted, but at this writing are so obsolete that they will not be discussed. The results of the exercise have been reported by Morel (Morel 1991), nearly 15 years after the exercise was first planned.

The outcome of this pioneering exercise influenced how future exercises were handled. In the later exercises described below, the participants brought their equipment to a common location and made measurements for a fixed time period, thus negating the requirement for sample shipment across international borders. The samples used in the PIDIE exercise are a well-documented legacy of the PIDIE measurements and are still used today at Los Alamos and elsewhere to characterize gamma-ray plutonium isotopic composition measurements (see for example Tables F-3 and IX-7).

2. Uranium Enrichment Measurement Exercise, IRMM 1996

The Uranium Enrichment Measurement Exercise, sponsored by the European Safeguards Research and Development Agency (ESARDA) was held at the Institute of Reference Materials and Measurements (IRMM) in Geel, Belgium in 1996. For this exercise the participants brought their own equipment to IRMM, where they were allotted one week for measurements on a set of well-characterized standards. The exercise took about a year to complete because there were so many participants. This year-long time span was much more rapid than the PIDIE exercise and the formal results were reported in less than two years (Morel 98, Morel 00).

Many participants made only “classical” infinite sample ^{235}U enrichment measurements, reporting results only for ^{235}U , as the exercise was organized primarily to test that method. Los Alamos participated with FRAM measurements giving results for ^{234}U , ^{235}U , and ^{238}U . The organizers only reported certified values for ^{235}U . Table IX-13 displays the average of all FRAM measurements made during this exercise.

The biases displayed are very similar to those shown in Fig. IX-15. Samples X and Y in Table IX-13 are of interest because they are freshly separated and the daughter products ^{234}Pa and $^{234\text{m}}\text{Pa}$ used to characterize ^{238}U in a FRAM measurement have been removed from the sample. They grow back in with the 24.1-day half-life of ^{234}Th . For samples X and Y in Table IX-13 we made a correction using the known separation time. This correction reduced the error from approximately 20% to the approximately 4% errors shown. The residual error may arise from an incomplete separation.

This separation time correction has been incorporated into version 4 of FRAM. To our knowledge, FRAM is the only gamma-ray isotopic analysis code available with the capability to make this correction. The user enters the known separation date to make the correction.

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Table IX-13. FRAM Results for IRMM Uranium Enrichment Exercise.

Sample	Measured wt % ^{235}U mean $\pm$ sigma(mean)	Certified wt % ^{235}U	% Difference $100 \cdot (M - C)/C$	Comment
1614	1.521 ± 0.011 (0.71%)	1.4972	1.59%	
1541	1.984 ± 0.018 (0.91%)	1.9952	-0.56%	
1542	2.826 ± 0.023 (0.80%)	2.8774	-1.79%	
1613	3.097 ± 0.061 (2.0%)	3.1094	-0.40%	
125VA	93.35 ± 0.048 (0.051%)	93.1556	0.21%	
X	3.316 ± 0.049 (1.48%)	3.4317	-3.37%	freshly separated
Y	2.547 ± 0.011 (0.43%)	2.6846	-5.13%	freshly separated
Average difference excluding freshly separated -0.19%				

3. The Pu-2000 Exercise

The most recent intercomparison exercise sponsored by the ESARDA NDA Working Group was conducted at IRMM during the calendar year 2000. This exercise was organized in a fashion similar to that of the Uranium Enrichment Measurement Exercise with participants using their own equipment in a one-week measurement window at IRMM. The principal purpose of this exercise, known as the Pu-2000 exercise, was to test the performance of recent isotopic analysis methods over a wide range of abundances and to investigate possible sources of error. Los Alamos was one of eight participating laboratories. Twenty unknown samples characterized by IRMM were available for measurement. Four additional certified samples were available as known references.

Seventeen of the twenty samples contained plutonium or MOX with ^{240}Pu ranging from 1.6 to 26.9 wt %. The remaining three samples were isotopically pure samples of ^{239}Pu , ^{240}Pu , and ^{241}Am .

Table IX-14 displays the average measured FRAM result and the IRMM certified result for the Los Alamos FRAM measurements. We did not measure all of the unknown samples because, in fact, samples E through K were known to us (the PIDIE samples) and we already had access to these in Los Alamos. In a few instances the IRMM certified value was known to have a large uncertainty and the average of all the results submitted by all participants is used instead. An asterisk denotes these cases.

Table IX-15 displays the results reported by FRAM for the three isotopically pure samples. The Los Alamos FRAM code was the only code to report results for all three samples. The versatility of the FRAM code allowed us to modify parameter files for these very special samples.

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Table IX-14. Los Alamos FRAM Results for the Pu-2000 Exercise, Unknown Samples (Results in wt % relative to total plutonium).

Sample	Type		²³⁸ Pu (sigma)	²³⁹ Pu (sigma)	²⁴⁰ Pu (sigma)	²⁴¹ Pu (sigma)	²⁴¹ Am (sigma)
A	4.23g PuO ₂	FRAM	0.1085 (0.0008)	79.747 (0.17)	18.756 (0.17)	0.724 (0.001)	1.699 (0.002)
		Certified	0.1086*	79.506	18.990	0.724	1.689*
B	4.66g PuO ₂	FRAM	1.415 (0.010)	62.016 (0.46)	26.258 (0.50)	4.255 (0.032)	8.381 (0.065)
		Certified	1.44	61.327	26.887	4.290	8.25*
C	7.38g PuO ₂	FRAM	0.0098 (0.0004)	93.479 (0.13)	6.357 (0.13)	0.114 (0.0004)	1.154 (0.004)
		Certified	0.0110	93.522	6.314	0.113	1.188
D	7.38g PuO ₂	FRAM	0.0104 (0.001)	93.537 (0.09)	6.298 (0.09)	0.115 (0.0003)	1.147 (0.003)
		Certified	0.0110	93.522	6.314	0.113	1.173
F	0.45g PuO ₂	FRAM	0.0207 (0.0008)	89.623 (0.07)	10.017 (0.08)	0.246 (0.0002)	0.452 (0.005)
		Certified	0.0209	89.571	10.073	0.242	0.457
G	0.45g PuO ₂	FRAM	0.0433 (0.0005)	85.243 (0.09)	13.927 (0.09)	0.550 (0.002)	1.074 (0.003)
		Certified	0.0428	85.029	14.150	0.542	1.061
I	0.45g PuO ₂	FRAM	0.118 (0.0008)	76.958 (0.11)	21.094 (0.11)	1.134 (0.002)	2.701 (0.006)
		Certified	0.121	76.716	21.338	1.129	2.650
J	0.45g PuO ₂	FRAM	0.857 (0.0014)	68.612 (0.06)	24.115 (0.05)	2.932 (0.010)	6.308 (0.025)
		Certified	0.871	68.254	24.450	2.938	6.091
K	0.45g PuO ₂	FRAM	1.173 (0.005)	64.755 (0.16)	25.867 (0.18)	3.644 (0.013)	6.739 (0.024)
		Certified	1.182	64.229	26.385	3.639	6.556
L	3.5g PuO ₂	FRAM	0.0043 (0.0007)	98.232 (0.12)	1.692 (0.12)	0.0483 (0.0002)	1.198 (0.007)
		Certified	0.0039*	98.295	1.630	0.0469	1.200
M	5.04g PuO ₂	FRAM	0.0109 (0.0001)	93.525 (0.05)	6.311 (0.05)	0.114 (0.0001)	0.205 (0.002)
		Certified	0.0110	93.546	6.292	0.112	0.203
N	2.21g PuO ₂	FRAM	1.302 (0.004)	64.883 (0.22)	24.250 (0.24)	4.963 (0.015)	5.214 (0.043)
		Certified	1.300	65.073	24.051	4.929	5.074
O	8.67g metal	FRAM	0.0063 (0.0009)	95.377 (0.12)	4.548 (0.12)	0.0618 (0.0002)	0.155 (0.0027)
		Certified	0.0060	95.418	4.510	0.0586	0.165
P	MOX pellet	FRAM	1.106 (0.007)	64.596 (0.20)	26.486 (0.21)	3.477 (0.020)	1.480 (0.006)
		Certified	1.107	64.777	26.262	3.510	1.394
Q	MOX sol.	FRAM	1.106 (0.013)	65.202 (0.21)	25.869 (0.20)	3.488 (0.03)	1.502 (0.009)
		Certified	1.107	64.777	26.262	3.510	1.394

* Average value from all participants

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Table IX-15. Los Alamos FRAM Results Reported for Isotopically Pure Samples. (Wt % Relative to Total Plutonium).

Sample	Type		^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{241}Am ($\mu\text{g/gPu}$)
R	Pu-239	FRAM	0.00031	99.964	0.0325	0.0029	75
		Certified	0.0000	99.979	0.0210	0.0001	3
S	Pu-240	FRAM	0.1027	0.0084	99.860	0.0001	13.6
		Certified	0.0119	0.023	99.935	0.00098	20.2
T	Am-241	FRAM					100.00
		Certified					100.00

D. Factors Influencing Measurement Bias

This section describes the many factors that influence the bias of a gamma-ray isotopic measurement, biases that have been extensively characterized for FRAM in the preceding sections.

1. Sample Composition Characteristics

The elemental makeup of the sample influences self-absorption in the sample and thereby influences the shape of the relative-efficiency curve. Version 4 of FRAM accounts for this effect by allowing up to three different elements or compounds to define the matrix. (Eq. II-11 and section II.F.5.) These elements or compounds may be chosen from a list of seven (aluminum, iron, cadmium, erbium, lead, water, and concrete). The available elements were chosen not only for their likelihood of being part of the sample, but also to sample the entire range of atomic number. If the matrix contains elements other than the three designated in the analysis parameter file, the FRAM software will use a linear combination of the three designated components to approximate the relative-efficiency curve. Differences from the true relative-efficiency curve are likely to be compensated for by the Hoerl function correction factor and the result is almost always a good fit to the relative-efficiency points, even if the three chosen components are not a good match for the actual sample matrix.

2. Branching Ratios

The branching ratios (gamma rays per decay) of the gamma rays used in the analysis directly affect the bias in the measured isotopic ratios (Eq. II-5). Most of the branching ratios for the gamma rays used in the analysis have been directly measured by gamma-ray spectrometry techniques. Absolute measurements of this type are very difficult and the very best results usually have an associated uncertainty of no better than 1% (relative). Later on we will discuss in more detail the removal of biases associated with the fundamental branching ratio data.

3. Coincidence Summing

Coincidence summing occurs when a gamma-ray decay includes cascades of two or more gamma rays that are emitted simultaneously in coincidence with each other. These two gamma rays may interact simultaneously in the detector and the single detected pulse will often not represent either gamma ray. This takes events away from the full energy peak in a manner that is dependent upon the measurement geometry.

Summing effects depend upon the square of the detector solid angle (Knoll 00) and can be reduced by increasing the sample-to-detector distance.

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For coincidence summing to be a problem for a specific isotope, the two coincident gamma rays must be of high enough intensity to be useful in the analysis. They also must be of high enough energy to escape the sample and its containment. Coincidence summing of a high-energy gamma ray with a low-energy (less than approximately 70 keV) gamma ray occurs fairly often in the complex uranium and plutonium decay schemes. However, the low-energy gamma ray is usually absorbed before it reaches the detector, averting a summing problem.

a. Uranium

Coincidence summing effects are present in low-enriched uranium measurements analyzed in the 120–1001 keV energy range. The 258-keV gamma ray from the ^{238}U daughter $^{234\text{m}}\text{Pa}$ is particularly affected. In general, measurements on highly enriched uranium are not affected because the 258-keV gamma ray is not used in the analysis. The ^{235}U isotopic result can be biased by as much as 15%, without correction, depending upon the sample-to-detector distance. Because of the solid angle dependence, the effects are particularly pronounced for sample-to-detector distances less than 5 cm. The effects become small at distances greater than 15 cm.

FRAM version 4 incorporates a correction factor for coincidence summing (Vo 99a). The correction factor is derived by examining the intensities of several gamma rays affected by coincidence summing in different proportions while knowing their correct branching ratios. This allows a correction to be made by comparing intensity ratios of the affected peaks to the ratios expected without coincidence summing.

b. Plutonium

Coincidence summing is not recognized to be a problem with plutonium measurements. Many of the possible opportunities do not occur because the filtering present for plutonium measurements removes the low energy coincident gamma rays.

4. Peak Area Determination

a. Background Shape

When we set up a parameter file for FRAM we pay very careful attention to setting the best regions of interest (peak and background) and choosing the most appropriate background shape (see section VI. C. 3.) to characterize the continuum underneath the peak region. Recall that the user can choose from seven background types, denoted as 1) flat, 2) linear, 3) quadratic, 4) exponential, 5) flat step, 6) linear step, or 7) bilinear step.

A parameter file is set up for application to a wide range of measurement conditions such as isotopic composition (including ^{241}Am content), sample mass, sample composition, sample container and shielding, detector resolution, and measurement geometry. Many of these measurement conditions affect the shape of the background continuum underneath the peak regions. The parameter file setup of the region data must allow for a background continuum shape (background type) that will adapt itself to many different conditions. A poor choice of background type can lead to a bias in the peak area determination and concomitant errors in the isotopic fractions. Some of the “tricky” regions are illustrated and discussed below.

Continuum at 160 keV The definition of the background type for the region around 160 keV is critical for ^{240}Pu analysis in the 120–450 keV region as the peak at 160.3 keV is the only peak available for analysis of ^{240}Pu in this region. We see in Fig. IX-16 that the background has an inflection point near this energy and has a generally concave upward shape. We customarily define a quadratic background for this region with background ROIs below 160 and above 165 keV. For coaxial detector parameter files we do

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not set a background ROI between 161.5 and 164 keV to allow for varying detector resolutions and the possible presence of ^{235}U at 163.3 keV.

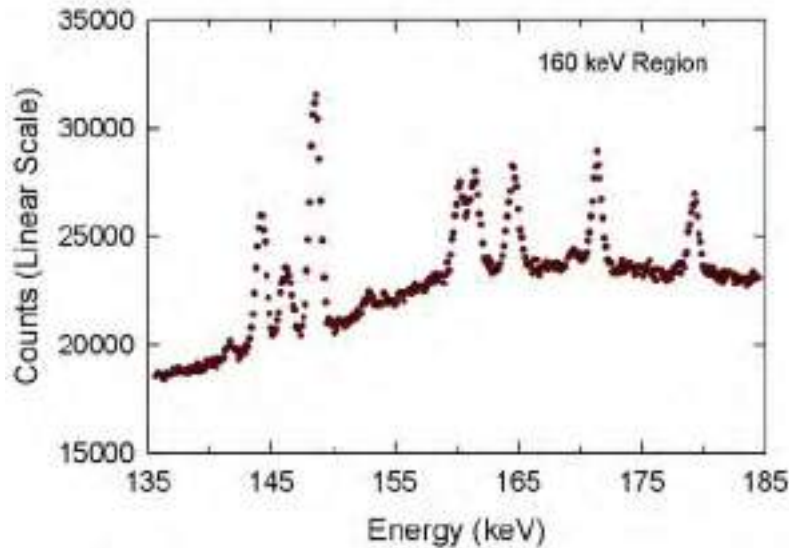


Fig. IX-16. The background in the region around 160 keV shows curvature making definition of the background continuum difficult. Poor definition can bias the ^{240}Pu peak area at 160.3 keV.

Continuum at 148 keV The background continuum underneath the 148.6-keV peak from ^{241}Pu is usually positively sloping as is shown in Fig. IX-17. One would like to use a linear background with a smoothed step function (linear step) to account for the increased Compton continuum below 148 keV, which arises from the 148-keV peak. However, since the background is higher above 148 keV than it is below, the “step” in the background goes the wrong way and becomes unphysical. FRAM can sense this condition and will automatically recalculate the background continuum with the simpler linear form that does not incorporate a step. The background ROIs are typically set below 140 keV, between 150 and 152 keV, and above 153 keV.

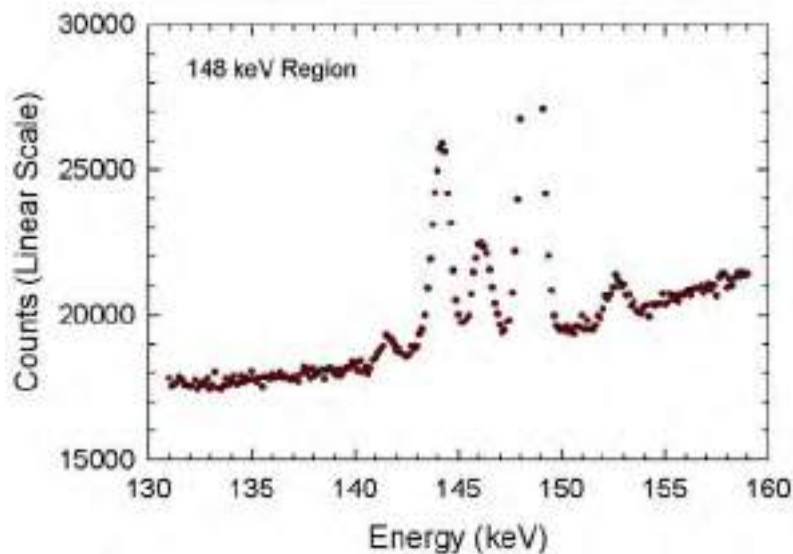


Fig. IX-17. The positive sloping background at 148 keV makes it difficult to calculate an accurate background continuum for the 148.6 keV from ^{241}Pu

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Continuum at 208 keV The ^{241}Pu – ^{237}U peak at 208 keV can vary in intensity over a factor of 500 relative to neighboring peaks, depending upon the isotopic composition of the sample. This peak usually presents the classic case of the linear step function background type. We see in Figs. IX-18 and XI-19 that the underlying continuum can change slope above and below 208 keV. While a linear step-function works well in Fig. IX-18, the continuum in Fig. IX-19 is better characterized by what we call a bilinear step, which has a different slope above and below the 208-keV peak. FRAM will automatically switch a bilinear step background type to a linear step if it finds the bilinear step inappropriate.

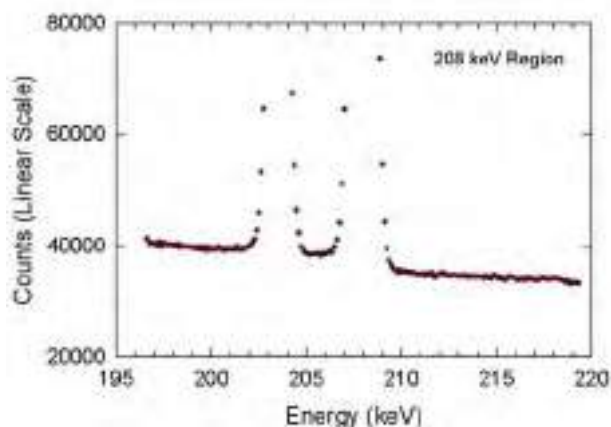


Fig. IX-18. The 208 keV region from a low burnup plutonium sample. The background continuum has the same slope above and below 208 keV.

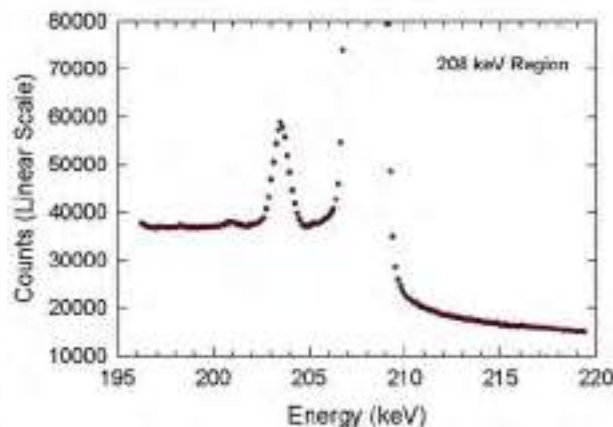


Fig. IX-19. The 208 keV region from a high burnup plutonium sample. The background continuum has different slopes above and below 208 keV.

b. Interferences

FRAM can be characterized as a response function code. The peak shapes are determined in the internal calibration phase of the analysis, and the peaks for analysis are predetermined by the setup of the parameter file (section VI. C. II.). An unexpected peak (a peak not accounted for in the peak list in the parameter file) appearing in an analyzed region of the spectrum, may bias the analysis of the designated peaks in the region. This bias can arise by direct interference with the peak area determination, or the interference may appear in a region used to define the background continuum, thus biasing the peak area via an incorrect background subtraction. The good news with FRAM is, of course, that once an interference peak is recognized, one can easily modify the parameter file to include the interference peak and reanalyze the data.

The general-purpose plutonium parameter files delivered with version 4 of FRAM are set up to include common interferences from ^{235}U , ^{243}Am – ^{239}Np , and ^{237}Np . The general-purpose parameter files are usually adequate for low concentrations of these interferences but may require modification for very high concentrations.

The user has another tool in FRAM to discover unexpected interference peaks. The user should open the spectrum data file in question using the **File | Open** option and then display the spectral data using the **Options | Plot Spectrum** option. Click on the **display...** button in the plotting window and then click on the **regions** button in the **Display Choices** window. Choose the parameter file to be used in the analysis from the pull down **FRAM Parameter Sets** window.

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The analysis regions for the selected parameter file appear highlighted in red, and the background regions appear highlighted in green. Examination of the highlighted spectrum will reveal if any unexpected interference peaks appear in a background region. Highlighting the analysis regions can be used to show if the energy calibration of the spectrum matches that set up in the parameter file. If the red-highlighted peak regions do not contain the peaks, the energy calibration in the parameter file may not be appropriate for the spectrum.

E. Bias Correction

We have developed several procedures for identifying and correcting biases in the isotopic results. In general, the procedures rely on measurement of standards, identification of the source of the bias, and correction of the bias, usually by adjustment of branching ratios.

The first step is to carefully set up the parameter file for the analysis. This includes identifying the full range of measurement conditions, isotopic compositions, ^{241}Am content, interferences, and any other parameters that might affect the gamma-ray spectrum. The user then very carefully establishes the peak and background ROIs based on representative spectra. This is perhaps the most important step in making bias corrections.

1. Adjustment of Branching Ratios

If we still observe biases even after careful set up of the parameter file, we will generally make an adjustment in the branching ratios to reduce or eliminate the bias. There is good justification for this approach, although it is questioned by some as inappropriate because branching ratios are (imperfectly) known constants of nature. Our reasoning is that we are making corrections for imperfections in the analysis in addition to correcting for uncertainties in our knowledge of the branching ratio values.

One type of bias arises from peak area uncertainties caused by imperfect background subtraction. A second peak area uncertainty comes from imperfections in the response function fitting of closely lying, overlapping peaks. A third uncertainty arises from biases and random errors in the published branching intensities. We have also previously mentioned imperfections in the modeling of the relative-efficiency curve as a contributor to bias. Imperfections in the coincidence summing correction (uranium) and unrecognized coincidence summing problems with plutonium also contribute. Finally, the model (Gaussian plus an exponential tail on the low-energy side of the peak) that is used to fit the peak areas is itself imperfect.

2. Branching Ratio Values

We have already noted (section IX. D. II.) that the branching ratio value directly affects the isotopic measurement result. There are two principle sources of branching ratio values for plutonium; the work of Gunnink and coworkers (Gunnink 76a) and the Table of the Isotopes (Firestone 96). Any adjustment of plutonium branching ratio values usually starts from the values in these sources.

3. Observation of Peak Area Biases

We can use the medium output of a FRAM analysis to look for inconsistencies in the activities calculated for a series of gamma rays from a single isotope. The ratio of $^{239}\text{Pu}/^{239}\text{Pu}$ from a medium printout are shown as an example in Table IX-16. The ratios are relatively consistent within the error (% RSD from counting statistics). When we look at the consistency we consider the counting statistics for analyses from many different samples. Any inconsistency that shows up regularly is examined in closer detail.

This analysis method only works for isotopes with several available analysis peaks. Usually we only have a single analysis peak for ^{238}Pu and ^{240}Pu .

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Table IX-16. FRAM Printout of Individual Isotopic Ratios (relative to ^{239}Pu) for Analysis Gamma Rays from ^{239}Pu .

pk	isotope	energy	area	error	activity ratios	mass ratios
4	Pu239	129.294	563932	0.27%	1.00039e+000	1.00039e+000
17	Pu239	161.482	30354	2.38%	9.66128e-001	9.66128e-001
24	Pu239	171.372	35361	2.10%	9.83841e-001	9.83841e-001
27	Pu239	203.545	309449	0.32%	9.98056e-001	9.98056e-001
36	Pu239	255.380	71442	0.85%	9.83843e-001	9.83843e-001
58	Pu239	345.011	777047	0.17%	9.99775e-001	9.99775e-001
66	Pu239	375.042	2368514	0.11%	9.99400e-001	9.99400e-001
71	Pu239	413.712	2433540	0.11%	1.00172e+000	1.00172e+000
76	Pu239	451.474	330898	0.24%	9.92351e-001	9.92351e-001

The correction of bias for an isotope with only a single gamma ray (^{238}Pu and ^{240}Pu are usually in this category) can be straightforward. We examine the bias as a function of the isotopic fraction, usually from data such as displayed in Table IX-7 above. A simple branching ratio adjustment is usually indicated when the data do not show a trend with changing isotopic composition. The situation is more complex, however, if there is a trend. This could indicate unresolved or imperfect subtraction of interferences or could indicate a background continuum subtraction that does not adapt well over the full range of data.

4. Least-Squares Adjustment of Branching Ratios

A more general adjustment method utilizes high precision data from multiple measurements on samples with well-characterized isotopic compositions. A “Downhill Simplex Method” is incorporated into a special developer’s version of FRAM and used to minimize the weighted chi-square of the chosen isotopic ratio(s). Multiple branching ratios are varied iteratively to find a minimum. The data sets span a wide range of isotopic compositions and ages. The large, varied data sets are especially important for the adjustment of branching ratios of ^{241}Am and ^{241}Pu – ^{237}U because much of the input data comes from coenergetic peaks—contributions from both ^{241}Am and ^{241}Pu – ^{237}U —that would otherwise not provide independent information for samples with nearly the same age.

With this method we can obtain accuracies of a percent (relative) or less for the individual isotopic ratios. This fine-tuning usually does not make large adjustments from the published values. Indeed, if the adjustment is large (say greater than 5%) then one should carefully examine the data in more detail to see if it is justified.

The proof of the appropriateness of this approach can be seen by examination of how well the adjusted branching ratios agree with the published values. Table IX-17 below lists several sources of branching ratios for the major analysis peaks of plutonium above 120 keV. Columns 3 and 4 are the references often used as starting points. These reference values are not independent as the Table of Isotopes is a compilation and uses much of the data published in UCRL-52139 (Gunnick 76a). The FRAM values arise from the two principal coaxial-detector parameter files used with version 4 of FRAM and have been determined in most part by the least-squares fitting method described above. The FRAM branching ratios agree with the fundamental published values validating the least-squares adjustment process.

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Table IX-17. Plutonium and Americium Branching Ratios (gammas/decay) for Major Gamma Rays.

Isotope	keV	UCRL-52139	Eight Edition Table of Isotopes	FRAM 120-450 keV	FRAM 200-800 keV
²⁴¹ Am	125.3	4.08 E-05	4.08 E-05	4.136 E-05	
²³⁹ Pu	129.3	6.26 E-05	6.31 E-06	6.29 E-06	
²⁴¹ Pu	148.6	1.87 E-06	1.85 E-06	1.894 E-06	
²³⁸ Pu	152.7	9.56 E-06	9.37 E-06	9.37 E-06	
²⁴⁰ Pu	160.3	4.02 E-06	4.02 E-06	4.035 E-06	
²⁴¹ Pu- ²³⁷ U	164.6	4.51 E-07	4.54 E-07	4.663 E-07	
²⁴¹ Am	164.6	6.67 E-07	6.67 E-07	6.879 E-07	
²³⁹ Pu	203.5	5.60 E-06	5.69 E-06	5.727 E-06	5.727 E-06
²⁴¹ Pu- ²³⁷ U	208.0	5.32 E-06	5.18 E-06	5.392 E-06	5.392 E-06
²⁴¹ Am	208.0	7.91 E-06	7.91 E-06	7.954 E-06	7.954 E-06
²⁴¹ Pu- ²³⁷ U	267.5	1.81 E-07	1.74 E-07	1.786 E-07	1.786 E-07
²⁴¹ Am	267.5	2.63 E-07	2.63 E-07	2.635 E-07	2.635 E-07
²⁴¹ Pu- ²³⁷ U	332.4	2.97 E-07	2.928 E-07	2.974 E-07	2.974 E-07
²⁴¹ Am	332.4	1.490 E-06	1.49 E-06	1.476 E-06	1.476 E-06
²⁴¹ Pu- ²³⁷ U	335.4	2.380 E-08	2.33 E-08	2.392 E-08	2.392 E-08
²⁴¹ Am	335.4	4.960 E-06	4.96 E-06	4.872 E-06	4.872 E-06
²³⁹ Pu	345.0	5.592 E-06	5.56 E-06	5.533 E-06	5.533 E-06
²³⁹ Pu	375.0	1.570 E-05	1.554 E-05	1.554 E-05	1.554 E-05
²³⁹ Pu	413.7	1.489 E-05	1.466 E-05	1.469 E-05	1.469 E-05
²³⁹ Pu	451.5	1.89 E-06	1.894 E-06	1.898 E-06	1.898 E-06
²⁴⁰ Pu	642.5	1.245 E-07	1.3 E-07		1.243 E-07
²³⁹ Pu	645.9	1.489 E-07	1.52 E-07		1.491 E-07
²⁴¹ Am	662.4	3.64 E-06	3.64 E-06		3.619 E-06
²⁴¹ Am	722.0	1.96 E-06	1.96 E-06		1.889 E-06
²³⁸ Pu	766.4	2.19 E-07	2.2 E-07		2.177 E-07

5. Use of Standards

All of the adjustment processes ultimately depend upon comparison of a measured value with a reference value. Thus while gamma-ray isotopic composition measurements do not directly depend upon standards (Eq. II-5), we do rely heavily on comparison with standards for ultimate validation of the technique as well as the “fine tuning” of the analysis process such as we have just described. We have discussed analytical characterization issues in section IX. B. 1. It is worth repeating here that analytical characterization problems are not recognized to affect ²³⁹Pu and ²⁴⁰Pu. Some characterization and traceability issues are still present with ²³⁸Pu and ²⁴¹Am. Problems with characterization of the ²⁴¹Pu isotopic fraction are seldom seen in the modern analytical laboratory.

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The FRAM analysis of a gamma-ray spectrum can only be as good as the data will permit. Poor quality spectral data may limit the ability of FRAM to derive accurate results from the measurement, although the flexibility of FRAM's analysis gives one a better chance of a good analysis than any other analysis method. Still, it is good to keep in mind the computer saying, "garbage in, garbage out." This chapter will present information on choosing and setting up equipment for gamma-ray spectrum measurements to be used for FRAM analysis.

A. Choice of Detector

FRAM has been used with a wide variety of HPGe detectors, both planar and coaxial, as well as with CdTe detectors. One doesn't have to know the ultimate detector or application before acquiring FRAM because the single version of the code (as of late 2002) can make such a wide range of analyses. Usually, the detector procurement question will revolve around what size and type of HPGe detector to procure.

The first consideration is the mix of samples to be measured and their packaging. A coaxial detector is the appropriate choice for the user who makes a wide range of measurements on samples contained both in thin-walled and heavy-walled or shielded containers. Coaxial detectors can literally "do it all" with the exception of analysis in the 100-keV region. Planar detectors can be a very good choice for samples in thin-walled containers and are required if one wishes to make measurements in the 100-keV region.

When coaxial detector analysis with FRAM was first developed in the early 1990s, we carefully considered the question of a standard detector and standard data acquisition conditions. We worked with the detector manufacturers to specify the best quality coaxial detector of modest size (to minimize the cost and optimize resolution) that could be reliably produced. At the same time we carried over some standard specifications for high-quality planar HPGe detectors that already had a successful track record for isotopic analysis applications. These specifications formed the basis for the line of Safeguards Detectors marketed by ORTEC. The characteristics of these detectors are given in Table X-1.

Many other types of HPGe detectors have been used for FRAM applications. Waste measurement applications have used coaxial detectors of nearly 100% relative efficiency. The poorer resolution of these larger detectors may introduce some biases and require ROIs to be enlarged. We have used large semi-planar detectors (70 mm diam. by 30 mm thick) very successfully for both plutonium and uranium analysis. Measurements made through large thick-walled containers are usually improved if the coaxial detectors have higher efficiency than the "standard" 25% in Table X-1.

A 25% coaxial detector is usually adequate for almost any measurement if one can achieve a small sample-to-detector distance (say 5–10 cm). However, many real world applications require much larger sample-detector distances and profit from a larger-diameter, higher-efficiency detector.

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Table X-1. HPGe Detector Specifications for General-Purpose FRAM Usage.

Coaxial Detector	
Geometry	Coaxial, P-type germanium ¹
Crystal Size	Approximate “square” size (diameter $\geq$ length) commensurate with efficiency
Efficiency	At least 25% relative efficiency at 1.33 MeV in the usual definition
Low Rate (1000 cps)	≤ 750 eV at ≤ 6 - μ s shaping time ²
Resolution at 122 keV	≤ 870 eV at ≤ 2 - μ s shaping time
Low Rate (1000 cps)	≤ 1.75 keV at ≤ 6 - μ s shaping time
Resolution at 1.33 MeV	≤ 1.95 keV at ≤ 2 - μ s shaping time
High Rate (30 kHz)	≤ 880 eV at ≤ 2 - μ s shaping time
Resolution at 122 keV	
High Rate (30 kHz)	≤ 2.00 keV at ≤ 2 - μ s shaping time
Resolution at 1.33 MeV	
Peak Shape	[FW1/50M]/FWHM ≤ 2.50 at all count rates ≤ 30 kHz and time constants from 2–6 μ s
Preamplifier/Energy Rate	Resistive feedback preamplifier with Energy Rate $\geq 50,000$ MeV/s
Planar Detector	
Geometry	Planar
Crystal Size	≥ 25 mm diameter, ≥ 13 mm thick
Low Rate (1000 cps)	≤ 520 eV at ≤ 6 - μ s shaping time
Resolution at 122 keV	
High Rate (50 kHz)	≤ 580 eV at ≤ 1 - μ s shaping time
Resolution at 122 keV	
Peak Shape	[FW1/50M]/FWHM ≤ 2.50 at all count rates ≤ 50 kHz and time constants from 1–6 μ s
Preamplifier/Energy Rate	Resistive feedback preamplifier with Energy Rate $\geq 10,000$ MeV/s ³

¹ We specify P-type germanium because the resolution is usually better than that of N-type for the same detector size. N-type detectors have also been used successfully with FRAM.

² Shaping times are specified for analog amplifiers.

³ The preamplifier energy rate for a planar detector is a tradeoff with low-rate resolution. This specification assures that the preamplifier will allow a maximum counting rate above 50 kHz for a typical plutonium spectrum. A more stringent low-rate resolution specification may be achieved at the expense of the maximum preamplifier count rate.

B. Choice of Energy Range

Planar Detector With a planar detector, one has the choice of 1) analyzing plutonium data above 120 keV (typically taken in 4096 channels at a gain of approximately 0.1 keV/ch to include 120–420 keV) or 2) analyzing the 100-keV region (typically taken in 4096 channels at a gain of approximately 0.075 keV/ch to include 0–300 keV). The 120–420 keV analysis provides more penetrability and will work through 12–15 mm of steel that will defeat analysis in the 100-keV region. The 100-keV region analysis provides better precision for plutonium in thin-walled containers at the same counting time or equivalent

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or better precision at shorter counting times, compared to the higher-energy analysis. Planar detectors are not usually used for uranium analysis in the 120–1001 keV region but can be used for this analysis (Sampson 01) if required.

Coaxial Detector A coaxial detector provides the most versatile detector choice if one is limited to choosing just a single detector. It can analyze all the samples that a planar detector can plus it can analyze samples contained in very substantially-shielded containers, up to and including approximately 25 mm of lead (Hypes 00). The amount of shielding governs the energy range used in the analysis. “Bare” samples are analyzed starting at approximately 120 keV. Samples shielded with approximately 6 mm lead or less are analyzed starting at approximately 200 keV. Analysis of samples with more than 12 mm of lead starts at about 300 keV, as all gamma rays below that energy are removed by the shielding.

We have chosen a recommended data acquisition range for use with coaxial detectors. We typically acquire data in 8192 channels at a gain of 0.125 keV/ch spanning the energy range of 0–1024 keV. This range is very convenient as it allows analysis of both uranium and plutonium spectra with the same electronic settings.

Table X-2 (similar to table VI-2) shows the analysis range and gain (keV/ch) combinations that have been used successfully with FRAM. The standard or recommended settings are shaded. Those entries that are not shaded also work but other choices may be more appropriate. Some choices are noted as “not recommended.” These choices have produced successful analyses but in general, the keV/ch value is too high (the peaks are too narrow at low energies) to produce a reliable internal peak-shape calibration (section V. B. 1. d.). When FRAM is used under these conditions we perform the shape calibrations offline and fix the shape parameters in the parameter file.

Table X-2. Successful Analysis Ranges for FRAM. (Recommended Choices are Shaded).

Detector	Element	Analysis Range (keV)	Gain (keV/ch)	Comment
Planar	Plutonium	120 – 420	0.10	Not recommended ¹
	Plutonium	120 – 420	0.105	
	Plutonium	120 – 307	0.075	
	Plutonium	30 – 210	0.075	
	Plutonium	60 – 210	0.075	
	Uranium	120 – 1001	0.25	
Coaxial	Plutonium	120 – 460	0.125	Not recommended ¹
	Plutonium	200 – 800	0.125	
	Plutonium	300 – 800	0.125	
	Plutonium	120 – 460	0.25	
	Plutonium	120 – 460	0.50	
	Uranium	120 – 1001	0.125	
	Uranium	120 – 1200	0.156	
	Uranium	120 – 1001	0.25	

¹Combination of energy range and keV/ch not recommended. Peaks are too narrow at low energies for reliable shape calibration.

The use of FRAM under “not recommended” conditions usually arises because of the requirement to perform an isotopic analysis on data that was originally acquired for other purposes (see Appendix B) or

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because the user is constrained to use data acquisition/MCA equipment that does not allow the recommended keV/ch (Sampson 01).

The theoretical peak width at low energies can be found from the quoted detector resolution at 122 keV and the keV/ch of the measurement setup. Dividing the detector resolution by the keV/ch gives an approximate peak width at 122 keV. The recommended analysis ranges for both planar and coaxial detectors all have peak widths at 122 keV of between 5 and 6 channels. The peak width values are on the order of 1.5 to 2 channels for the conditions that are “not recommended.” Values below about 3 channels are generally not recommended.

C. Collection of Pulse Height Spectra

1. Electronics

Data acquisition electronics used to collect spectral data for isotopic analysis span the range from simple analog systems to highly sophisticated modern digital data-acquisition systems. Both types of systems have been implemented in mains-powered and battery-powered versions. The MCAs that record the spectra have advanced over the years from dedicated standalone desktop units to modern units consisting solely of a computer and MCA emulator software.

The functions necessary for data acquisition are best illustrated by noting the specific modules present in an analog NIM data acquisition system.

High-Voltage Bias Supply This module provides low-noise, high-voltage bias to the HPGe detector. Planar detectors usually operate in the range from 1000V to 2500V. Coaxial detectors usually operate in the range from 3000V to 5000V.

Preamplifier The preamplifier processes the pulse directly from the detector and provides an output pulse compatible with the input of the spectroscopy amplifier. The preamplifier is almost always an integral part of the HPGe detector and does not have to be procured separately. The user may be offered the choice between resistive feedback and pulsed optical feedback. Isotopic analysis systems use resistive feedback preamplifiers because of their superior throughput characteristics.

Spectroscopy Amplifier The spectroscopy amplifier processes the pulse from the preamplifier and produces a shaped, low-noise pulse of 0–10 V amplitude suitable for amplitude analysis. Commercial spectroscopy amplifiers with pole zero cancellation, baseline restoration, Gaussian and triangular shaping, and a time constant range from 0.5 to 8 μ s are the standard for a high-quality NIM system. Planar detectors use analog shaping times of 1–2 μ s while coaxial detectors typically operate in the 2–4 μ s range. Very large coaxial detectors may require an even longer time constant. These larger systems will suffer throughput degradation as a result of the longer time constant.

Digital Stabilizer A digital stabilizer will correct for gain and baseline drifts in the modules preceding it. Digital stabilizers are recommended to reduce peak broadening from electronic drift and to assure that peaks fall at their expected location. FRAM can accommodate significant peak drift when it finds the peaks for the internal energy calibration (see section V.B. 1. a.).

ADC The analog-to-digital converter converts the linear output of the analog amplifier to a digital signal. The clock speed in a modern Wilkinson type ADC should be a minimum of 100 MHz with 400–500 MHz ADCs being more desirable. Successive approximations ADCs with analysis times of less than 10 μ s are recommended. Little is gained using successive approximations ADCs with analysis times less than approximately 2 μ s as the analog amplifier’s pulse length will control the dead time in these cases.

MCA The multichannel analyzer used with a FRAM system should have a memory of at least 8192 (8K) channels if it is to be used with all detector types. Memory of 4096 (4K) channels is adequate for a system used only below 500 keV with planar detectors.

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All of these functions are integrated into smaller, portable, battery-powered systems suitable for field use. The portable MCAs also operate from mains power, making them useful in both the laboratory and the field. The small size and low power requirements of portable, battery-powered analog systems usually extract a toll in system performance when compared to NIM module systems (Sampson 01a).

Digital data acquisitions systems have now reached the stage of full commercial application. These systems remove the analog amplifier and ADC by digitizing the signal directly out of the preamplifier. Digital data acquisition systems are available in both portable and mains-powered units. They offer an expanded selection of time constants and simultaneously improve performance of both resolution and throughput over that from corresponding analog systems (Vo 98, Sampson 01a). Digital systems, even in their portable, battery-powered form, demonstrate performance superior to even the best analog systems. We recommend that new procurement of a data acquisition system for isotopic analysis be a digital system.

Vo has performed extensive testing of the performance of many commercially available data acquisition systems. The first tests (Vo 98) reported a comparison between the first commercially available completely digital spectroscopy unit with a standard NIM-based analog system. Further testing (Vo 99b) evaluated 9 different digital and analog MCAs with both planar and coaxial (up to 92% relative efficiency) detectors. Other tests (Vo 99c) compared first- and second-generation digital spectroscopy systems (DSPEC and DSPEC Plus) from ORTEC. The most recent testing (Vo 02a) has evaluated portable, battery powered digital spectrometer systems, the Inspector 2000 and the DigiDART, in comparison with a mains-powered digital system (DSPEC Plus) and an analog NIM system.

The web sites of Canberra and ORTEC (Canberra 02, ORTEC 02), the two major manufacturers of nuclear instrumentation, can be accessed for additional information on availability and application of nuclear instrumentation. These manufacturers provide a large amount of very useful information of direct applicability to FRAM measurements. FRAM, under license from Los Alamos, can be purchased from both manufacturers. Additional information concerning data acquisition for gamma spectrometry can be found in the PANDA (Passive Nondestructive Assay of Nuclear Materials) manual (Parker 91a).

2. Electronics Interconnections and Settings

In the previous section we listed the functions necessary for a data acquisition system, broken down to commonly available NIM modules. Below we show how these modules might be interconnected in a typical NIM system. The example is just one of the myriad ways one can connect the many available NIM modules from different manufacturers. We show specific modules from two different manufacturers as an example of a system that was assembled at Los Alamos. We wish to emphasize that other modules from the same or different manufacturers may be used. While the ADC, MCA, and digital stabilizer are usually chosen from the same manufacturer, the example below in Fig.X-1 shows a configuration that is an exception. Figure X-1 also contains a timer/counter, a module not included in the functional list given earlier. While this module is not required, it is very useful for monitoring the absolute counting rate coming out of the amplifier and is strongly recommended for every NIM-based FRAM system.

Figure X-2 shows a system with the same functionality using a digital data acquisition system. The interconnections are greatly simplified. A separate timer/counter is usually not required with the digital systems because they can display the count rate on the computer display.

Some typical system settings for plutonium measurements for an 8192-channel, coaxial detector system are shown in Table X-3. We recommend a 30-kHz maximum count rate for the coaxial detector system with analog electronics. We recommend a maximum counting rate of about 40–50 kHz for a coaxial detector used with a digital data acquisition system.

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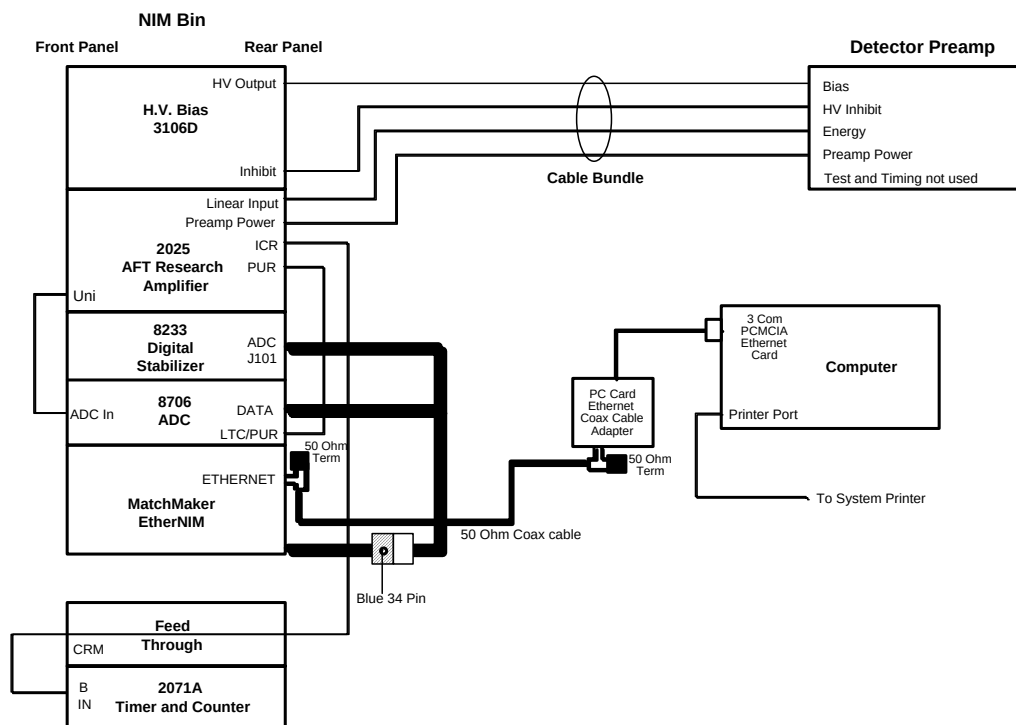
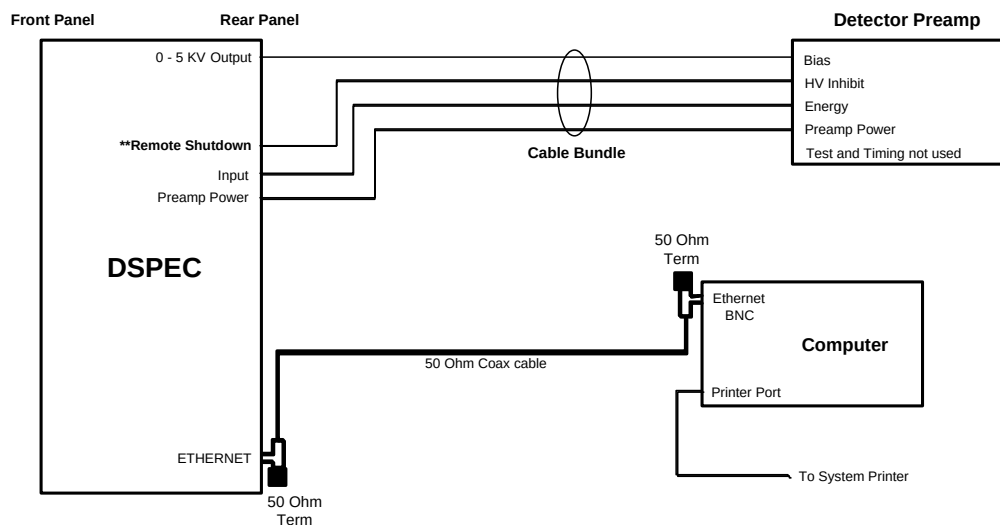


Fig. X-1. Interconnections of the electronics in an analog NIM system used for isotopic analysis with FRAM.



**** Remote Shutdown**---Check DSPEC manual for use with an incompatible (non ORTEC) detector.

Fig. X-2. Interconnections with a typical digital data acquisition system used for isotopic analysis with FRAM.

The digital stabilizer settings for both uranium and plutonium are shown. The first settings at 208 and 662.4 keV are recommended for plutonium because you can measure most shielded as well as unshielded samples without making any changes. Optional settings for plutonium when measuring and analyzing

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data in the 120–450 keV region are also given. The only change that is made when you switch measurements between uranium and plutonium is the setting of the digital stabilizer.

The other widely used option, a planar-detector system, uses 4096 channels at 0.1 keV/ch with a 10-keV offset collecting data from 10–420 keV (0–420 keV) for plutonium measurements. This gain and offset is historical, allowing an easy conversion of channel number to energy, and is not required. Indeed, it cannot be used with a DSPEC because of the lack of a zero adjustment on the DSPEC. A slightly lower gain of about 0.105 keV/ch with no zero offset also works well. The planar detector system typically uses a 1- μ s, triangular shaping time (equivalent to a 2- to 2.4- μ s rise time on the DSPEC), with zero stabilization at 129 keV and gain stabilization at 413.7 keV for plutonium. Its maximum count rate for an analog system is usually limited to less than 40 kHz.

Table X-3. Typical Analog System Settings (Coaxial detector, 8K ch, 0.125 keV/channel).

H. V. Power Supply

Kilovolts	(as required by detector)
Polarity:	positive (for most coaxial detectors, check to be sure)
Voltage dial:	(as appropriate for chosen unit)

Spectroscopy Amplifier

Coarse Gain:	as appropriate for detector
Fine Gain:	as appropriate for detector
Uni Shaping:	Triangle
PZ:	Auto
Shaping Time:	2 μ s
BLR Rate:	Auto
Input:	as appropriate for detector

ADC

Gain:	8K
Range:	8K
Offset:	0

Digital Stabilizer

Zero	Peak: ch 1664 (208 keV) plutonium
	Peak: ch 1034 (129 keV) plutonium (optional)
	Peak: ch 1486 (186 keV) uranium
Gain	Peak: ch 5299 (662.4 keV) plutonium
	Peak: ch 3310 (413.7 keV) plutonium (optional)
	Peak: ch 8008 (1001 keV) uranium

3. Counting Rate Considerations

The importance of the system's counting rate in the collection of high-quality spectra cannot be overestimated. Too high a counting rate may lead to degraded detector resolution, tailing caused by pulse pileup, and random sum peaks, all of which can lead to measurement biases. Conversely, very low counting rates yield spectra with fewer counts and poorer statistical precision. Increasing the counting time to compensate for low counting rates often leads to unacceptably low sample throughput rates. The

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counting rate–resolution–throughput tradeoff is one that needs to be evaluated for every measurement system and measurement situation. Many of the factors contributing to this question have been discussed in section IX.A.2 and have also been described by Parker (Parker 91a).

One of the first tests that a user can perform is the simultaneous measurement of throughput and resolution under realistic end-use measurement conditions. For these measurements the user selects a prominent peak in the spectrum and measures its net peak area and FWHM for a fixed counting time (true time or real time) while varying the input counting rate for a constant value of the time constant. The required peak areas and FWHMs can be obtained from the MCA or MCA emulator. The peak can be from a standard test source, ^{57}Co at 122 keV, ^{137}Cs at 661.6 keV, or more realistically from plutonium at 129.3 keV and 208.0 keV. The throughput and resolution can be plotted as shown in Fig. X-3 (shown previously as Fig. IX-1). The user then repeats the measurements for other time constants.

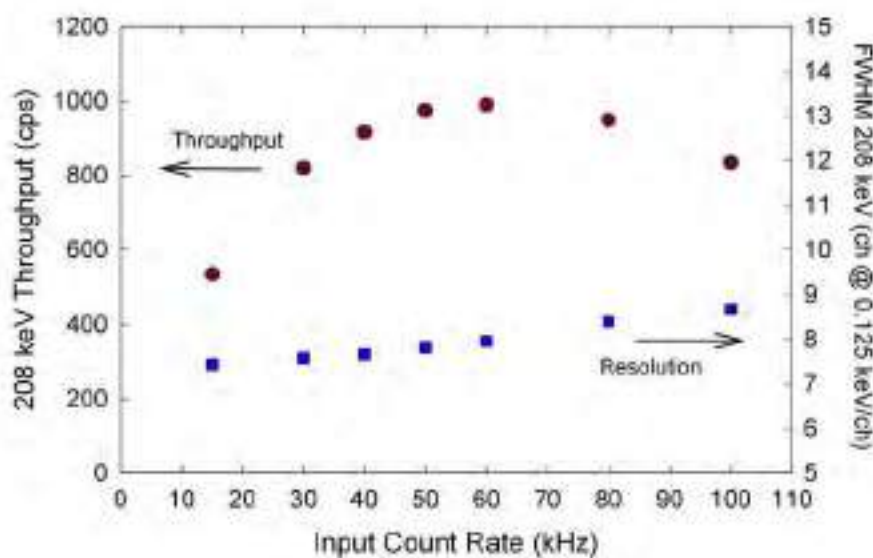


Fig. X-3. Throughput and resolution for 208-keV peak of ^{241}Pu – ^{237}U with 965 g PuO_2 with 16.85% ^{240}Pu , a 25% relative-efficiency HPGe detector, and an ORTEC DSPEC operated at 4 μs rise time.

Shorter time constants will usually increase the throughput, move the throughput maximum to a higher input rate value, and make the resolution poorer (larger FWHM). For analog systems, the resolution may worsen very rapidly at higher counting rates. If possible you should choose to operate at an input rate about 50%–70% of the rate at peak throughput. This operating point captures over 80% of the maximum throughput while minimizing the resolution.

There are measurement situations where the sample-to-detector distance is constrained and fixed. A large sample may produce an unacceptably high counting rate leading to resolution that is too poor for a successful FRAM analysis. These cases benefit greatly from the use of a digital spectrometer system. FRAM has been successfully used with a digital spectroscopy system operating with input count rates up to 100 kHz and has made bias-free analyses for all of the conditions displayed in the curves in Fig. X-3 above (Kelley 99).

The type of detector and analysis region chosen for the system can influence whether one chooses to optimize resolution or throughput. We give some general suggestions below.

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100-keV region, planar detector Optimization for measurements in the 100-keV region should concentrate on obtaining the best resolution at the expense of throughput. The larger branching intensities in this region can make up for lowered throughput arising from increasing the time constant to 2 μ s or even 3 μ s from the usual 1- μ s time constant.

120–420 keV region, planar detector Optimization in this case usually concentrates on maximizing throughput by use of a 1- μ s time constant and perhaps increasing the area of the detector. Resolution is secondary because we routinely use coaxial detectors with great success in this same region. Coaxial detector resolution at 122 keV is typically 1.5 times larger than that of a planar detector.

120–450 keV region, coaxial detector We tend to optimize for throughput in this region because of the lower intrinsic intensity of the gamma rays. Digital spectrometer use can simultaneously improve resolution and throughput for this case. Analog time constants can be as low as 2 μ s for top quality 25%–30% relative-efficiency coaxial detectors. Higher-efficiency detectors usually require a longer time constant.

200–800 keV region, coaxial detector This region is difficult to optimize. The intrinsic plutonium gamma-ray intensities are low, which calls for larger, generally poorer-resolution detectors. The peak fitting in the 637–646 keV peak region, containing five peaks including the important ^{240}Pu peak at 642.5 keV, demands the best possible resolution. Digital spectrometers improve the measurements in this region allowing FRAM to work at input rates as large as 100 kHz (Kelley 99).

120–1024 keV region, coaxial detector, uranium The uranium spectrum is not as complex as for plutonium and does not demand as good resolution. Systems for uranium can usually be optimized for throughput.

4. Pulse Pileup

a. Coincidence Summing

Coincidence summing occurs when two gamma rays are emitted in coincidence from cascade decay. It is possible for these two gamma rays with energies E_1 and E_2 to be detected simultaneously in the HPGe detector in a much shorter time than the resolving time of the pulse processing electronics. The result is a new, full-energy peak at the energy of the sum of the two gammas, $E_{\text{sum}} = E_1 + E_2$. More important for isotopic analysis measurements is the diminution of the individual peak areas at E_1 and E_2 from this summing. Coincidence summing is dependent on the isotope and decay scheme and does not cancel out in isotopic analysis measurements as random summing does. The effect is proportional to the solid angle of the detector as seen from the sample and can be reduced by increasing the sample-to-detector distance. Vo (Vo 99a) has studied this problem extensively. He finds that coincidence summing for uranium measurements can be important for small sample-to-detector distances (less than 5–10 cm). The effect becomes unimportant for distances exceeding approximately 15 cm but that sample-to-detector distance usually leads to very low counting rates for low-enriched uranium samples. This makes the correction for coincidence summing very important for good FRAM performance. We have briefly discussed, in section IX.D.3, the results of the coincidence summing corrections in version 4 of FRAM on uranium measurement bias.

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b. Random Summing

Random pulse pileup occurs when two pulses from independent decays arrive at the detector with a time separation shorter than the pulse-processing time of the analysis system. The output of the analysis system will be a single distorted pulse with a pulse height that is not related to either input pulse. When the pileup occurs from random events it can be minimized by a proper pole-zero cancellation adjustment on the analog amplifier, or the proper pulse shape optimization on a digital spectroscopy system. Pileup rejection circuitry in modern amplifier systems can reject the storage of these pileup pulses if they can be resolved by the timing circuitry of the pileup rejector, which is typically on the order of 0.5 μ s.

In addition to the electronic pileup reduction methods there are also two system setup conditions that affect random pulse pileup. Pulse pileup can be reduced by operating at a shorter time constant or by operating at a lower counting rate.

Pulse pileup can affect an isotopic analysis measurement. The principal effect of random pulse pileup is to add misshapen peaks and structure to the spectrum. If these additional peaks fall inside a peak or background region defined in the parameter file, the analysis of that region will likely result in a bias. An example of random summing or random pulse pileup is shown in Fig. X-4 and tabulated in Table X-4. This example shows the summing of the 59.54-keV ^{241}Am peak with several peaks in the 100-keV region. The arrows show the location of the full energy of the sum peaks. The random sum peak that falls directly under the 160.3-keV ^{240}Pu peak is especially important. Its presence will cause a bias in the 160.3-keV peak area and its presence may not be noticed if the other sum peaks are weak.

Random summing is assumed to result in peak losses that are equal throughout the entire spectrum. Thus, isotopic ratio methods should be unaffected by the peak losses. This assumption may not hold precisely because peak widths increase with energy, but it appears that the peak losses occurring from random summing do not materially affect isotopic ratio measurements.

5. Filtering

Spectroscopists place absorbing materials or “filters” in front of the detector when they want to preferentially absorb lower-energy radiation that is not useful for the measurement. Filters are typically chosen to have their K-absorption edge near to but below the energy of the radiation to be absorbed. This maximizes the absorption of the filter and minimizes its effect on higher-energy gamma rays. The removal of unwanted low-energy gamma rays eliminates them as a source of pulse pileup summing, both random and coincidence summing.

The 59.54-keV gamma ray of ^{241}Am is most often targeted for filtering. The activity of this gamma ray is about 3–5 orders of magnitude greater than that of any other widely used plutonium gamma ray. This gamma ray will dominate the spectrum of any plutonium in a thin-walled container, often being many thousands of times more intense than any other gamma ray in the spectrum. Even when filtered, its presence can disturb the spectrum by random summing, as has been shown in Fig. X-4. If not filtered, the dead time produced by the analysis of this gamma ray will prevent any useful spectroscopic information from being recorded. The unfiltered counting rate from this gamma ray can be so intense as to paralyze the detector and counting electronics.

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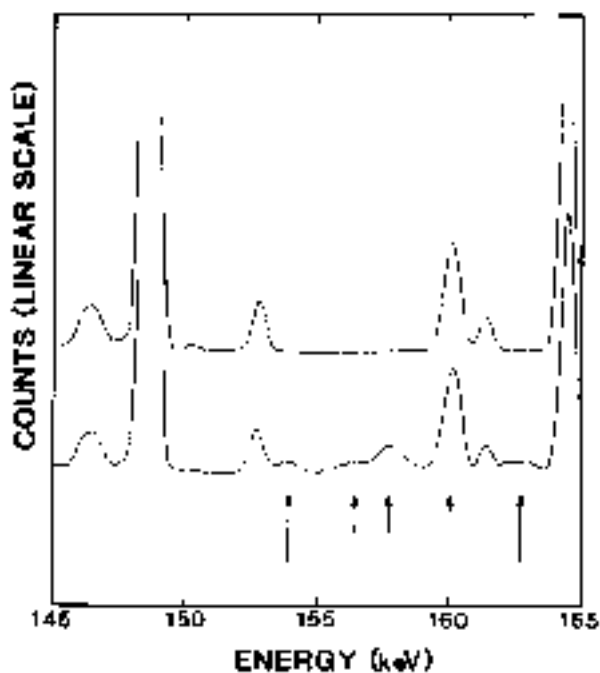


Fig. X-4. The effect of random pulse pileup on the 160 keV region of the plutonium spectrum from a planar HPGe detector can be dramatic. The top trace is a spectrum without pileup peaks. The bottom trace shows the effects of pileup of the 59.54 keV ^{241}Am peak with other peaks in the 100 keV region. The arrows mark the location of the pileup peaks.

Table X-4. Strongest Sum Peaks from ^{241}Am 59.54 keV and 100-keV region Peaks.

100-keV region Peak Energy (keV)	Origin	Sum Peak Energy (keV)
94.66	UK α 2	154.20
97.07	NpK α 2	156.61
98.44	UK α 1	157.98
101.07	NpK α 1	160.61
102.97	^{241}Am	162.51
103.75	PuK α 1	163.29

Thin sheets of cadmium (Cd, $Z = 48$, K shell binding energy = 26.71 keV) are most widely used for filtering a plutonium spectrum. This material can be cut into disks and placed on the detector's end cap or can be wrapped around the sample. Tin (Sn, $Z = 50$, K shell binding energy = 29.20 keV) is used in situations where environmental concerns preclude the use of cadmium. Lead (Pb, $Z = 82$, K shell binding energy = 88.00 keV) is also used because of its wide availability.

A widely used "rule of thumb" is that the filter for a plutonium measurement should be thick enough to reduce the intensity of the 59.5-keV gamma ray of ^{241}Am to the same magnitude as the intensity of the 100-keV complex of gamma rays and x-rays. When this condition is met one does not observe pileup in the 160-keV region (see top trace in Fig. X-4).

The FRAM systems used at the Los Alamos Plutonium Facility measure the isotopic composition of plutonium over a very wide range of ^{241}Am content (from less than 100 ppm to more than 500,000 ppm) where ppm is parts per million with respect to total plutonium. This dynamic range of nearly 10,000 makes it difficult to optimize the amount of filtering for all measurements. At Los Alamos we have

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chosen to use a single filter for all measurements, a filter that is thick enough to filter the ^{241}Am 59.5-keV gamma ray at the highest concentrations. The choice of a single filter is made for operational purposes so the instrument operator does not have to make any filtering decisions.

The filter used at Los Alamos consists of approximately 0.080 in. of Cd backed by 0.010–0.020 in. of copper. This total cadmium thickness of approximately 2mm is the same thickness recommended by the IAEA for their plutonium inspection/verification measurements. The purpose of the copper (or like Z material) is to absorb any x-rays produced in the cadmium. We use this type of graded filter to keep the portion of the spectrum below 80 keV as free as possible from photopeaks. This minimizes pileup summing originating from strong, low-energy peaks. We adhere to the philosophy that any low-energy peak (below 100 keV) that is not used in the analysis is a “bad” peak. It cannot help in the measurement and may hurt the measurement by contributing to sum peaks.

The “one-size-fits-all” filter does degrade the intensity of useful photopeaks below 200 keV. Measurement precision for the ^{241}Am peak at 125.3 keV and the ^{240}Pu peak at 160.3 keV can be improved if one uses less filtering for samples with ^{241}Am less than 10,000 ppm. The precision of measurements in the 100-keV region will usually be improved using filters that are less than 0.080 in. of cadmium because the sum peaks do not fall into an energy region that is used in the analysis. The user, for each specific measurement situation, can carry out the optimization of cadmium thickness. Table X-5 displays the transmission of common filter components at several important gamma ray energies. The results for tin will be approximately the same as for cadmium. The transmission of copper used to filter x-rays from cadmium is shown in Table X-6.

Table X-5. Transmission of Common Filter Components.

Energy (keV)	Cadmium			Lead	
	0.016 in	0.032 in	0.080 in	0.016 in	0.032 in
59.5	0.127	0.016	0.000032	0.118	0.014
104.2	0.638	0.407	0.105	0.109	0.012
125.3	0.756	0.571	0.247	0.251	0.063
160.3	0.856	0.733	0.461	0.474	0.224

Table X-6. Transmission of Copper Used to Suppress X-rays from Cadmium.

Energy (keV)	Copper	
	0.010 in	0.020 in
26	0.027	0.0007

6. Shielding

The shielding used around the HPGe detector for analysis of plutonium isotopic composition is usually tailored to the energy range of the analysis; the main purpose of the shielding is to reduce direct photopeak interferences from other plutonium stored in the vicinity of the measurement system. A system making high-energy measurements in the 600–800 keV range requires more shielding than a system used in the 100-keV region. If size, space, and weight constraints permit, the shielding around the

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lateral surface of the detector should provide an attenuation of at least a factor of 100 for the highest-energy gamma ray critical to the analysis. Back shielding or shielding behind the detector is certainly desirable if the detector's cryostat and dewar design permit. Most isotopic systems use minimal collimation in front of the detector and thus will benefit from shadow shielding behind the sample.

The shielding for direct photopeak interferences is of primary importance, as these interferences will directly bias the measurement. The shielding for continuum gamma rays is of secondary importance. Background gamma rays falling in the continuum will worsen measurement precision but usually will not bias the measurement.

Lead (Pb) and machinable tungsten (W) are commonly used for shields. Lead is an environmental hazard and is often canned into a steel container to alleviate that concern. Machinable tungsten is used where maximum shielding is required for minimum size and is usually used without the necessity for additional canning. Tungsten is, however, very expensive, precluding its use in many cases. Table X-7 below shows the thickness of lead and tungsten shields required to provide a factor of 100 attenuation at commonly used analysis energies.

Table X-7. Thickness in cm (in.) for Factor of 100 Attenuation.

Energy (keV)	Pb ($\rho = 11.35$)		W ($\rho = 15$)	
104	0.084	(0.033)	0.080	(0.032)
185	0.362	(0.143)	0.351	(0.138)
208	0.476	(0.187)	0.461	(0.181)
414	2.00	(0.787)	1.82	(0.715)
662	3.94	(1.55)	3.33	(1.31)
766	4.61	(1.82)	3.84	(1.51)
1001	5.97	(2.35)	4.83	(1.90)

The weight of the shield becomes an overriding consideration for portable measurement systems, which are often operated with inadequate shielding simply because of the weight. Sampson (Sampson 99c) describes uranium isotopic measurements with FRAM on UF_6 cylinders arranged in a stacked array, a commonly found condition. Because FRAM uses energies up to 1001 keV, he concluded that the measurements using a portable hand-held HPGe detector suffered from inadequate shielding (~ 0.5 in. Pb was used) even when using the thickest shield that was practical for mobile measurements.

We have used FRAM at the Los Alamos Plutonium Facility in a mobile, mains-powered system that can be easily transported to the measurement site. Figure X-5 shows this system as initially configured on a commercial thyroid scanner cart and Fig. X-6 shows the system in use measuring a 200-liter waste drum. This system uses approximately 0.75 in. of machinable tungsten shielding which Table X-7 shows provides about a factor of 100 attenuation at 414 keV.

Fixed station FRAM systems are usually configured with at least a 2-in.-thick lead shield around the lateral surface whether used with a coaxial or planar HPGe detector. This configuration will provide a factor of 160 attenuation at 766 keV, the highest-energy routinely analyzed in a shielded-sample measurement.

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Fig. X-5. A mobile PC/FRAM system configured on a commercial thyroid scanner cart for use at the Los Alamos Plutonium Facility. The shielding around the detector is 0.75 in. of machinable tungsten.



Fig. X-6. A mobile FRAM system measuring the isotopic composition of the contents of a 200-liter waste drum.

Table X-7 shows that for the same attenuation, a machinable tungsten shield will be thinner than a lead shield. This leads to tungsten shields that are more compact than lead shields. The actual design and dimensions of the shield will determine if the tungsten shield is lighter. For a cylindrical shield with a 3-in. inner diameter typically used for HPGe detectors, tungsten and lead with $\times 100$ attenuation will have essentially the same mass per unit length.

XI. MODIFYING PARAMETER FILES FOR SPECIAL CASES

XI. MODIFYING PARAMETER FILES FOR SPECIAL CASES

A. Standard Parameter Files

The distribution of FRAM includes several standard, general-purpose parameter files for plutonium analysis in various energy ranges and also a parameter file for uranium analysis. These parameter files can be used for most routine analyses and can also be used as the basis for building a parameter file for special problems. Two parameter files are listed in Appendix C. The first is for plutonium analysis with a coaxial detector in the 120–450 keV region. The second is for uranium analysis with a coaxial detector in the 120–1001 keV energy range.

The standard parameter file for coaxial detector analysis of plutonium in the 120–450 keV region (Coax_Widerange3) analyzes for $^{238-241}\text{Pu}$ and ^{241}Am and obtains ^{242}Pu by either a correlation or operator entry. The results are presented as wt % relative to total plutonium with ^{241}Am presented in units of $\mu\text{g }^{241}\text{Am/gPu}$. In addition, the analysis directed by this parameter file quantifies the ratio of several other isotopes (^{237}Np , ^{235}U , and ^{239}Np – ^{243}Am) with respect to total plutonium. Typical results for the plutonium isotopes and ^{241}Am as well as limited results for ^{235}U have been previously discussed. We are not able to present any comparisons for ^{237}Np and ^{239}Np – ^{243}Am because samples with certified values of these isotopes are not available.

The standard parameter file for coaxial detector analysis of uranium in the 120–1001 keV region (U121_1001Coax) directly analyzes for ^{234}U , ^{235}U , and ^{238}U . Uranium-236 does not have any detectable gamma rays and is determined by an empirical correlation (or operator entry), much in the same manner as for ^{242}Pu . The correlation calculation for ^{236}U is unique to FRAM, version 4. This parameter file has been demonstrated to work over the enrichment range from 0.2% to more than 99% ^{235}U . Results for the ratio of $^{228}\text{Th/U}$ are presented for each analysis. The specific power in watts/gU is also calculated, as calorimetry is a practical measurement method for multi-kg quantities of highly enriched uranium.

B. General Approach to Parameter File Modification

The parameter files delivered with FRAM are suitable for almost every routine application. Nevertheless, it is desirable to be able to modify a parameter file for special analyses. The user has password-protected control over five groups of parameters, previously discussed in Chapter VI.

- Fitting parameters
- Peaks
- Regions
- Isotopes
- Application Constants

1. Start With Existing Parameter File

It is almost always easiest to start with an existing parameter file and edit existing values rather than start from a completely new and empty parameter file. One accesses the parameter file by entering the Password-protected Change Parameter Utility **Edit | Parameters**. Then one selects the parameter file in **File | Open** and chooses the parameter file from the pull down menu that is presented.

2. Set Energy Calibration Defaults and Isotopes for Analysis

The Default Energy Calibration can be accessed from the Change Parameter Utility after choosing **Edit | Fitting parameters**. These two parameters are changed to accommodate spectra with different energy calibrations. Set the **Gain (keV/ch)** and **Offset (keV)** to match the spectra being analyzed. We have already discussed acceptable values for these parameters in section X.B.

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The other default values for the FWHM parameters and tailing parameters can usually remain at their default values as long as the new energy calibration is not significantly different from the old one. If the change is more than 50%, new values should be obtained from the medium printout of the analysis of a good quality spectrum where all fitting parameters are NOT Fixed.

Designate the isotopes to be used in the analysis by selecting **Edit | Isotopes** in the Change Parameter Utility. This window has been discussed in section VI.C.4.

3. Select Gamma-Ray Peaks for Analysis

Next the user enters the information on the peaks to be analyzed after selecting **Edit | Peaks** in the Change Parameter Utility. The parameters in this window have been discussed in section VI.C.2.

4. Select Regions for Analysis

The boundaries of the regions for analysis and the background regions are entered next as discussed in section VI.C.3. The selection of region boundaries is somewhat of an art. It is not difficult to do for a single specific spectrum and can be done in many equally acceptable ways in this case. It does become more difficult if one wants to make the new parameter file applicable to a wider range of samples. In this case one must be especially aware of the positioning of the background ROIs. An ROI that is satisfactory for one spectrum may not be applicable to another spectrum that has additional interference isotopes present. Changing ^{241}Am concentrations can be troublesome in this regard and it is best to guide your region setup using a spectrum with the highest ^{241}Am concentration available. A listing of gamma rays from the plutonium isotopes and ^{241}Am , such as is found in Appendix D (Gunnink 76a), is useful for setting up both the region boundaries as well as the gamma-ray peaks.

5. Select Peaks for Internal Calibrations

The user now designates the peaks to be used in the internal calibrations, although this can also be done when the peaks were selected (sec. XI.B.3 above). This is a critical part of the parameter file setup because poor internal calibrations will quickly invalidate an analysis. Sometimes this is all that has to be done to modify a parameter file. Peaks chosen for internal calibration of energy, FWHM, and peak shape should be, to the greatest extent possible, clean single peaks. Peaks selected for the internal shape calibration should be completely free from interferences to at least $1.5 \times \text{FWHM}$ below the peak centroid.

The piecewise linear internal energy calibration requires a minimum of two peaks. The FWHM calibration requires a minimum of three peaks, preferably sampling the extremes of the analysis range. The shape calibration should also come from peaks at high and low energies. Two peaks are sufficient but they should be intense peaks so that the tailing can be pulled out of the noise. The shape calibration requirements are often the most difficult to satisfy and lead to our recommendation of fixing the shape parameters for most analyses.

One can recalibrate the shape parameters offline if they seem to have changed. You observe this by examining the peak fits using **Options | Display Fits**. Poor fits in the tail region are a signal that the shape calibration should be updated. Acquire several spectra with good counting statistics and analyze them with the shape parameters set to be free (remove the check in the Fixed box for the Default tailing constants, Edit Fitting Parameters, Change Parameter Utility). Updating of shape parameters should be infrequent but will probably need to be done as the detector ages and absorbs neutron damage over its lifetime. Enter the new parameters obtained from a medium printout and continue analysis, fixing the new parameters.

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6. Edit Application Constants

The user can edit the Application Constants last as most of these constants do not affect the analysis. To clean up the application constants the user should first make sure that the peak channels in the diagnostic tests agree with the default energy calibration, because the diagnostic test channels are not linked to the default energy calibration. One should check that the interference peaks are appropriate for the data to be analyzed. The user will usually not change the isotopic correlation constants for ^{242}Pu or ^{236}U or change the FRAM SUMMARY TYPE.

The penalty for not changing the application constants is often a large number of error messages. The messages usually do not signify that anything is wrong with the analysis but are very disconcerting to an auditor looking over formal measurement results. Be sure to clean up the application constants before any new parameter file is put into formal use.

C. Discussion of Special Cases

In the following sections we will discuss examples of parameter file modifications made to analyze spectra not readily analyzed by the standard parameter files delivered with FRAM. The average user may not encounter very many, if any, of these cases. However, we believe the discussion will make the user more familiar with FRAM's versatility and guide the user to the modifications required to address their own special cases. The Los Alamos Safeguards Science and Technology staff is also available to help users with unusual analysis problems.*

1. Very Low Plutonium-240

This material type can be defined roughly as having a ^{240}Pu content less than approximately 2%. Spectra from these materials usually have very little ^{241}Pu so the ^{241}Pu - ^{237}U peaks may not be strong enough to use for internal calibrations. Plutonium-239 lines are strong and suffer little interference because of the low ^{241}Pu and ^{238}Pu content in the sample. The gamma-ray lines from ^{239}Pu at 129, 203, 345, 414, and 451 keV are ideal to use for the internal calibrations. Figure XI-1 displays the 120–210 keV portion of a gamma-ray spectrum from a plutonium sample with 2% ^{240}Pu . At these low levels, the 208-keV gamma ray from ^{241}Pu - ^{237}U is less intense than the ^{239}Pu gamma ray at 203.5 keV. This is just the reverse of what is usually seen in plutonium spectra from higher burnup samples. This spectrum represents the approximate limit of the analysis range of the standard parameter files supplied with FRAM. The analysis can be improved by removing weak ^{241}Pu - ^{237}U peaks from the internal calibrations. Note that the 152.7-keV ^{238}Pu peak is essentially undetectable.

We have analyzed the isotopic composition of research grade samples of pure ^{239}Pu with FRAM. One such analysis compared with the mass spectrometry certificate values is shown in Table XI-1. FRAM also obtained values for ^{238}Pu , ^{241}Pu , and ^{241}Am at extremely low levels but still much higher than the certified values. These FRAM values are thought to arise from interference and increased background from other plutonium samples in the vicinity of the measurement.

* A Word Regarding Analysis of Isotopically Pure Samples: The results that are shown, for cases in which the major isotope comprises over 99% of the sample, can be somewhat misleading. FRAM is able to obtain results for these analyses in all cases whereas analysis with other codes fails completely. That is the good news. The absolute error and bias on the major isotope results is extremely small but the user may see very large relative errors for the minor constituents. Each analysis must be examined for the causes of the minor isotope errors. Many times the peaks from the minor isotopes are simply below the level at which FRAM or any gamma-ray analysis code can analyze. Other sources of error at these ultralow levels can arise from background from plutonium stored in the vicinity of the measurement or background from neighboring measurements. The normalization condition – all of the plutonium isotopic fractions must sum to unity – more or less guarantees that the 99+ % abundant major isotope will be measured accurately. The minor constituents are another story.

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Research grade samples with 99+ % ^{240}Pu do require parameter file modifications. Plutonium-239 lines are too weak for use in determining the relative-efficiency or performing the internal calibrations. The samples of this type that we have seen do have some strong lines from the small amounts of the minor isotopes such as ^{238}Pu , ^{243}Am - ^{239}Np , ^{237}Np , and ^{241}Am . We use gamma-ray lines from these isotopes for the internal calibrations and the relative-efficiency curve. Spectra from these very high purity samples also exhibit some of the weak gamma-ray lines from ^{240}Pu that are not visible in normal spectra. These lines at 212 and 687 keV may be used in the analysis for activity and relative efficiency. We analyze the entire energy range from 120 keV to 800 keV.

Table XI-3. FRAM Analysis of a Sample with 99.9+ % ^{240}Pu .

	Pu-240
FRAM measured	99.860
Mass spectrometry	99.935

3. Very High Neptunium-237

In the United States we account for ^{237}Np at the gram level just as for plutonium. This isotope is present in almost every plutonium sample as a direct decay product of ^{241}Am and the ^{237}U daughter of ^{241}Pu . The levels vary as a function of the age of the sample, the burnup of the sample (initial ^{241}Pu content), and the chemical processing history. The Los Alamos archival plutonium samples used to characterize FRAM performance (see Table F-1, for example) have $^{237}\text{Np}/\text{Pu}$ ratios in the range from 10^{-5} to 10^{-3} . The standard plutonium parameter files for analysis in the 120–450 keV region and the 200–800 keV region delivered with version 4 of FRAM quantify the $^{237}\text{Np}/\text{Pu}$ ratio on every measurement without the need for any operator intervention (see Fig. IX-4).

We characterize the concentration of ^{237}Np in plutonium by analysis of the gamma rays from its ^{233}Pa daughter ($T_{1/2} = 27.0$ d). The gamma-ray activity from ^{233}Pa will be in secular equilibrium with ^{237}Np after about 150 days. This condition does not present a problem except for materials fresh from chemical processing. The decay of ^{233}Pa produces intense gamma rays at 271.5, 300.1, 311.9, 340.5, 375.4, 398.5, and 415.8 keV that can be used for the quantification of the $^{237}\text{Np}/\text{Pu}$ ratio and/or must be considered as interferences for the plutonium isotopic composition measurement. Table XI-4 tabulates the branching ratios for these gamma rays.

For “normal” $^{237}\text{Np}/\text{Pu}$ ratios in the range from 10^{-5} to 10^{-3} we quantify $^{237}\text{Np}/\text{Pu}$ using the 312.2-keV line. We also account for the 375.4 and 415.8 keV lines because of their interference with prominent ^{239}Pu gamma rays.

Plutonium-bearing samples containing ^{237}Np at levels above a $^{237}\text{Np}/\text{Pu}$ ratio of approximately 10^{-2} usually require additional analysis. (Figure XI-2 shows a spectrum with a concentration near this limit.) At this level the 312-keV gamma ray is the most intense gamma ray in the spectrum. The ^{233}Pa gamma rays begin to contribute significantly to the dose from the sample. At Los Alamos, samples containing significant quantities of ^{237}Np are usually packaged in lead- shielded containers to reduce the dose to those who handle the samples. The lead shielding eliminates all gamma rays below 200 keV, necessitating analysis in the 200–800 keV region. This analysis with a suitably modified parameter file works up to $^{237}\text{Np}/\text{Pu}$ ratios of approximately 1 for samples shielded with 3 mm of lead. At a $^{237}\text{Np}/\text{Pu}$ ratio of approximately 1 the ^{233}Pa gamma rays dominate

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Table XI-4. A Partial List of ^{233}Pa Gamma Rays (Firestone 96).

Energy (keV)	Branching Ratio
271.5	0.00328
300.3	0.0662
312.2	0.386
340.8	0.0447
375.4	0.00679
398.5	0.0139
415.8	0.0175

the spectrum, making the analysis of the plutonium gamma rays very difficult (see Fig. XI-3). Sum peaks from the intense ^{233}Pa gamma rays dominate the region around 640 keV. FRAM can analyze spectra from samples shielded with 3 mm of lead with $^{237}\text{Np}/\text{Pu}$ ratios up to approximately 2. With suitably modified data acquisition conditions (addition of extra lead filtering) we would expect to be able to analyze spectra with $^{237}\text{Np}/\text{Pu}$ ratios up to approximately 10.

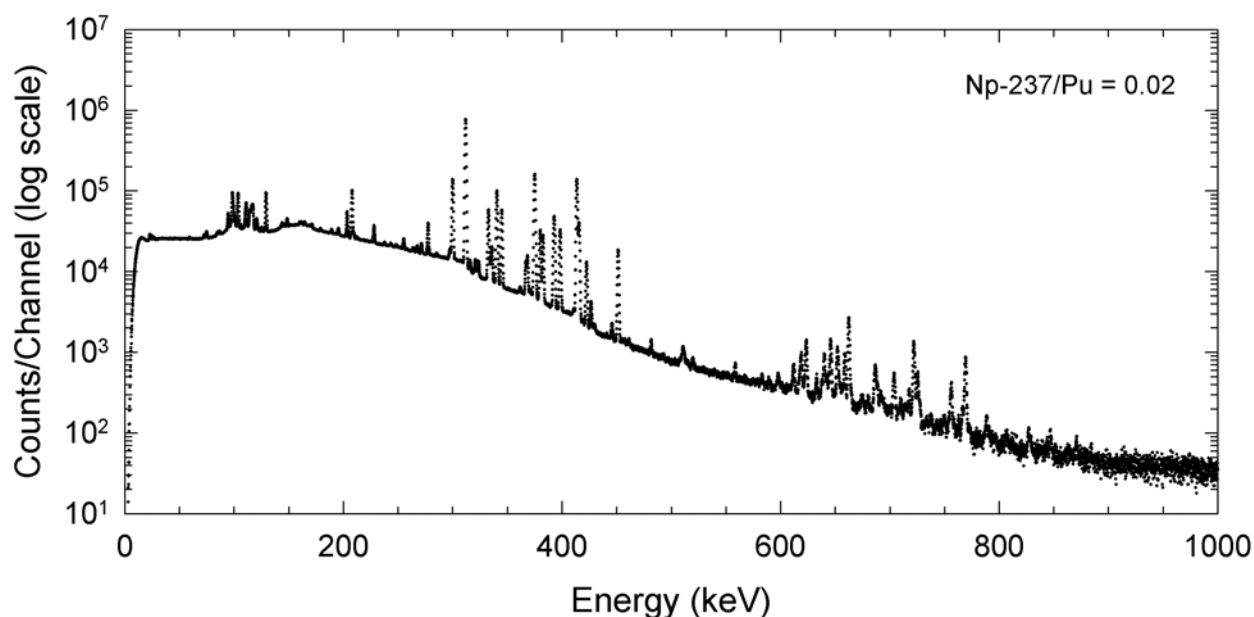


Fig. XI-2. A plutonium spectrum, measured with a coaxial detector, from an unshielded sample with a $^{237}\text{Np}/\text{Pu}$ ratio of 0.02. This concentration is at the upper end of the range that can be analyzed with standard FRAM parameter files. The most intense peak in the spectrum is the 312-keV gamma ray from the ^{233}Pa daughter of ^{237}Np , but all the major plutonium gamma rays are visible. This spectrum can be analyzed in either the 120–450 keV region or in the 200–800 keV region.

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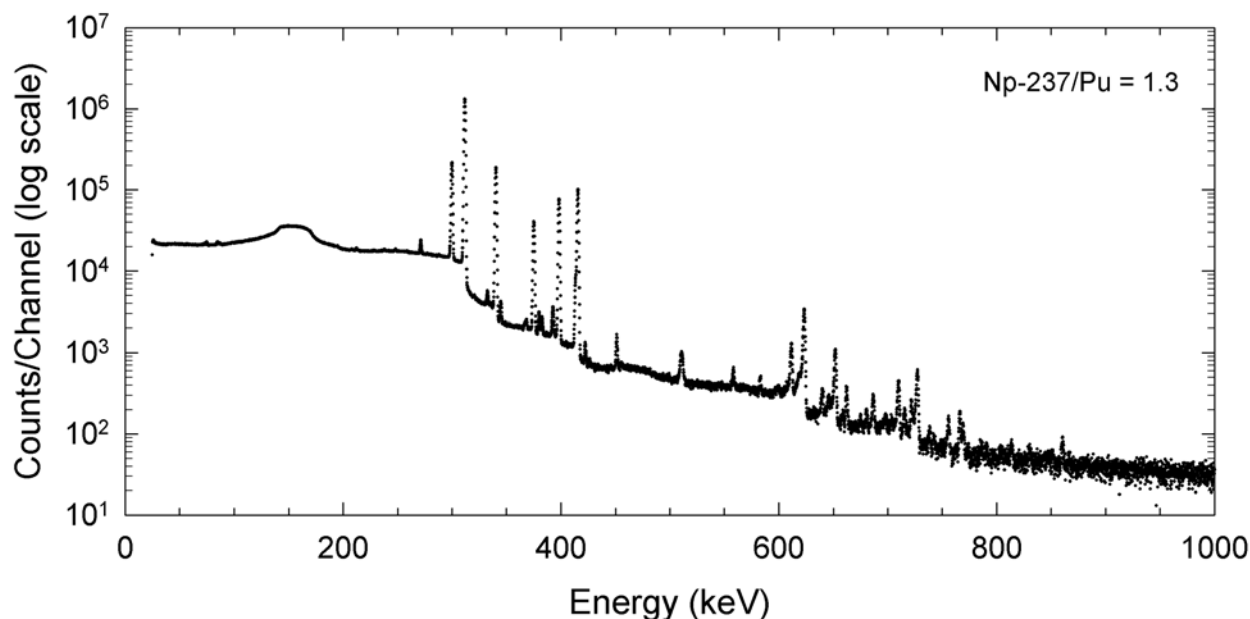


Fig. XI-3. A plutonium spectrum, measured with a coaxial detector, from a shielded sample with a $^{237}\text{Np}/\text{Pu}$ ratio of 1.3. This concentration is at the upper limit for analysis with a specially modified parameter file for high neptunium. The six major peaks in the 300–400 keV region are all ^{237}Np related. They overpower the plutonium peaks in this region. The three most intense peaks in the 600–650 keV region arise from sum peaks from ^{233}Pa gamma ray and likewise overpower the plutonium gamma rays in this region.

4. Very High Americium-241

There is naturally a continuum of $^{241}\text{Am}/\text{Pu}$ concentrations that FRAM measures. The concentration that qualifies as “very high ^{241}Am ” is ill defined, but falls in the range of $^{241}\text{Am}/\text{Pu}$ greater than 0.1. This is a convenient dividing line because most plutonium samples containing ^{241}Am solely from the decay of ^{241}Pu will be at levels below this limit. Americium-241 concentrations above 10% relative to plutonium usually arise only in residues and wastes containing ^{241}Am concentrated from purification processes.

The ^{241}Am in a typical plutonium sample produces almost as many gamma rays as ^{239}Pu . The ^{239}Pu isotopic fraction may change by less than a factor of two over the entire range of plutonium samples encountered. In comparison, the $^{241}\text{Am}/\text{Pu}$ ratio may change over a range of 10^6 considering all of the material streams in a plutonium processing facility. Ratios of ^{241}Am to plutonium may approach 1:1 in residues from purification processes.

Problems arise in the analysis of the gamma-ray spectra from very high concentration americium samples in several areas:

1. Americium gamma-ray activity will dominate the spectrum. The peaks remaining from plutonium that haven’t been swamped by americium gamma rays will ride on top of a large continuum from the americium gamma rays. The resulting signal/background ratio will be poor and the plutonium gamma-ray peaks will have poor statistical precision.
2. Americium peaks normally too weak to be visible above the background continuum will suddenly appear in the spectrum. These “new” peaks interfere with peak and background ROIs established for analyses of samples with “normal” americium concentrations.

The second problem can be handled by using a spectrum with a very high ^{241}Am concentration to guide the set up of the peak and background regions. The first problem is more or less intractable as it resides in the data. At Los Alamos, items containing $^{241}\text{Am}/\text{Pu}$ greater than 0.1 are often packaged in lead-lined

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containers, making it necessary to analyze the data in the 200–800 keV region and extracting ^{240}Pu at 642 keV. The data in Fig. XI-4 show that the analysis for ^{240}Pu in this region can be difficult to essentially impossible for samples with very high ^{241}Am because the ^{241}Am peak at 641.5 keV swamps the ^{240}Pu peak at 642.6 keV.

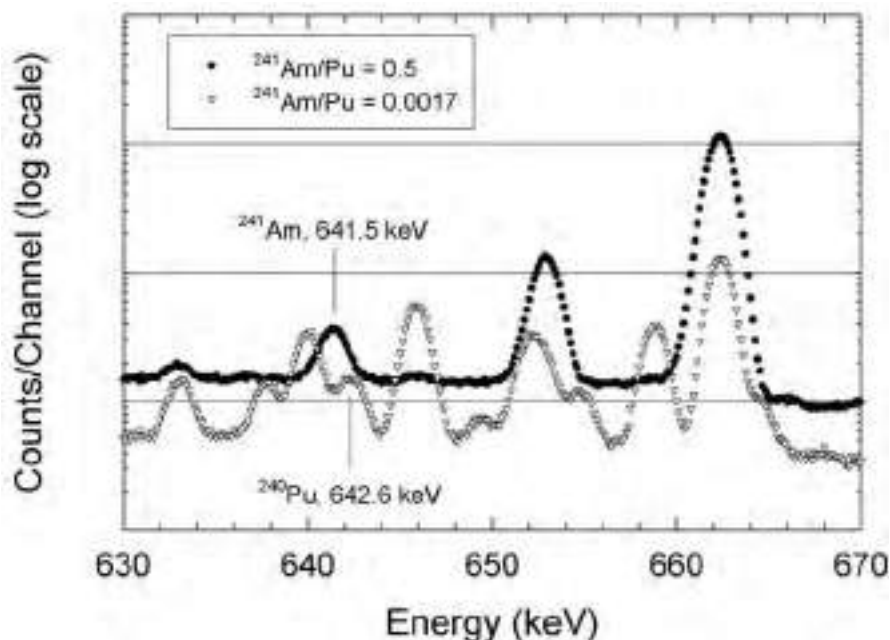


Fig. XI-4. The ^{240}Pu peak in the 600-keV region is hidden in the spectra from samples with very high ^{241}Am .

The FRAM analysis (200–800 keV region) of the spectrum ($^{241}\text{Am}/\text{Pu} = 0.5$) in Fig. XI-4 produces a result for ^{240}Pu that has a RSD of 30%. This is more or less at the limit of detectability. However, the analysis can still be used to interpret a calorimetry measurement because over 95% of the power arises from ^{241}Am . The % RSD for P_{eff} is less than 1% for the same analysis.

5. Heterogeneous Am/Pu

Pyrochemical purification processes such as molten salt extraction and electrorefining produce residues where the americium and plutonium are in different matrices. The americium is concentrated in a low-Z matrix in the form of AmCl_3 , whereas small amounts of plutonium metal are imbedded in the low-Z matrix. The relative-efficiency curve will be different for an americium gamma ray escaping from a chloride matrix from that for a plutonium gamma ray escaping from plutonium metal. The FRAM code calculates the different relative-efficiency curve shapes for americium and plutonium based on a model proposed by Fleissner (Fleissner 83), (see section II.F.6). The plutonium metal pieces found in a molten salt extraction residue are shown in Fig. XI-5. Most of the very high concentration americium samples contain these heterogeneous Am/Pu residues.

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Fig. XI-5. The dressing jar lid contains small plutonium metal pieces sieved from a molten salt extraction residue.

The user sets up the heterogeneous analysis through the Change Parameter Utility in FRAM. First select **Edit | Parameters** to enter the Change Parameter Utility. Next open the desired parameter file with **File | Open**. Then select **Edit | Isotopes** and assign efficiency function = 2 for americium. FRAM can accommodate multiple relative-efficiency curves but Los Alamos only has experience using two.

The analysis results for the ratio of $^{241}\text{Am}/^{239}\text{Pu}$ can be simply checked by visual examination of the pulse height spectrum. In Appendix E we have used the fundamental expression for isotopic ratios (Eq. II-5) to tabulate the $^{241}\text{Am}/^{239}\text{Pu}$ ratio for closely spaced peaks under the condition of equal peak heights. (The authors are indebted to Jack Parker for first producing this table.)

6. Plutonium with Cs-137 Interference

Cesium-137 emits a well-known gamma ray at 661.66 keV. The cesium gamma ray interferes with the ^{241}Am gamma ray at 662.40 keV that is usually used as an internal self-calibration peak for energy and FWHM.

a. Analysis in the 600-keV region

The energy calibration using the ^{241}Am gamma ray at 662.4 keV will be incorrect for situations where the cesium gamma ray dominates the americium gamma ray and its presence is unrecognized. We handle this case easily by

1. adding ^{137}Cs to the isotope list,
2. placing the 661.66 keV ^{137}Cs gamma ray in the peak list,
3. using the cesium gamma ray for activity,
4. adjusting the ROI boundaries, if needed, to account for both ^{241}Am and ^{137}Cs , and
5. using the americium gamma ray only for activity. Delete any assignment for energy calibration, FWHM calibration, or shape. You may continue to use the ^{241}Am peak at 722 keV for the energy calibration.

These changes allow the quantification of $^{137}\text{Cs}/\text{Pu}$ while still allowing the 662.40-keV ^{241}Am gamma ray to contribute to the analysis.

b. Analysis below 450 keV

Cesium-137 does not contribute any direct interference to the 120–450 keV region. Analysis for plutonium and americium can proceed normally in most cases. A problem could arise from a very high

XI. MODIFYING PARAMETER FILES FOR SPECIAL CASES

cesium concentration. In this case the Compton continuum from the 661.6-keV cesium gamma ray could swamp the lower energy plutonium gamma rays making it difficult to obtain a plutonium isotopic analysis.

7. Uranium with Cs-137 Interference

FRAM has been applied to the analysis of the $^{137}\text{Cs}/\text{U}$ ratio in critical assembly fuel plates to determine burnup or neutron exposure in the fuel. Cesium-137 does not contribute any direct interferences; one modifies the normal uranium parameter file by

1. adding ^{137}Cs to the isotope list,
2. placing the 661.66 keV ^{137}Cs gamma ray in the peak list,
3. using the cesium gamma ray for activity,
4. assigning a peak region for the 661.6 keV peak, and
5. using the cesium peak for energy, FWHM, and shape calibration as desired.

These changes produce the usual uranium isotopic composition plus the $^{137}\text{Cs}/\text{U}$ ratio. We have seen the situation where the Compton continuum from the 661.6-keV cesium gamma ray swamps the lower-energy uranium gamma rays.

8. Heat Source Grade Pu-238

FRAM has analyzed the gamma-ray spectra from numerous items containing heat source grade ^{238}Pu . The first waste shipments to the Waste Isolation Pilot Plant (WIPP) from Los Alamos contained items with heat source grade plutonium. FRAM successfully analyzed all of these items (Mercer 99).

Heat source grade plutonium typically contains approximately 80% ^{238}Pu , and 2%–4% ^{240}Pu with the remainder being mostly ^{239}Pu . Plutonium-241 and ^{241}Am are also present and can be analyzed. The ^{236}Pu that is originally present in parts per million (ppm) amounts produces strong gamma-ray peaks from its thorium daughter decay products. We use the thorium daughter gamma-ray peaks to help define the relative-efficiency curve.

We analyze data in the energy range from 140 keV to 860 keV from a coaxial detector operating in 8192 channels at the standard gain of 0.125 keV/ch. The analysis includes the well-known ^{238}Pu peaks at 152.7 and 766.4 keV and also includes weaker ^{238}Pu peaks at 201.0, 742.8, and 786.3 keV. The analysis for ^{239}Pu and ^{241}Pu is straightforward using the major higher energy peaks. The usually strong 129.3 keV ^{239}Pu peak is not visible and the 203.5 keV ^{239}Pu peak is also not useful.

Plutonium-240 is the most difficult isotope to analyze, as its peaks at 160.3 and 642.5 keV are essentially undetectable. This results in very large % RSD values for ^{240}Pu as shown in the output listing in Fig. XI-6. The user must use prior knowledge or stream average data for ^{242}Pu as the standard FRAM isotopic correlation does not apply.

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*****
PC FRAM (4.2) Isotopic Analysis 26-Nov-2002 18:32:18
(Fixed energy Response function Analysis with Multiple efficiencies)
System ID: T. Sampson, Carefree Office

spectrum source: c:\documents and settings\tsampson\desktop\fram isotopics\isotopic
                  spectra\isotopic spectra\pu238\std1493.s01
spectrum date:   17-Jun-1998 06:07:30
live time:      6252 s
true time:      7200 s
num channels:   8192

parameter set: Pu238_Coax (2002.11.26 18:03)
               Coax, .125 kev/ch, ~80% Pu238 125-780 kev
*****
*****
diagnostics passed.

                                     (OpEntry)   (ug/gPu)

      Pu238      Pu239      Pu240      Pu241      Pu242      Am241
mass%  79.1196    15.9171    4.0773    0.3861    0.5000    2501.5
sigma  1.4407     0.3093    1.7420    0.0087    0.0000    61.6
%RSD   1.82%     1.94%    42.72%    2.27%    < .01%    2.46%

%TotPwr 99.80     0.07     0.06     < .01     < .01     0.06

Specific Power (W/gPu):   ( 449.9543 +/- 0.7242)e-003 ( 0.16%)

Effective Pu240 fraction: ( 204.2987 +/- 4.0269)e-002 ( 1.97%)

Time since chemical separation: 3803.7 +/- 64.4 days ( 1.69%)

Relative mass (Th228 / Pu):  1.285e-008 ( 1.83%)
Relative mass (Np237 / Pu):  4.464e-004 ( 2.65%)
*****

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Fig. XI-6. Output from the analysis of a sample of heat source grade ^{238}Pu .

9. Uranium-Plutonium Mixed Oxide (MOX)

We no longer consider MOX analysis to be a “special case” when using the current versions of FRAM, although historically there have not been many opportunities for MOX analysis in the United States. This may change in the future if current plutonium disposition plans are carried out.

The standard coaxial detector parameter files for plutonium (both shielded and unshielded) also analyze for uranium, if present. Some of these results have been presented previously in section IX.B.4, which discusses MOX measurement bias.

The standard plutonium parameter file for analysis in the 120–450 keV region also analyzes for ^{235}U at 185.7 keV and includes ^{235}U peaks at 143.8, 163.4, 202.1, and 205.3 keV as interference peaks.

The standard plutonium analysis in the 200–800 keV region analyzes for ^{235}U at 185.7 keV (this peak may not be present if there is shielding around the sample) and analyzes for ^{238}U at 1001.0 keV. The parameter file also has interference peaks from ^{235}U at 202.1 and 205.3 keV as well as a ^{238}U interference peak at 766.4 keV. Plutonium-238 and ^{238}U both contribute to peaks at 766.4 and 1001.0 keV. All four of these peaks are included in the parameter file. In most MOX samples, the 766.4-keV peak arises mainly from ^{238}Pu , and the 1001.0-keV peak arises mainly from ^{238}U . We account for this by fixing the ^{238}U component at 766 keV to the ^{238}U component at 1001 keV and fixing the ^{238}Pu component at 1001 keV to

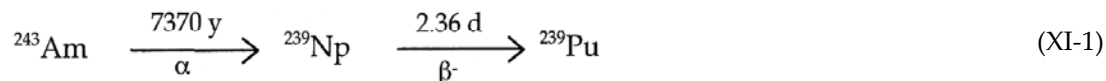
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the larger ^{238}Pu component at 766 keV. The iterative FRAM analysis then further refines this starting point.

The reader is referred to Appendix A for more details. In this appendix we have described in some detail the considerations that have gone into the setup of parameter files for MOX analysis.

10. Am-243–Np-239

Americium-243 may be present in plutonium samples. This isotope decays as shown in Eq. XI-1 below.



The short half live of ^{239}Np means that it will be in equilibrium with ^{243}Am and gamma rays from ^{239}Np can be used to characterize ^{243}Am . We do not see the gamma rays from the direct decay of ^{243}Am but the gamma rays from the decay of ^{239}Np are very strong and easily identified in a plutonium spectrum. We list the strongest gamma rays from ^{239}Np in Table XI-4. These gamma rays, along with a few weaker neighboring gamma rays, are accounted for in analysis for ^{243}Am .

Table XI-5. Prominent Gamma Rays from the Decay of ^{239}Np .

Energy (keV)	Branching Fraction
209.75	0.0342
228.18	0.108
277.60	0.144
334.31	0.0207

We must account for these gamma rays in every plutonium spectrum, even if we are not directly interested in the ^{243}Am concentration. The background region above the 208.00-keV ^{241}Pu - ^{237}U peak usually must be adjusted to account for the possible presence of the 209.75-keV gamma ray from ^{239}Np . The 334.31-keV peak of ^{239}Np provides a direct interference in the 332–336 keV analysis region. The 228.18-keV peak is analyzed for the activity of ^{243}Am . We do not use the 277.6-keV peak because of other weak interferences that are usually present in this region. However, its presence, along with the 228-keV peak, provide unambiguous visual identification of the presence of ^{243}Am .

The standard FRAM parameter files easily analyze spectra from samples with “normal” concentrations of ^{243}Am . Very high concentrations are characterized by the peak height of the 209-keV ^{239}Np peak being an appreciable fraction of or greater than the peak height of the 208.00-keV ^{241}Pu - ^{237}U peak. These cases should be examined more closely as it may be necessary to “tweak” the boundaries of some of the ROIs to obtain the best results.

11. Physically, Spatially, and Isotopically Heterogeneous Waste

Waste drums packaged for disposal are the principal representatives of this material category. Users often fill waste drums with many smaller containers of individually packaged waste. Even if the small containers have been segregated by ^{240}Pu value, the small containers, taken all together, will likely be isotopically heterogeneous at some level. A waste drum specified to contain plutonium with a nominal ^{240}Pu concentration of 6% might actually contain packages with ^{240}Pu contents ranging from 4 to 7 percent. Similarly, the other isotopic components could easily vary over a range of a factor of two or more. The

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isotopic heterogeneity may not simply be confined to different isotopic vectors in different containers. Some drums might contain packages that, in addition, exhibit an Am/Pu ratio heterogeneity as described in XI.C.5 above.

The individual packages almost always contain waste that is physically heterogeneous and their distribution in a waste drum adds an additional dimension of spatial heterogeneity.

These multiple factors, including, a spread of isotopic distributions, physical heterogeneities within a package, spatially heterogeneous distribution of packages in the drum, and Am/Pu heterogeneities within a package, combine to produce an extremely difficult problem for any isotopic analysis software.

There is no single FRAM parameter file designed for this situation. The best we can do is to give some guidelines that may help to mitigate the biases caused by these effects.

- Carry out the analysis at high energies using parameter files set up to analyze in the 200–800 keV region, assuming that the counting rate will permit. The increased penetrability of the higher-energy gamma rays allows better averaging, both spatially and isotopically.
- Use a parameter file set up for Am/Pu heterogeneity if you have knowledge that those waste streams may be represented in some of the packages.
- Use rotation and translation of the waste drum during the measurement.

XII. DIFFICULT MEASUREMENT SITUATIONS

XII. DIFFICULT MEASUREMENT SITUATIONS

A. Using FRAM With Rate-Loss Correction Sources

We have successfully analyzed data taken with a rate-loss correction source attached to the detector (a rate-loss correction source is used in systems such as an SGS or tomographic gamma scanner (TGS) performing transmission-corrected passive assay). A rate-loss correction source complicates the FRAM analysis in two ways. The rate-loss correction source may have gamma rays that interfere directly with plutonium gamma rays used in the FRAM analysis. In addition, the gamma or x-rays from the rate-loss source may randomly sum with plutonium gamma rays to produce unwanted interferences.

FRAM has analyzed data from both situations. We present a detailed discussion on using FRAM with rate-loss sources in Appendix B.

B. Simultaneous FRAM/AWCC Measurements

An AWCC user wished to perform passive coincidence counting measurements with the AWCC (no neutron sources and no nickel ring) while simultaneously making an isotopic measurement with an HPGe detector. The user suggested modifying the AWCC with a hole through the wall to bring out an unattenuated gamma-ray beam to the detector.

Thinking that the hole was unnecessary, we made direct measurements using a 25% relative-efficiency coaxial detector on plutonium inside an *unmodified* AWCC. The sample was a container holding 847 g PuO₂ with nominal 16% ²⁴⁰Pu. Table XII-1 displays the isotopic composition of the sample on the measurement date.

The face of the detector was positioned about 1.5 in. from the cylindrical outer surface of the AWCC giving a gross counting rate of 40 kHz. The center line of the uncollimated detector was positioned vertically at 1.5 in. above the bottom of the container. The total sample-to-detector distance was about 12 in. We made 10 measurements of 30 minutes each.

Table XII-1. Isotopic Composition (wt %) on Measurement Date.

Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
0.053	82.554	16.449	0.601	0.343	0.796

We were able to analyze each spectrum in the 120–450 keV region and also in the 200–800 keV region. That is to say, the attenuation provided by the body of the AWCC did not completely attenuate the gamma rays below 200 keV. There were even visible peaks in the 100-keV region. Table XII-2 below gives the results of the two analyses of the 10 measurements.

The measurement results are clearly more precise using the 200–800 keV analysis. Both sets of results show that spectra suitable for FRAM analysis can be obtained by collecting the spectra data through the body of the neutron counter.

XII. DIFFICULT MEASUREMENT SITUATIONS

Table XII-2. FRAM Analysis Results through AWCC Wall (Pu-242 operator entered).

Analysis	Pu-238	Pu-239	Pu-240	Pu-241	Am-241
<u>120–450 keV Analysis</u>					
Avg: Measured/Accepted	0.9745	0.9999	1.0010	0.9842	1.0127
% RSD distribution	13.0	1.3	6.4	1.4	2.5
<u>200–800 keV Analysis</u>					
Avg: Measured/Accepted	1.0163	1.0049	0.9747	1.0163	0.9868
% RSD distribution	3.5	0.26	1.4	0.90	0.91

C. Measurements Through Thick Shielding

FRAM's ability to make measurements through very thick shielding is, perhaps, its most important, useful, and well-known characteristic. While we cannot document all possible measurement scenarios, we will give some examples of the extreme measurement conditions encountered for shielded samples.

1. Steel Shielding

A thickness range of 10–12 mm of steel is the limit for reliable measurements using gamma rays and x-rays in the 100-keV region.

a. Plutonium

Very early in the application of FRAM we showed that FRAM could easily analyze plutonium isotopic data collected in the 120–450 keV region taken through 12.5 mm (0.5 in.) of steel. This is a routine capability of FRAM using the standard parameter file for analysis in the 120–450 keV region.

Somewhat later (Sampson 99c) we demonstrated the analysis of a plutonium spectrum taken through 25 mm of steel. In this case the analysis was performed using the standard parameter file for analysis in the 200–800 keV region. It is clear that FRAM can perform plutonium isotopic measurements through steel much thicker than 25 mm but we have not yet performed the experiments to define a higher limit.

b. Uranium

A common uranium measurement problem is that of the measurement of the enrichment or isotopic composition of low-enriched uranium in UF₆ cylinders. Cylinders containing UF₆ with enrichments in the 1%–5% range typically have a wall thickness of 13 mm. The wall material may be nickel or a nickel alloy possessing approximately the same absorption properties as steel. Depleted or natural UF₆ is often found in cylinders with 16-mm-thick walls.

FRAM does not have any problem analyzing coaxial detector data from uranium samples shielded with 16 mm of steel (Sampson 01). We have made numerous measurements with a 28% relative-efficiency coaxial detector on enrichment standards in a geometry that simulates the measurement of a UF₆ cylinder. Figure XII-1 displays this geometry.

XII. DIFFICULT MEASUREMENT SITUATIONS

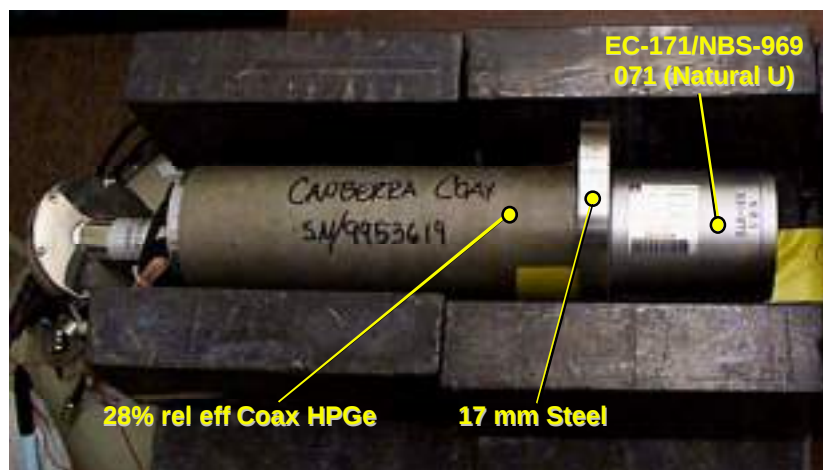


Fig. XII-1. Measurement geometry, with detector, steel absorber, and sample, that simulates the measurement of a UF_6 cylinder.

In Fig. XII-2 we display, as a function of enrichment and counting time, the relative standard deviation of a single measurement obtained from the distribution of 15 replicates of these mockup measurements.

We repeated these measurements using a 70-mm-diam. by 30-mm-thick semiplanar detector to see if the larger detector diameter would improve the peak-to-background ratio at 258 keV. We obtained the same results as for the coaxial detector. This is thought to occur because much of the continuum underneath the 258-keV peak arises from bremsstrahlung, not Compton scattering.

Los Alamos personnel have used FRAM to analyze spectra that were acquired from type 30B UF_6 cylinders at the ABB Atom fuel fabrication facility in Vasteras, Sweden (Sampson 99c). A type 30B UF_6 cylinder has 13-mm-thick steel walls. These measurements were made with a 26% relative-efficiency coaxial detector in 8192 channels. The measurements on 30B cylinders showed a measurement precision or repeatability of 6%–8% (1 RSD) for 20–30 minute measurements covering enrichments from natural to 4.7%. This is consistent with the results in Fig. XII-2 and even better than the results shown in Fig. XII-2 for natural uranium.

In the report describing the measurements at ABB Atom we made several observations comparing FRAM isotopic analysis measurements with the classical enrichment meter method (Smith 91).

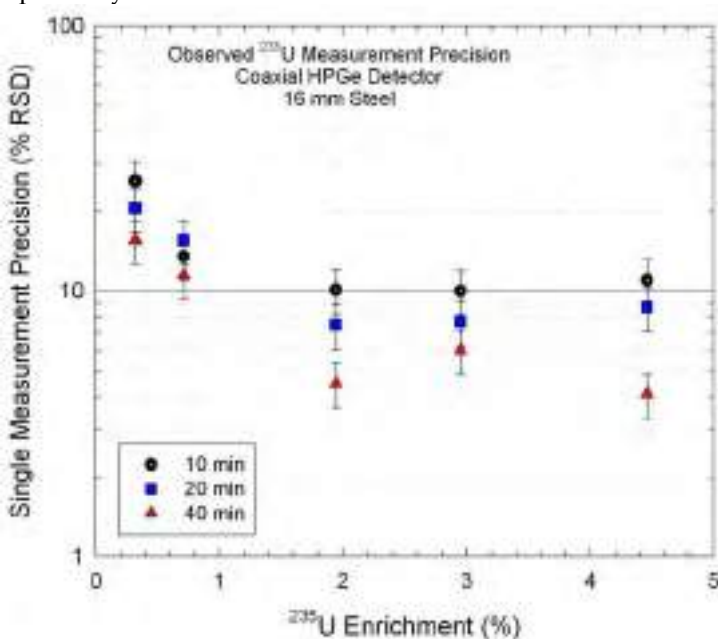


Fig. XII-2. Single measurement precision of the ^{235}U fraction calculated from 15 replicates. The five standards were measured in 8192 channels with a 28% relative-efficiency coaxial HPGe detector and analyzed with the FRAM software. The measurements were made in the mockup geometry of Fig. XII-1.

XII. DIFFICULT MEASUREMENT SITUATIONS

One should consider the following when choosing between FRAM or the classical enrichment method for UF₆ cylinder measurements. Note that we do not compare measurements in the 100-keV region because they are unreliable for the 13–16-mm-thick cylinder walls.

The advantages of using FRAM include the following:

- Because FRAM does not require calibration, it is faster for a limited number of measurements than the classical enrichment method.
- The classical enrichment method requires an auxiliary measurement of the wall thickness of the cylinder. This ultrasonic measurement adds time and uncertainty to the measurement process as well as requires additional equipment.
- The FRAM measurement has no geometric reproducibility requirements. The classical enrichment method requires that the measurement geometry for the unknown be the same as for the calibration.
- FRAM can measure other materials in the facility such as scrap, waste, oxide powder, and anything else that might be encountered. The classical enrichment method is not able to do most of the other measurements without a new calibration and the assurance of a geometry that possesses “infinite thickness.”

There are situations in which it is advantageous to use classical enrichment methods:

- The classical enrichment method has a shorter measurement time after calibration is complete.
- FRAM requires decay equilibrium (approximately 100 days from separation of daughter products) in the ²³⁸U decay. The classical enrichment method does not because it measures ²³⁵U directly.
- Shielding requirements are more stringent with FRAM because FRAM measures gamma rays up to 1 MeV. The system must provide shielding against background at this energy. The classical enrichment method measures at 185 keV.

The discussion of gamma-ray isotopic analysis measurements on UF₆ cylinders would not be complete without noting the capability of planar HPGe detectors for this application. Planar HPGe detectors have long been considered to be too small and not efficient enough for the FRAM type measurements that measure up to 1 MeV.

The IAEA has many planar HPGe detectors (25 mm diam. by 15 mm thick) that are routinely used for isotopic measurements on plutonium with analysis in the 100-keV region. Because of the availability of these detectors they wished to use these same detectors for uranium measurements on UF₆ cylinders. The experience of IAEA personnel showed that uranium isotopic analysis methods using the 100-keV region with the Multi Group Analysis Uranium software (MGAU) failed because of the attenuation in the thick steel walls of the UF₆ cylinders. IAEA personnel also knew that FRAM could successfully analyze data from measurements of UF₆ cylinders taken with coaxial HPGe detectors.

Los Alamos was asked to put the two together to see if FRAM could analyze data from planar HPGe detector measurements on UF₆ cylinders. An additional requirement was that the data was to be acquired in 4096 channels to match the IAEA’s standard MCAs. We set up the measurement geometry as pictured in Fig. XII-1 using a 25-mm-diam. by 16-mm-thick planar detector in place of the coaxial detector pictured.

These measurements on uranium using a planar HPGe detector operating at 0.25 keV/ch (4096 channels spanning 0–1024 keV) were very difficult for FRAM to analyze. The spectra were weak because of the small detector. Even more important was the low number of channels/keV resulting in very narrow

XII. DIFFICULT MEASUREMENT SITUATIONS

peaks at low channel numbers for the high-resolution planar detector. The full width at half maximum for the 185-keV ^{235}U peak was less than 3 channels. We made measurements on samples with enrichments of 0.31, 0.71, 1.94, 4.46, and 10.09 wt % using steel thicknesses of 13 and 16 mm and count times of 15, 30, and 60 minutes. Each combination was measured 24 times for a total of 720 measurements.

The results (Sampson 01) from the most difficult measurements (0.31 wt % ^{235}U for a 15-minute count time) are shown in Table XII-3. The % RSD is that for a single measurement determined from the distribution of the 24 repeated measurements.

The measurements displayed in Table XII-3 demonstrate that FRAM can perform these measurements successfully in a count time as short as 15 minutes, albeit with quite large statistical uncertainties. Coaxial detector measurements are still the measurement of choice as the precision is about a factor of two better, (see Fig. XII-2), than that of the planar detector.

Table XII-3. Twenty-Four 15-Minute Measurements, Planar HPGe detector (25 mm by 16 mm).

Sample	Accepted wt % ^{235}U	16 mm Steel Absorber			13 mm Steel Absorber		
		Measured wt % ^{235}U	Meas./Accept.	% RSD	Measured wt % ^{235}U	Meas./Accept.	% RSD
EC-171-031	0.3166	0.3131	0.9889	37.4	0.3556	1.1232	27.9
A1-408-1	0.7135	0.7231	1.0135	16.9	0.7100	0.9951	14.1
EC-171-194	1.9420	1.9495	1.0039	18.6	1.9968	1.0282	15.7
EC-171-446	4.4623	4.5950	1.0297	20.9	4.3954	0.9850	11.9
A1-324-1	10.086	10.093	1.0007	14.9	10.453	1.0364	8.0
		Average	1.0073		Average	1.0336	

2. Lead Shielding

The ability of FRAM to analyze data acquired through lead shielding was one of the first “difficult applications” demonstrated for FRAM. Numerous examples of FRAM measurement performance on relatively lightly lead-shielded samples have been given in chapter IX. Hypes (Hypes 00) has demonstrated that FRAM can obtain a complete isotopic analysis from measurements made through as much as 25 mm of lead. Figure XII-3 displays spectra for lead thicknesses of 0, 12, and 25 mm.

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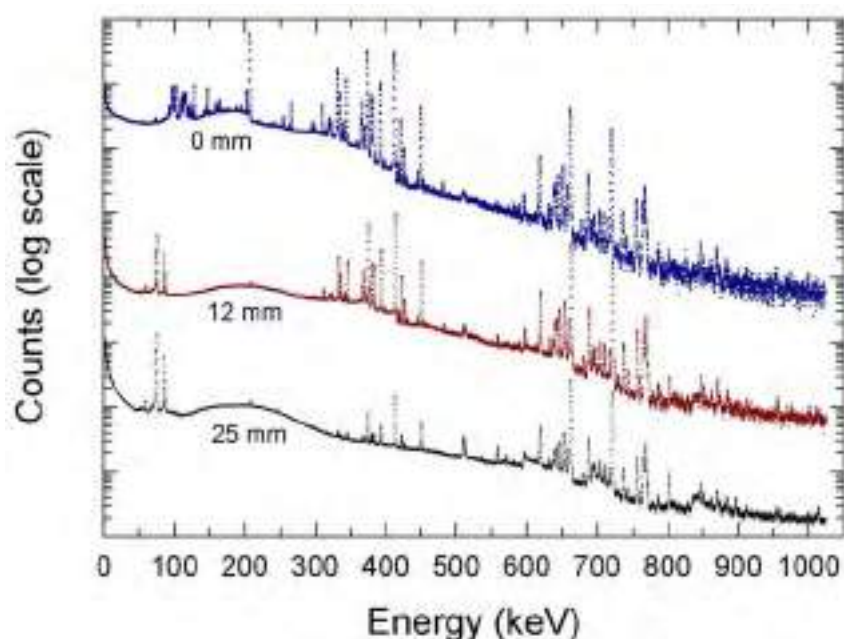


Fig. XII-3. HPGc detector gamma ray spectra from a sample shielded with 0, 12, and 25 mm of lead. The peaks around 75 keV are Pb x-rays from the lead shielding in front of the detector.

These extreme thicknesses require some parameter file modification because lower-energy gamma rays “disappear” as the lead thickness increases. The 203-keV and 208-keV peaks of ^{239}Pu and ^{241}Pu - ^{237}U respectively are present and can be analyzed for most samples for lead shielding thicknesses up to about 6 mm. At double this thickness, 12 mm of lead, we see gamma-ray peaks only above approximately 300 keV. This still allows analysis for ^{241}Pu using the 330-keV region and the 370-keV region. With shielding of 25 mm of lead the 330-keV region becomes very weak and one is forced to measure ^{241}Pu using gamma rays in the 370-keV region. If the attenuation becomes still greater and the 370-keV region is not available one will not be able to measure the ^{241}Pu isotopic fraction as 370.94 keV is the highest-energy gamma ray emitted by ^{241}Pu or its ^{237}U daughter. It is also of interest to note the differential attenuation of the 375- and 414-keV gamma rays from ^{239}Pu . These gamma rays are the most intense peaks in the 375-425 keV region in the above plot. Visually the peaks are of approximately equal height with no shielding, as expected because their branching intensities differ by only about 6% (see Appendix D). The differential attenuation becomes visually apparent for 12 mm of lead shielding and is approximately a factor of two for the 25-mm lead thickness.

We also note that 148.6 keV is the highest measurable gamma ray directly from ^{241}Pu . All the higher energy gamma rays come from the ^{237}U daughter of ^{241}Pu . This means that ^{241}Pu - ^{237}U decay equilibrium (more than 45 days from chemical separation) must be present for measurement of ^{241}Pu for any samples shielded with enough lead to remove the 148-keV gamma ray (approximately 1 mm of lead).

3. 9975 Shipping Container

The 9975 shipping container provides a real-world example of a container that is difficult to measure. This shipping drum is used by DOE facilities to ship and store plutonium-bearing materials slated for disposition or long-term storage. This shipping drum will hold the nominal 5-in.-diameter DOE 3013 plutonium storage container. A view of the interior of a 9975 is shown in Fig. XII-4.

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Fig. XII-4. A view of the interior of a 9975 shipping drum showing four different layers of materials surrounding the central cavity. These layers consist of approximately 0.75 in. steel, 0.5 in. lead, and 5 in. of Cellutex.

A coaxial detector gamma-ray spectrum from a sample of approximately 4 kg of weapons plutonium contained in a 9975 (Hypes 01) is presented in Fig. XII-5 below. It is not very much different from the spectrum seen through 25 mm of lead, shown in Fig. XII-3.

Data from samples contained in a 9975 shipping container are analyzed with a FRAM parameter set that uses gamma rays above 300 keV. The sawtooth structure in the spectrum at energies of 600 keV and above arises from neutron inelastic scattering from the germanium in the detector crystal.

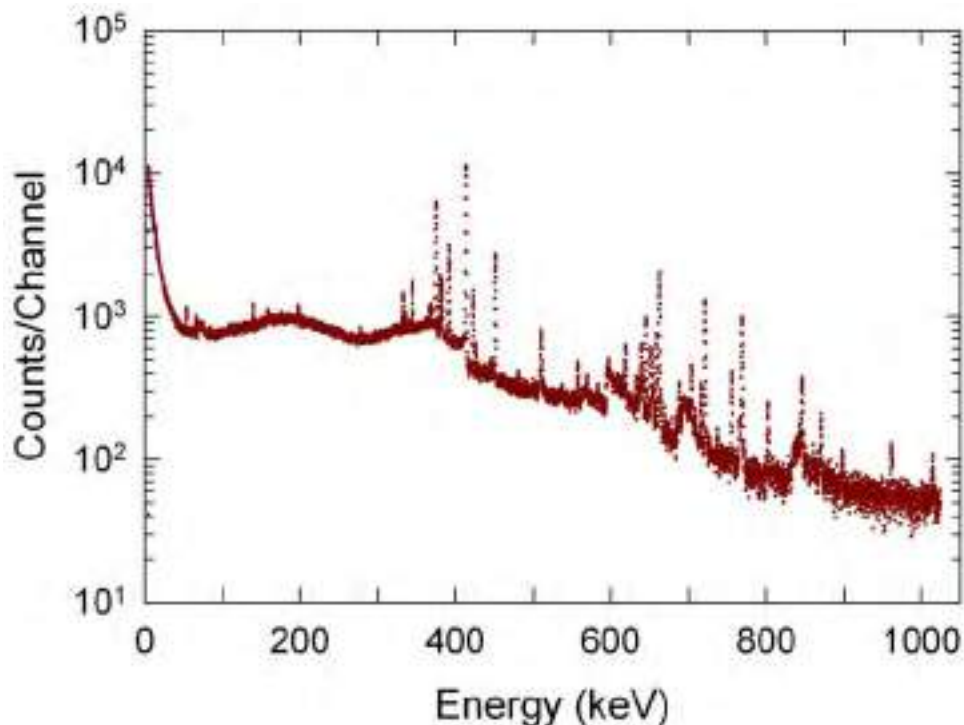


Fig. XII-5. A spectrum taken with a coaxial detector from 4 kg of weapons plutonium inside a 9975 shipping container

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D. Measurements on Am-Be Neutron Sources

Hypes (Hypes 02) used FRAM to analyze data from americium-beryllium (AmBe) neutron sources to quantify other heat-producing isotopes in addition to ^{241}Am . These measurements were performed to support calorimetry measurements of the sources prior to disposal. He analyzed for ^{239}Pu , ^{243}Am , ^{237}Np , and ^{239}Np relative to the principal heat-producing isotope of ^{241}Am .

Data acquisition can be a problem for measurements on neutron sources, in the long term, because of the potential for neutron damage to the HPGe crystal. These measurements did not result in any noticeable neutron damage and successfully demonstrated the ability of FRAM to analyze spectra containing neither plutonium nor uranium.

XIII. FRAM APPLICATION WITH CADMIUM TELLURIDE (CDTE) DETECTORS

XIII. FRAM APPLICATION WITH CADMIUM TELLURIDE (CDTE) DETECTORS

The successful application of an unmodified version 4 of FRAM to data taken from a 10-mm by 10-mm by 1.5-mm Peltier-cooled CdTe detector is another demonstration of the extreme versatility of the FRAM isotopic analysis software (Vo 02). This is the first successful application of an unmodified general-purpose isotopic analysis code to any room temperature semiconductor detector.

Several characteristics of the spectra from CdTe detectors provide an extreme challenge for FRAM. The energy calibration is not linear, unlike the highly linear energy calibration from HPGe detectors. This is easily handled by the piecewise linear energy calibration built into FRAM. The very large tails on the photopeaks are discussed in detail in (Vo 02) and are the greatest limitation for the use of the unmodified version 4 of FRAM for analysis of CdTe.

The spectra from NaI, CdZnTe, and HPGe detectors are overlaid with a CdTe spectrum for two different plutonium isotopic compositions in Figs. XIII-1,2.

Note the region around 203–208 keV. The two gamma-ray peaks at 203.5 keV (^{239}Pu) and 208.0 keV (^{241}Pu - ^{237}U) are completely resolved in the HPGe spectra of both samples. The peaks are partially resolved in the CdTe spectrum from the 94% ^{239}Pu sample but the 203.5-keV peak is completely hidden under the tail of the 208-keV peak in the spectrum from the 64% ^{239}Pu sample. This difficult analysis situation contributes to the significantly larger errors seen in the CdTe analysis when compared to the HPGe analysis. Nevertheless, FRAM successfully analyzes the complete isotopic distribution for samples with ^{240}Pu ranging from 3% to 26%.

Table XIII-1 displays the bias for a group of measurements from a CdTe detector used to measure standards at LANL. The description of the standards is included in Table F-1 in Appendix F.

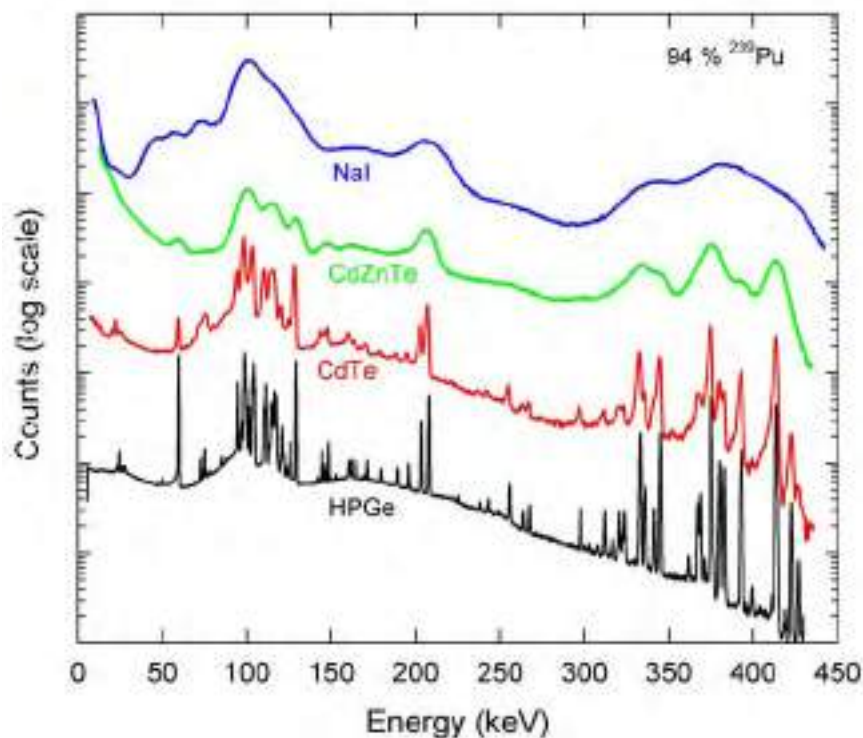


Fig. XIII-1. Comparison of the gamma ray spectra from a sample containing 94% ^{239}Pu , 6% ^{240}Pu for four different detectors. Version 4 of FRAM can obtain the complete isotopic distribution from the HPGe detector and from the CdTe detector.

XIII. FRAM APPLICATION WITH CADMIUM TELLURIDE (CDTE) DETECTORS

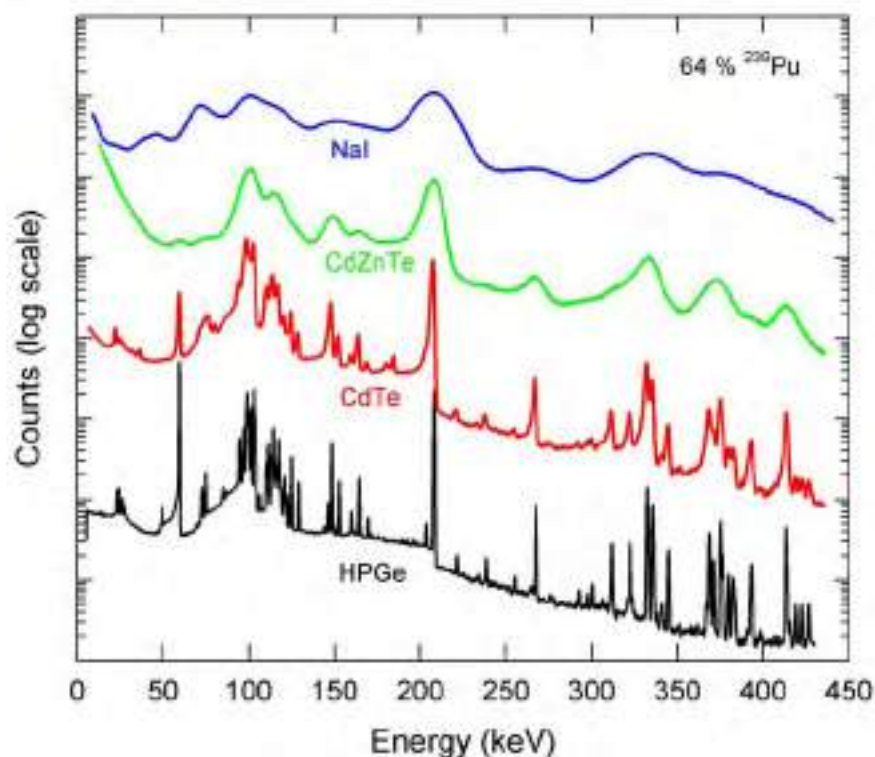


Fig. XIII-2. Comparison of the gamma-ray spectra from a sample containing 64% ^{239}Pu and 26% ^{240}Pu for four different detectors. Version 4 of FRAM can obtain the complete isotopic distribution from the HPGe detector and from the CdTe detector.

Table XIII-1. Percent Bias in the FRAM Analysis of CdTe Detector Spectra from Reference Standards.

Sample	^{240}Pu mass %	Percent Bias = $100 * (\text{Measured} - \text{Accepted}) / \text{Accepted}$					
		^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{241}Am	P_{eff}
STDISO03	3.56	-30.23	-0.33	8.98	-1.00	-3.06	0.19
PIDIE6_1	5.99	-76.71	-0.06	0.97	3.00	-9.33	-2.77
STDISO06	6.13	6.32	-0.67	10.24	-1.04	9.25	2.18
CBNM93	6.31	8.69	-0.45	6.67	0.68	-24.23	-1.25
STDISO09	6.90	-0.53	1.41	-18.93	-2.74	-0.83	-2.65
STDISO12	11.85	-6.31	0.81	-5.79	-3.13	3.25	-0.91
PIDIE6_3	14.20	-17.7	-0.37	2.31	-1.32	2.26	0.03
CBNM84	14.27	-10.67	-0.14	1.06	-5.40	-4.95	-1.86
STDISO15	15.52	-6.56	0.33	-1.61	-1.08	2.12	-1.07
CBNM70	18.81	-6.99	-3.75	16.38	-6.98	-6.21	-3.65
PIDIE6_5	21.41	-15.82	1.99	-6.80	-4.43	-6.59	-5.68
CBNM61	26.29	-4.08	-0.37	1.50	-3.19	-3.66	-2.92
PIDIE6_7	26.39	-4.44	1.16	-2.39	-1.64	-0.32	-2.01
	Avg Bias	-12.69	-0.03	0.97	-2.17	-3.25	-1.72
	% RSD	21.73	1.39	8.86	2.59	8.02	1.96

XIII. FRAM APPLICATION WITH CADMIUM TELLURIDE (CDTE) DETECTORS

The larger bias of the CdTe measurements, compared to the bias seen in HPGe detector measurements, arises from two sources. First, the counting statistics are poorer because of the small size of the crystal—over 500 times smaller in volume than a typical 25% relative-efficiency coaxial HPGe detector used by FRAM. The second source arises from the imperfect fit of the HPGe detector peak-shape model to the severely tailed peaks from CdTe.

The CdTe results can be significantly improved by modifying the analysis to include peak shape models that are more applicable to CdTe and applying this new analysis to the 100-keV region.

We note that the FRAM analysis was successfully applied to spectra from a CdTe detector, not CdZnTe. While CdZnTe is in more common use, its resolution is too poor (see Figs. XIII-1 and XIII-2) to allow analysis of its spectra by an unmodified version of FRAM.

XIV. FRAM APPLICATIONS IN AUTOMATED SYSTEMS

XIV. FRAM APPLICATIONS IN AUTOMATED SYSTEMS

A. ROBOCAL

FRAM is now being applied in robotic, automated systems designed to operate continuously and unattended, 24 hours a day. This places an additional burden on the FRAM software because FRAM may not know anything about the type of material being measured.

ROBOCAL (robotic calorimetry) is a robotic system for remote calorimetric and gamma-ray isotopic analysis of special nuclear materials that has been operating at the Plutonium Facility of the Los Alamos National Laboratory since 1990 (Hurd 89, Harp 91). ROBOCAL has recently been upgraded (Bonner 01) with new robotics, new computers and software, and a FRAM isotopic analysis system called the Intelligent Isotopic Unit (IIU).

1. Intelligent Isotopic Unit Autoanalysis

Because ROBOCAL runs unattended and without the opportunity for operators to input information on the items to be analyzed, the IIU is designed to assay an extended range of samples, consisting of normal samples or pyrochemical residues in shielded or unshielded containers, all without operator intervention. Normally, when a varied range of sample types is presented to FRAM in a manual mode, the operator must choose an appropriate parameter set for each sample, based on existing knowledge of the sample. This knowledge may be imperfect and the analysis may have to be repeated if the initial choice was bad.

In the FRAM software for the IIU, we have incorporated some additional logic and diagnostic tests, based on the actual spectrum under analysis, to choose the best parameter set for the analysis. The automated logic or intelligence in the modified version 4 of FRAM for the IIU automatically chooses from six different parameter sets that accommodate all combinations of unshielded, shielded, homogeneous or heterogeneous Am/Pu, and very high ^{241}Am .

The automatic selection process starts with acquisition of data with an Autoanalysis flag set. The IIU acquires this data using a 25%–30% efficient coaxial HPGe detector. The spectral data is first analyzed in the 120–450 keV region, assuming the sample is unshielded. The data is reanalyzed, if necessary, with other members of the six parameter sets based on the results of three diagnostic tests described next.

- Test for Shielded Sample This test forms the ratio of the relative efficiency of a peak at high energy relative to one at low energy. The ratio is tested against an empirical limit. If the ratio is less than the limit, the sample is not shielded; if it is greater than the limit, the sample is shielded. This test is based on the fact that absorbers attenuate low-energy peaks (and hence decrease the relative efficiency) more than at high energies.
- Test for Am/Pu Heterogeneity This test forms the ratio of Am/Pu from a low-energy peak to Am/Pu from a high-energy peak. If americium and plutonium are in the same matrix, this ratio should be unity. If americium is in a different matrix (heterogeneous Am/Pu) than the plutonium, the ratio will differ from unity because of the different attenuation suffered by americium and plutonium gamma rays at the same gamma-ray energy. The test also accounts for the statistical uncertainties in the two Am/Pu ratios. When Am/Pu heterogeneity is detected, the spectrum is reanalyzed with a second relative efficiency curve assigned to americium.
- Test for High Americium Concentration This test compares the measured Am/Pu fraction against a user-defined limit. A different parameter file is used for high americium because of the

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additional americium peaks appearing in the spectrum that are not visible for lower concentrations. A typical user-defined limit for High Americium is $Am/Pu > 0.1$.

2. Intelligent Isotopic Unit Hardware

The IIU hardware provides for motion with three degrees of freedom. The sample is rotated and translated vertically in front of the detector. In addition, the detector is mounted on a platform that moves in the horizontal plane to vary the sample to detector distance. The sample rotation and vertical translation evens out the response from heterogeneous samples. The horizontal motion of the detector allows the system to position the detector to optimize the system counting rate.

The hardware for the FRAM system in the upgraded ROBOCAL environment is shown in Fig. XIV-1. Figure XIV-2 shows the system inside the ROBOCAL work envelope with a sample about to be placed on the sample table.



Fig. XIV-1. The hardware for the IIU at the Los Alamos Plutonium Facility is shown before its installation.

XIV. FRAM APPLICATIONS IN AUTOMATED SYSTEMS



Fig. XIV-2. The ROBOCAL robot is about to place a container on the sample table of the IIU at the Los Alamos Plutonium Facility.

B. ARIES NDA System

ARIES (Advanced Retirement and Integrated Extraction System) is a series of processes designed to extract plutonium metal from retired weapons components, convert it to plutonium oxide, and package it for long-term storage, disposition, or feed for MOX fuel fabrication. The ARIES NDA system consists of three NDA instruments and a robot, under central host-computer control, that nondestructively quantify the plutonium mass in the containers of oxide produced by the ARIES processes. The three NDA instruments are a heat flow calorimeter, an active-passive neutron multiplicity counter, and a FRAM gamma-ray isotopic analysis system.

The FRAM gamma-ray isotopic analysis system is similar in concept and execution to the ROBOCAL system previously described. The experience from ROBOCAL in the area of robotics and host computer-instrument-robot communications has been invaluable in the development of the ARIES NDA system. One major departure from ROBOCAL is that the overall ARIES NDA system was designed for glove box operations. While this requirement is no longer applicable, the original design requirement is responsible for the glove box size and configuration of the NDA system pictured in Fig. XIV-3. A close-up of the FRAM detector is seen in Fig. XIV-4.

XIV. FRAM APPLICATIONS IN AUTOMATED SYSTEMS



Fig. XIV-3. The ARIES NDA system installed at the Los Alamos Plutonium Facility.



Fig. XIV-4. A closeup of the FRAM isotopic analysis station in the ARIES NDA system.

The FRAM system in ARIES uses a 25-mm-diam. by 16-mm-thick planar HPGe detector and collects and analyzes data in the 120–420 keV region. Several standards have been fabricated for use in the calibration and measurement control for the instruments in the ARIES NDA system. The characteristics of the ARIES NDA standards are displayed in Table F-4 in Appendix F. Some measurement results for FRAM analysis of data from these standards are shown in Table XIV-1.

Table XIV-1 displays the results of several sets of repeated measurements on the standards characterized in Table XIV-1. Each entry (row) shows the unweighted average (over the No. Meas.) of the Measured/Accepted value for the displayed parameter. The obs % RSD is obtained from the distribution of individual repeated measurements and is an estimate of the standard deviation of a single measurement arising from counting statistics. All measurements were for one hour.

Personnel at Los Alamos are continuing to refine this system, and they plan to test other measurement regimes using different detector types and different energy regions for analysis. The data displayed and discussed in chapter IX indicate that other detector-energy region combinations may offer improved precision over the results in Table XIV-1.

XIV. FRAM APPLICATIONS IN AUTOMATED SYSTEMS

Table XIV-1. Results from FRAM Analysis of Spectra from ARIES NDA Standards.

Ratio = Average Measured/Accepted (²⁴² Pu by Operator Entry)														
Sample	No. Meas	Pu238		Pu239		Pu240		Pu241		Am241		Peff		eff Pu240
		obs %rsd		obs %rsd		obs %rsd		obs %rsd		obs %rsd		obs %rsd		obs %rsd
Calex	15	1.0106	11.1	0.9997	0.11	1.0041	1.83	1.0110	0.36	1.0193	0.77	1.0028	0.30	1.0041
Calex	15	0.9691	13.2	0.9999	0.17	0.9969	2.71	1.0048	0.38	0.9985	0.46	0.9987	0.45	1.0039
Calex	5	1.0288	8.5	0.9999	0.09	1.0023	1.37	1.0044	0.33	0.9935	0.62	1.0001	0.18	1.0023
Avg Calex		1.0028		0.9998		1.0011		1.0067		1.0037		1.0005		1.0034
MC005	15	0.9691	7.76	1.0005	0.14	0.9917	2.26	0.9943	0.32	1.0230	1.47	0.9994	0.30	0.9917
MC005	5	1.0072	6.50	0.9994	0.16	1.0092	2.50	0.9895	0.48	0.9903	1.14	1.0008	0.36	1.0091
MC005	5	1.0199	3.51	1.0000	0.12	0.9997	1.96	0.9899	0.32	0.9920	1.11	1.0001	0.22	0.9999
MC005	5	1.0627	5.60	0.9998	0.10	1.0029	1.55	0.9916	0.14	0.9921	1.35	1.0018	0.29	1.0033
MC004	13	1.0064	7.20	0.9996	0.13	1.0057	2.07	0.9882	0.30	0.9841	1.20	1.0000	0.32	1.0059
MC004	20	1.0424	10.40	1.0000	0.10	0.9997	1.64	0.9893	0.32	0.9897	1.54	1.0006	0.33	1.0000
MC003	14	1.0167	7.79	0.9999	0.17	1.0022	2.67	0.9874	0.43	0.9845	1.15	0.9998	0.49	1.0023
MC003	14	0.9921	7.50	0.9995	0.11	1.0076	1.67	0.9905	0.38	0.9865	1.20	0.9999	0.29	1.0075
Avg all MC		1.0146		0.9999		1.0023		0.9901		0.9928		1.0003		1.0025

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APPENDIX A Measurement Of MOX With PC/FRAM

APPENDIX A**PC/FRAM Technical Note****Measurement Of Mox With PC/FRAM****INTRODUCTION**

The measurement of the ratio of $^{235}\text{U}/\text{Pu}$ in mixed uranium–plutonium oxides is an important problem for gamma-ray spectrometry measurements of the isotopic composition of plutonium. This problem is generally straightforward, as the most prominent gamma ray from ^{235}U at 185.7 keV is usually easy to detect in the gamma-ray spectrum of MOX. This technical note will describe how this measurement is carried out in the PC/FRAM isotopic analysis software and will also describe some of the pitfalls and problems that can arise with the measurement. We will illustrate the performance of FRAM on several types of MOX samples and will describe how the user can “fine tune” FRAM for the particular type of MOX being measured. The note will illustrate the limits of this measurement with respect to the $^{235}\text{U}/\text{Pu}$ ratio.

MEASUREMENT ASSUMPTIONS

The principal assumption that is made when measuring MOX is one of homogeneity. The uranium and plutonium powders are assumed to be uniformly mixed and also assumed to have the same particle size.. Deviations from these assumptions will produce biases. Biases from these effects are not discussed in this note.

GAMMA-RAY MEASUREMENT CHARACTERISTICS OF ^{235}U

The PC/FRAM software can account for the major gamma rays from ^{235}U when it is needed for isotopic ratio measurements or to account for interferences with plutonium gamma rays. The principal gamma rays from ^{235}U and their use in PC/FRAM are tabulated in Table A-1.

The branching ratios are taken from Banham and Jones (Banham 83). Fixed to/Free refers to the condition that all of the ^{235}U gamma-ray peak areas are determined by a ratio to the 185-keV peak, which accounts for branching fractions and relative-efficiency differences. We determine the ^{235}U activity solely from the 185.7-keV peak. The interference regions refer to regions of the spectrum containing other gamma rays used in the MOX analysis.

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Table A-1. U-235 Gamma Rays Used in PC/FRAM MOX Parameter File.

Branching (keV)	Branching Fraction	Fixed to/Free	Purpose
143.78	1.07 e-1	Fix to 185	Interference 141-148 keV
163.36	4.97 e-2	Fix to 185	Interference 160-164 keV
182.72	3.39 e-3	Fix to 185	Interference 185 keV
185.715	5.73 e-1	Free	U-235 activity
194.94	6.26 e-3	Fix to 185	Interference 195 keV
202.13	1.08 e-2	Fix to 185	Interference 203-208 keV
205.31	5.05 e-2	Fix to 185	Interference 203-208 keV

FRAM MOX MEASUREMENTS

FRAM has demonstrated the ability to analyze MOX measurements over a $^{235}\text{U}/\text{Pu}$ range from 0.005 to 35—a dynamic range of 7000. The measurement of the plutonium isotopic composition is very difficult at the high end of this range (above a ratio of approximately 10) because the ^{235}U gamma rays tend to overwhelm the plutonium gamma rays. Test spectra, taken with HPGe detectors, are included with the standard FRAM software distribution and give spectra with ratios from 0.01 to 35. Two parameter files are available for planar detector measurements over this wide range.

We have developed and tested a parameter file for coaxial detectors for analysis over the $^{235}\text{U}/\text{Pu}$ range from 0.005 to 8. An additional set of test spectra for coaxial detector MOX measurements has been developed for distribution with FRAM. The characteristics of these samples are shown in Table A-2.

Measurement results for a subset of these samples are presented in Table A-3. These measurements were made with a 28% relative-efficiency coaxial HPGe detector under the conditions given in Table A-2. The values in the table are the average of 12–15 one-hour measurements. The apparent bias in ^{238}Pu likely arises from contamination of the mass spectrometry measurement. Biases in the $^{235}\text{U}/\text{Pu}$ ratio can arise from several sources. A bias can arise from particle size differences between the uranium and plutonium powders. There is little the user can do about this. A bias can also arise in the $^{235}\text{U}/\text{Pu}$ ratio from the definition of the background regions around the 185.7-keV ^{235}U gamma-ray peak. The current parameter file for MOX measurements with a coaxial detector (MOXCoax3.pst) is set up as a compromise to measure over as wide a dynamic range of $^{235}\text{U}/\text{Pu}$ ratios as possible. For very low $^{235}\text{U}/\text{Pu}$ ratios one wants to set the background ROIs tightly around the 185-keV peak with the background ROI on the high side being between the 185-keV peak and the 188.2–189.3 keV ^{239}Pu peaks. For higher ratios it is probably better to move this background above the 189.3-keV peaks. Some portion of the biases from the analysis of the MOX test spectra arises from this compromise.

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Table A-2. PC/FRAM MOX Test Spectra.

File	Pu Declared Values (wt %)					ppm		
	Pu238	Pu239	Pu240	Pu241	Pu242	Am241	mW/gPu	wt % Pu240eff
HUA 5062	0.0614	87.397	11.831	0.533	0.178	15864	4.7020	12.284
HUA5065	0.0613	87.399	11.831	0.531	0.178	16062	4.7244	12.284
HUA5069	0.0558	87.554	11.693	0.510	0.187	13960	4.4452	12.147
HUA 5301	0.0464	87.629	11.668	0.472	0.185	8180	3.7306	12.095
HUA 8971	0.0549	87.377	11.826	0.533	0.21	9431	3.9297	12.316
PUEU6	0.0137	93.852	5.864	0.204	0.0659	947	2.4186	6.009
PUEU5	0.0137	93.852	5.864	0.204	0.0659	947	2.4186	6.009
PUEU4	0.0137	93.852	5.864	0.204	0.0659	947	2.4186	6.009
9116	0.0209	91.934	7.766	0.226	0.053	10 000	3.5916	7.908
D051	1.029	65.972	24.34	4.753	3.906	49 460	14.652	33.495

File	Pu Mass	U Mass	U235	Ct. Rate		Ct. Time		
	(g)	(g)	(%)	U235/Pu	(kHz)	(h)	Date	Note
HUA 5062	241.6	393.8	0.727	0.0118	30	1	8-Apr-99	
HUA5065	304.9	438.8	0.769	0.0111	30	1	30-Apr-99	
HUA5069	113.6	679.4	1.073	0.0642	30	1	28-Apr-99	
HUA 5301	367.8	805.8	0.225	0.00495	30	1	5-May-99	
HUA 8971	234.8	626	1.022	0.0272	31.5	1	20-Mar-99	
PUEU6	1308	422	93.084	0.301	na	2	3-May-95	1
PUEU5	348	1352	93.084	3.61	na	2	4-May-95	1
PUEU4	174.5	1523	93.084	8.12	na	2	18-May-95	1
9116	54	445	29	2.39	na	0.5	na	
D051	531	1864	48.5	1.70	na	0.38	na	

¹Strong low-energy attenuation from shipping container.

Table A-3 FRAM MOX Measurement Results

Sample	Ratio: Measured/Declared							
	Pu238	Pu239	Pu240	Pu241	Am241	mW/gPu	Pu240eff	U235/Pu
HUA 5301	0.957	1.0004	0.997	0.990	0.968	0.9886	0.9971	0.869
HUA 5062	0.971	1.0048	0.965	0.992	1.021	1.0012	0.9657	1.026
HUA 5065	0.979	1.0023	0.983	0.989	1.015	1.0019	0.9838	0.993
HUA 5069	0.983	0.9998	1.002	0.985	1.003	1.0001	1.002	0.970
HUA 8971	0.965	1.0000	1.000	0.983	1.014	1.0013	1.000	0.927

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Analysis of the $^{235}\text{U}/\text{Pu}$ ratio from HUA 5301 ($^{235}\text{U}/\text{Pu} = 0.0049$) shows that the ^{235}U is at the limit of detectability at this level for this sample. The statistical precision on the $^{235}\text{U}/\text{Pu}$ ratio for a one-hour measurement is about 25% (1 relative standard deviation). The 185-keV region for three different $^{235}\text{U}/\text{Pu}$ ratios is shown in Fig. A-1. You can infer the detectability limit from this figure as well as noting the possible problems in setting the optimum background ROIs. We suggest that the user tailor the 185 keV peak background ROIs specifically for the MOX material types being measured.

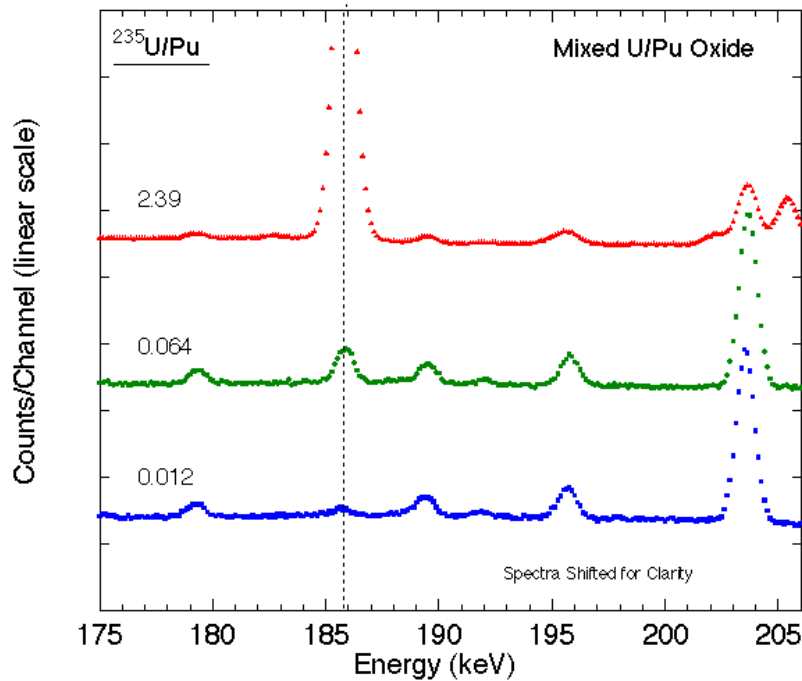


Fig.A-1. Spectra in the 185-keV region from MOX samples with varying $^{235}\text{U}/\text{Pu}$ ratios.

APPENDIX B Considerations For The Use Of FRAM With Rate-Loss Correction Sources

APPENDIX B**PC/FRAM Technical Note****Considerations For The Use Of FRAM With Rate-Loss Correction Sources****INTRODUCTION**

We describe the complications that can arise in a FRAM plutonium analysis when the spectrum is contaminated with gamma-ray peaks from an external rate-loss correction source. We describe two situations where FRAM has been asked to analyze spectra originally acquired for transmission-corrected passive assay [Segmented Gamma Scanner (SGS) or Tomographic Gamma Scanner (TGS)] purposes. We describe the methods used and compromises necessary to accommodate these measurements and also make some general recommendations and observations on this approach.

USE OF A ^{109}Cd RATE-LOSS CORRECTION SOURCE

FRAM has been used to analyze plutonium gamma-ray spectra taken originally for TGS applications. The TGS used a ^{109}Cd source for rate-loss corrections required for that technique, with the ^{109}Cd source fixed to the end cap of the HPGe detector. The system also uses a cadmium metal filter between the detector and the measured sample to reduce the intensity of the 59.54-keV ^{241}Am peak present from plutonium-bearing samples. For the case at hand, the 1.5-mm-thick cadmium did not completely attenuate the 59.54-keV ^{241}Am gamma ray, so there was still a 59.54-keV americium photopeak in the spectrum.

Random summing between the 59.54-keV ^{241}Am peak and the 88.034-keV ^{109}Cd photopeak produces a sum peak around 147.6 keV. This sum peak interferes with the important 148.6-keV gamma ray from ^{241}Pu . The 148.6-keV gamma ray is the strongest and only measurable gamma ray arising directly from ^{241}Pu (not from a daughter) in the energy range above 120 keV and, as such, plays an important role in the plutonium isotopic analysis. If uncorrected, this sum peak interference would bias the 148.6-keV peak area.

SUM PEAK CORRECTION METHODS**Add Additional Filtering**

The simplest way to solve this problem is to add more cadmium filtering to the detector to completely absorb the 59.54-keV ^{241}Am gamma ray. A filter of about 2 mm of cadmium will completely absorb the americium gamma ray for most samples. This solves the problem because there is no longer any gamma ray in the spectrum that can sum with 88 keV to produce an interference at 148 keV. At Los Alamos, we routinely use 2 mm of cadmium as a filter for all FRAM measurements.

Have FRAM Fit the Sum Peak

A less desirable method to make a first-order correction for this effect is to add a peak corresponding to the 147.6-keV sum peak to the Peak List in FRAM. Figure B-1 shows the region around 148 keV for a

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sample of plutonium with 6% ^{240}Pu and about 2000 ppm ^{241}Am . An arrow marks the position of the random sum peak (not present in this picture) from ^{241}Am and ^{109}Cd .

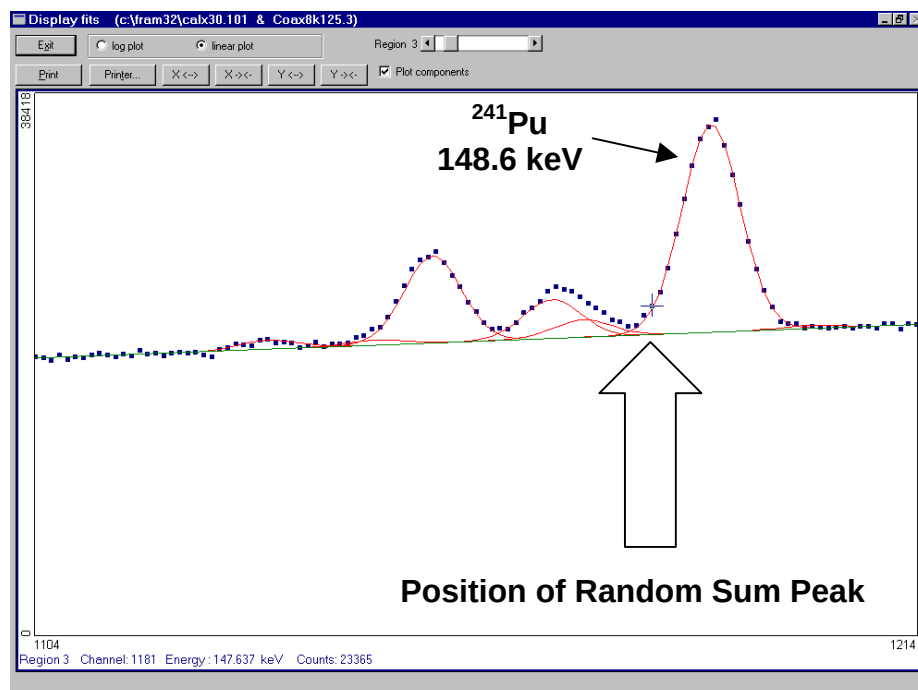


Fig.B-1. The 14- keV region from a low burnup sample of plutonium. The arrow indicates where the random summing peak should appear. No peak is present in this spectrum.

This is termed a first-order correction because sum peaks typically do not have a nice Gaussian shape. They usually tail off slowly on the low energy side of the sum peak because of the finite resolving time of the pileup rejector. This means that the fits may not be as good as they would be with a normal gamma-ray peak. This “fix” is, however, expected to make a reasonably good correction to the ^{241}Pu peak area at 148.6 keV that is the principal peak of interest in the analysis.

PROCEDURE TO ADD SUM PEAK TO PEAK LIST

Select **Edit** from the main menu. Then select **Parameters** from the drop down menu. Complete the User Validation screen according to the passwords on the system. Now you are in the Change Parameter Utility.

Select **File** from the Change Parameter Utility main menu. Then select **Open** from the drop down menu. Choose the parameter file to be modified. Select **Edit** from the Change Parameter Utility main menu. Then select **Peaks** from the drop down menu. Click the box at the left of the row for the 148.567-keV peak of ^{241}Pu . Select **Insert a new row** from the window that will appear. An empty new row will be put into the peak list above the row for the 148-keV peak.

1. Leave the isotope name blank.
2. Fill in the peak energy as 147.57.
3. Fill in 0.00 for the branching ratio.
4. Set fix area to = 0.
5. Set sum area with = 0.
6. The remainder of the boxes are unchanged.

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This section of the peak list should now look similar to that shown below in Fig. B-2.

	isotope	peak energy	line width	branching ratio	fix area to	sum area with	used for eff	used for act	used for ecal	used for fcal	used for scal
7	Pu239	141.657	0.00	3.20000e-007	9	0	☐	☐	☐	☐	☐
8	Pu239	143.350	0.00	1.73000e-007	9	0	☐	☐	☐	☐	☐
9	Pu239	144.211	0.00	2.84000e-006	0	0	☐	☒	☐	☐	☐
10	Pu239	146.077	0.00	1.19000e-006	9	0	☐	☐	☐	☐	☐
11	Am241	146.557	0.00	4.61000e-006	0	0	☐	☐	☐	☐	☐
12		147.570	0.00	0.00000e+000	0	0	☐	☐	☐	☐	☐
13	Pu241	148.567	0.00	1.83200e-006	0	0	☒	☒	☒	☒	☐
14	Am241	150.110	0.00	7.20000e-007	11	0	☐	☐	☐	☐	☐
15	Pu238	152.720	0.00	9.05000e-006	0	0	☐	☒	☐	☐	☐
16	Pu241	153.855	0.00	6.45000e-006	0	0	☐	☐	☐	☐	☐

Fig. B-2. Row 12 has been added to account for the random sum peak. The peak is free in the fitting and no isotope has been assigned for the peak.

This process has allowed us to fit the random sum peak, if present, and remove its effect, to a first-order, from the fitting of the 148.6-keV ^{241}Pu peak area.

USE OF A ^{133}Ba RATE-LOSS CORRECTION SOURCE

We have also been asked to perform a FRAM isotopic analysis on data from an SGS that used a ^{133}Ba source for its rate-loss correction source. Barium-133 has prominent gamma rays at 276.4, 302.9, 356.0, and 383.9 keV. A weaker, but still very visible, gamma-ray peak also occurs at 160.6 keV. This peak causes a direct interference (as opposed to a sum peak) in an already difficult area, the 160-keV region that contains contributions from three isotopes, including the only gamma ray (160.3 keV) from ^{240}Pu between the 100-keV region and the 640-keV region. This additional interference makes it very difficult to independently determine the ^{240}Pu contribution in this region. This region is shown in Fig. B-3 from a spectrum of a sample with 6% ^{240}Pu .

This specific problem posed a much greater difficulty than the illustration of Fig. B-3 would indicate because the data to be analyzed were taken at a conversion gain of 0.5 keV/ch, a factor of four higher than the 0.125 keV/ch illustrated above. The peaks were thus defined with one-fourth as many channels as in Fig. B-3. This was too coarse a spectrum to analyze accurately in this region. The ^{133}Ba interference peak was comparable in magnitude to the ^{240}Pu peak, causing even more difficulties.

APPENDIX B Considerations For The Use Of FRAM With Rate-Loss Correction Sources

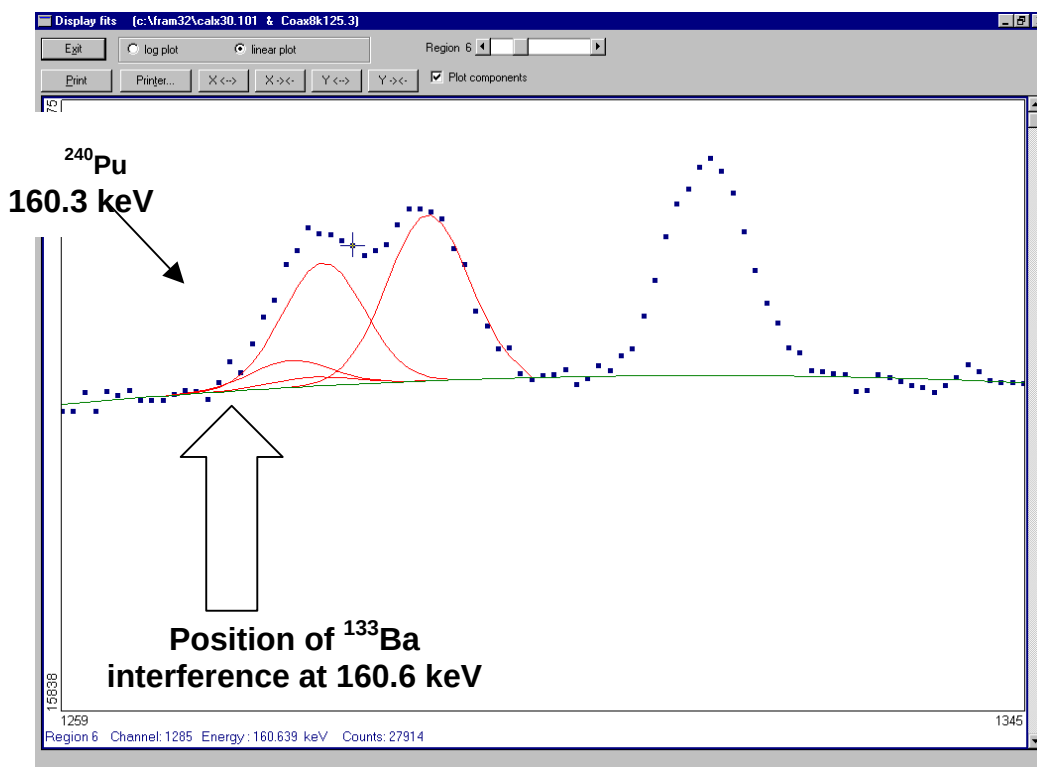


Fig. B-3. 160-keV region for a sample with 6% ^{240}Pu . The large arrow shows where the ^{133}Ba interference would fall. The component of the ^{240}Pu peak at 160.3 keV is identified.

Analysis Approach

The spectra were analyzed in the normal manner, including the ^{133}Ba peak, as described above. We realized that the result for the ^{240}Pu fraction reported by FRAM would not be accurate. However, the other isotopic ratios, Pu238/Pu239, Pu241/Pu239, and Am241/Pu239, would not suffer this bias and their values were extracted from the results for these fundamental ratios displayed in the Medium Output. These ratios were combined with “acceptable knowledge” of the stream average values for ^{240}Pu to extract a reasonable estimate of the entire isotopic distribution, within the limitations of the very coarse nature of the 0.5 keV/ch data.

OBSERVATIONS AND RECOMMENDATIONS

A user will usually obtain inferior isotopic measurements from data taken with an instrument optimized for transmission-corrected passive assay (TCPA), i.e., SGS or TGS. The counting statistics are usually degraded compared to a dedicated isotopic system because of the collimation required for a TCPA. Counting statistics are also degraded, given the total TCPA measurement time, because isotopic data cannot be acquired during the transmission portion of the TCPA measurement. FRAM measurements are most always made without any collimation except for very hot samples measured in restricted geometries.

Detector resolution requirements are more demanding for isotopic analysis than they are for TCPA. Typical TCPA data resolution is usually poorer than that recommended for isotopic analysis, again producing an inferior isotopic result, although it is very difficult to quantify the degree of degradation of the isotopic results arising from poor detector resolution.

APPENDIX B Considerations For The Use Of FRAM With Rate-Loss Correction Sources

The advantages of this method are savings in hardware costs associated with the detector, data acquisition electronics (in some cases), and shielding and sample presentation fixtures. Reduced floor space requirements are often an additional important advantage. Reduced sample handling has the important benefit of lowering radiation exposure to the material handlers.

However, there are seldom throughput advantages to the combination measurement when samples are measured on a continuing basis. Exceptions to this can arise when instrument location gives rise to additional material movement and handling costs. Indeed, there are great flexibility advantages to be derived from separate, dedicated, isotopic analysis systems, as not all samples require both TCPA and isotopic analysis.

Much of the performance degradation could be recovered in a TCPA system designed with a second, additional detector dedicated to the isotopic measurement. This would enable the detector and collimation to be optimized for isotopic analysis while still minimizing material handling and movement costs, thereby reducing total hardware costs and minimizing facility floor space requirements. This type of system has not yet been built, to our knowledge.

Finally, we recommend a gain of less than 0.15 keV/ch for best plutonium isotopic analysis with a coaxial detector in the 120–450 keV energy range. The normal operating gain for FRAM in this energy range is 0.125 keV/ch, although we have used other gains as described above.

APPENDIX C Parameter File Listings

APPENDIX C**Parameter File Listings****Standard Parameter File for Plutonium Analysis, 120-450 keV**

Below is the parameter file listing for Coax_Widerange3, the standard parameter file for plutonium analysis in the 120–450 keV region using data from a coaxial detector and version 4 of FRAM. The parameter file is fully explained in the software user guide for version 4 of FRAM (Kelley 02). The text has been edited slightly for readability.

```
// fit information
name: Coax_Widerange3
desc: "Coax .125 kev/ch, HomoAm/Pu, Equ., 3-25% Pu240,<450 keV "
date: "2002.06.10 18:25"
ecal: 1.250000e-001 5.000000e-003
fix-ecal: N
fcal: 1.500000e+001 1.800000e-001 2.000000e+003
fix-fcal: N
scal: -4.200000e+000 3.000000e-003 2.700000e-001 0.000000e+000
fix-scal: Y

// peak information
num_peaks: 77
1 "Pu239" 124.490 0.000 6.000000e-007 0.000000e+000 0 0 N N N N N 2
2 "Pu239" 125.200 0.000 6.560000e-007 0.000000e+000 4 0 N N N N N 2
3 "Am241" 125.292 0.000 4.136000e-005 0.000000e+000 0 0 N Y N N N 2
4 "Pu239" 129.294 0.000 6.290000e-005 0.000000e+000 0 0 Y Y Y Y Y 1
5 "Pu239" 141.657 0.000 3.341000e-007 0.000000e+000 8 0 N N N N N 0
6 "Pu239" 143.350 0.000 1.806000e-007 0.000000e+000 8 0 N N N N N 4
7 "U235" 143.780 0.000 1.070000e-001 0.000000e+000 25 0 N N N N N 4
8 "Pu239" 144.211 0.000 2.888000e-006 0.000000e+000 0 0 N N N N N 4
9 "Pu239" 146.077 0.000 1.224000e-006 0.000000e+000 8 0 N N N N N 4
10 "Am241" 146.557 0.000 5.150000e-006 0.000000e+000 0 0 N N N N N 4
11 "Pu241" 148.567 0.000 1.894000e-006 0.000000e+000 0 0 Y Y Y Y Y 4
12 "Am241" 150.113 0.000 7.570000e-007 0.000000e+000 0 0 N N N N N 4
13 "Pu238" 152.720 0.000 9.370000e-006 0.000000e+000 0 0 N Y N N N 5
14 "Pu241" 159.970 0.000 6.700000e-008 0.000000e+000 11 0 N N N N N 7
15 "Pu239" 160.180 0.000 5.768000e-008 0.000000e+000 17 0 N N N N N 7
16 "Pu240" 160.308 0.000 4.035000e-006 0.000000e+000 0 0 N Y N N N 7
17 "Pu239" 161.482 0.000 1.229000e-006 0.000000e+000 0 0 N Y N N N 7
18 "Am241" 161.540 0.000 1.900000e-008 0.000000e+000 3 0 N N N N N 7
19 "U235" 163.363 0.000 4.970000e-002 0.000000e+000 25 0 N N N N N 6
20 "Pu241" 164.597 0.000 4.663000e-007 0.000000e+000 0 0 Y Y Y Y Y 6
21 "Am241" 164.597 0.000 6.879000e-007 0.000000e+000 3 0 N N N N N 6
22 "Am241" 165.930 0.000 2.300000e-007 0.000000e+000 0 0 N N N N N 6
23 "Am241" 169.567 0.000 1.739000e-006 0.000000e+000 0 0 N Y N N N 8
24 "Pu239" 171.372 0.000 1.130000e-006 0.000000e+000 0 0 N Y N N N 8
25 "U235" 185.718 0.000 5.730000e-001 0.000000e+000 0 0 N Y N N N 3
26 "U235" 202.130 0.000 1.080000e-002 0.000000e+000 25 0 N N N N N 9
27 "Pu239" 203.545 0.000 5.727000e-006 0.000000e+000 0 0 Y Y N N N 9
28 "U235" 205.311 0.000 5.050000e-002 0.000000e+000 25 0 N N N N N 0
29 "Pu241" 208.000 0.000 5.392000e-006 0.000000e+000 0 0 Y Y Y Y Y 10
30 "Am241" 208.000 0.000 7.954000e-006 0.000000e+000 3 0 N N N N N 10
```


APPENDIX C Parameter File Listings

```

31 "Am243" 209.750 0.000 3.420000e-002 0.000000e+000 34 0 N N N N N 10
32 "Am243" 226.360 0.000 2.800000e-003 0.000000e+000 34 0 N N N N N 11
33 "Am243" 227.810 0.000 5.100000e-003 0.000000e+000 34 0 N N N N N 11
34 "Am243" 228.160 0.000 1.076000e-001 0.000000e+000 0 0 N Y N N N 11
35 "Am243" 254.400 0.000 1.100000e-003 0.000000e+000 34 0 N N N N N 12
36 "Pu239" 255.380 0.000 7.987000e-007 0.000000e+000 0 0 Y Y N N N 12
37 "Pu239" 263.930 0.000 2.498000e-007 0.000000e+000 0 0 N N N N N 13
38 " " 264.850 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 13
39 "Pu239" 265.700 0.000 1.507000e-008 0.000000e+000 37 0 N N N N N 13
40 "Pu241" 267.540 0.000 1.786000e-007 0.000000e+000 0 0 Y Y Y N N 13
41 "Am241" 267.540 0.000 2.635000e-007 0.000000e+000 3 0 N N N N N 13
42 "Pu239" 311.700 0.000 2.617000e-007 0.000000e+000 58 0 N N N N N 14
43 "Np237" 311.900 0.000 3.860000e-001 0.000000e+000 0 0 N Y N N N 14
44 "Pu239" 319.828 0.000 4.545000e-008 0.000000e+000 0 0 N N N N N 15
45 "Pu239" 320.868 0.000 5.026000e-007 0.000000e+000 0 0 N N N N N 15
46 "Am241" 322.526 0.000 1.498000e-006 0.000000e+000 0 0 N Y N N N 15
47 "Pu239" 323.828 0.000 5.377000e-007 0.000000e+000 0 0 N N N N N 15
48 "Pu241" 332.387 0.000 2.974000e-007 0.000000e+000 0 0 N Y N N N 17
49 "Am241" 332.387 0.000 1.476000e-006 0.000000e+000 53 0 N N N N N 17
50 "Pu239" 332.850 0.000 4.940000e-006 0.000000e+000 58 0 N N N N N 17
51 "Am243" 334.310 0.000 2.070000e-002 0.000000e+000 34 0 N N N N N 17
52 "Pu241" 335.432 0.000 2.392000e-008 0.000000e+000 29 0 N N N N N 17
53 "Am241" 335.432 0.000 4.872000e-006 0.000000e+000 0 0 N Y N N N 17
54 "Pu239" 336.112 0.000 1.144000e-006 0.000000e+000 58 0 N N N N N 17
55 " " 337.720 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 17
56 " " 340.450 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 16
57 "Pu239" 341.495 0.000 6.603000e-007 0.000000e+000 58 0 N N N N N 16
58 "Pu239" 345.011 0.000 5.533000e-006 0.000000e+000 0 0 Y Y Y Y Y 16
59 "Pu239" 367.054 0.000 8.590000e-007 0.000000e+000 0 0 N N N N N 19
60 "Pu239" 368.534 0.000 8.992000e-007 0.000000e+000 66 0 N N N N N 19
61 "Pu241" 368.605 0.000 1.039000e-008 0.000000e+000 29 0 N N N N N 19
62 "Am241" 368.605 0.000 2.115000e-006 0.000000e+000 0 0 N Y N N N 19
63 "Pu241" 370.934 0.000 2.747000e-008 0.000000e+000 0 0 N N N N N 19
64 "Am241" 370.934 0.000 5.119000e-007 0.000000e+000 53 0 N N N N N 19
65 " " 372.450 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 19
66 "Pu239" 375.042 0.000 1.554000e-005 0.000000e+000 0 0 Y Y Y N N 18
67 "Np237" 375.300 0.000 6.790000e-003 0.000000e+000 43 0 N N N N N 18
68 "Am241" 376.610 0.000 1.520000e-006 0.000000e+000 0 0 N N N N N 18
69 "Pu239" 410.900 0.000 3.933000e-008 0.000000e+000 0 0 N N N N N 20
70 " " 412.000 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 20
71 "Pu239" 413.712 0.000 1.469000e-005 0.000000e+000 0 0 Y Y Y Y N 20
72 " " 414.800 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 20
73 "Np237" 415.731 0.000 1.745000e-002 0.000000e+000 43 0 N N N N N 20
74 " " 415.800 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 20
75 "Am241" 419.270 0.000 2.874000e-007 0.000000e+000 0 0 N N N N N 0
76 "Pu239" 451.474 0.000 1.898000e-006 0.000000e+000 0 0 Y Y Y Y Y 21
77 "Am241" 452.450 0.000 2.400000e-008 0.000000e+000 53 0 N N N N N 21

```

```
// region information
```

```
num_regions: 21
```

```

1 127.600 131.000 127.100 127.700 131.000 131.600 131.800 132.400 0.000 0.000 6 "linear step"
2 124.200 126.500 126.600 127.100 127.100 127.700 0.000 0.000 0.000 0.000 2 "linear"
3 184.100 186.800 183.400 184.100 186.700 187.200 0.000 0.000 0.000 0.000 2 "linear"
4 142.700 150.900 138.100 139.200 151.000 151.400 0.000 0.000 0.000 0.000 2 "linear"
5 151.600 153.900 151.000 151.400 154.100 154.900 0.000 0.000 0.000 0.000 2 "linear"
6 162.800 166.700 162.500 163.100 166.900 167.800 0.000 0.000 0.000 0.000 2 "linear"
7 158.900 163.400 157.900 158.600 162.300 163.100 0.000 0.000 0.000 0.000 2 "linear"
8 168.500 172.700 167.700 168.300 173.000 173.600 0.000 0.000 0.000 0.000 2 "linear"
9 201.800 205.000 201.000 201.500 201.500 202.000 204.900 205.400 0.000 0.000 2 "linear"
10 205.900 211.500 205.100 205.700 211.700 212.400 212.700 213.400 0.000 0.000 6 "linear step"
11 226.300 229.300 223.100 223.900 229.600 230.400 0.000 0.000 0.000 0.000 2 "linear"
12 253.900 256.900 252.700 253.200 253.300 253.800 257.100 257.800 0.000 0.000 2 "linear"
13 262.600 269.500 261.900 262.600 269.600 270.200 270.400 270.900 0.000 0.000 6 "linear step"
14 310.100 313.700 309.200 309.700 313.900 314.400 0.000 0.000 0.000 0.000 2 "linear"
15 318.700 325.200 317.500 318.000 318.000 318.500 325.400 325.900 326.100 326.600 5 "flat step"
16 339.500 347.300 328.800 329.400 329.500 330.100 347.800 348.400 348.800 349.400 5 "flat step"
17 330.000 339.000 328.800 329.400 329.500 330.100 347.800 348.400 348.800 349.400 5 "flat step"

```

APPENDIX C Parameter File Listings

```

18 373.000 378.000 363.800 364.400 364.500 365.100 385.500 386.100 386.200 386.800 5 "flat step"
19 365.300 372.900 363.800 364.400 364.500 365.100 385.500 386.100 386.200 386.800 5 "flat step"
20 409.200 417.200 404.000 404.600 404.900 405.500 432.200 432.800 433.000 433.600 5 "flat step"
21 449.000 453.500 448.200 448.800 455.900 456.500 0.000 0.000 0.000 0.000 5 "flat step"

```

```
// isotope information
```

```
num_isotopes: 9
```

```

1 "Pu239" 2.411900e+004 years 239.05220 1.92880 0.0000 1
2 "Pu241" 1.434800e+001 years 241.05690 3.41120 0.0000 1
3 "Am241" 4.336000e+002 years 241.05679 114.20000 0.0000 1
4 "Pu238" 8.774000e+001 years 238.04961 567.57000 2.5200 1
5 "Pu240" 6.564000e+003 years 240.05380 7.08240 1.0000 1
6 "Pu242" 3.763000e+005 years 242.05874 0.11590 1.6800 1
7 "Np237" 2.140000e+006 years 237.04817 0.00000 0.0000 1
8 "U235" 7.038100e+008 years 235.04390 0.00000 0.0000 1
9 "Am243" 7.370000e+003 years 243.06140 0.00000 0.0000 1

```

```
// appcon information
```

```
num_appcons: 65
```

```

1 "pu242_correlation" "1.1174"
2 "pu238_exponent" ".5"
3 "pu239_exponent" "-1.5"
4 "pu240_exponent" ".75"
5 "pu241_exponent" ".25"
6 "FRAM_SUMMARY_TYPE" "PLUTONIUM"
7 "num_ecal" "2"
8 "ecal_energy[1]" "208.00"
9 "ecal_channel[1]" "1664.00"
10 "ecal_limit[1]" "3.0"
11 "ecal_energy[2]" "662.456"
12 "ecal_channel[2]" "5299.40"
13 "ecal_limit[2]" "4.0"
14 "num_fwhmcal" "1"
15 "fcal_energy[1]" "413.714"
16 "fcal_limit[1]" "1500."
17 "num_tailfract" "1"
18 "scal_energy[1]" "413.714"
19 "scal_limit[1]" "5.0"
20 "num_intf" "1"
21 "intf_1st_energy[1]" "185.720"
22 "intf_2nd_energy[1]" "203.545"
23 "intf_limit[1]" "0.2"
24 "intf_msg[1]" "*** U235 TOO HIGH, USE MOXCOAX3 PARAMETER FILE ***"
25 "intf_1st_energy[2]" "228.140"
26 "intf_2nd_energy[2]" "203.545"
27 "intf_limit[2]" ".025"
28 "intf_msg[2]" "*** possible presence of Np239 ***"
29 "intf_1st_energy[3]" "311.887"
30 "intf_2nd_energy[3]" "345.011"
31 "intf_limit[3]" "2."
32 "intf_msg[3]" "*** possible presence of Np237 ***"
33 "num_samptype" "2"
34 "type_1st_peak[1]" "11"
35 "type_2nd_peak[1]" "20"
36 "type_lower_limit[1]" ".9"
37 "type_upper_limit[1]" "1.1"
38 "type_msg[1]" "Possible non-equilibrium or heterogeneous sample."
39 "type_1st_peak[2]" "3"
40 "type_2nd_peak[2]" "53"

```

APPENDIX C Parameter File Listings

```

41 "type_lower_limit[2]" ".93"
42 "type_upper_limit[2]" "1.07"
43 "type_msg[2]" "Possible heterogeneous (Am/Pu) sample."
44 "fix_bad_bkg" "TRUE"
45 "AutoShieldTest" "yes"
46 "AutoShieldPass" "ShCoax_Widerange3"
47 "Shield_LowEnergy" "129.294"
48 "Shield_HighEnergy" "413.712"
49 "Shield_HighToLowLimit" "20"
50 "AutoHeteroTest" "yes"
51 "AutoHeteroPass" "Coax_HeteroAmPu3"
52 "Hetero_Energy[1]" "125.292"
53 "Hetero_Energy[2]" "335.422"
54 "Hetero_LowerLimit" ".9"
55 "Hetero_UpperLimit" "1.05"
56 "eff_use_dflts" "yes"
57 "eff_det_type" "1"
58 "eff_upu_min" "0.001"
59 "eff_upu_max" "20."
60 "eff_abs_name[1]" "Fe"
61 "eff_abs_min[1]" "0.10"
62 "eff_abs_max[1]" "6.0"
63 "eff_abs_name[2]" "Cd"
64 "eff_abs_min[2]" "0.20"
65 "eff_abs_max[2]" "3.0"
// end

```

APPENDIX C Parameter File Listings

Standard Parameter File for Uranium Analysis

Below is the parameter file listing for U121_1001Coax, the standard parameter file for uranium analysis in the 120–1001 keV region using data from a coaxial detector and version 4 of FRAM. The parameter file is fully explained in the software user guide for version 4 of FRAM (Kelley 02). The text has been edited slightly for readability.

```
// fit information
name: U121_1001Coax
desc: " U Only, All Enrichments, 0.125 keV/ch, Coax Detector"
date: "2002.06.10 18:27"
ecal: 1.250000e-001 0.000000e+000
fix-ecal: N
fcal: 1.920000e+001 1.760000e-001 1.550000e+003
fix-fcal: N
scal: -4.870000e+000 3.840000e-003 1.530000e-001 0.000000e+000
fix-scal: Y
// peak information
num_peaks: 27
1 "U234" 120.905 0.000 3.390000e-004 0.000000e+000 0 0 N Y N N N 1
2 "U235" 140.760 0.000 2.620000e-003 0.000000e+000 0 0 N N N N N 2
3 "U235" 143.760 0.000 1.095000e-001 0.000000e+000 0 0 Y N Y Y Y 2
4 " " 145.940 0.000 0.000000e+000 0.000000e+000 0 0 N N N N N 2
5 "U235" 163.330 0.000 5.089000e-002 0.000000e+000 0 0 Y N Y Y Y 3
6 "U235" 182.610 0.000 4.024000e-003 0.000000e+000 0 0 N N N N N 4
7 "U235" 185.715 0.000 5.739000e-001 0.000000e+000 0 0 Y Y Y Y Y 4
8 "U235" 202.110 0.000 1.100000e-002 0.000000e+000 0 0 N N N N N 5
9 "U235" 205.311 0.000 4.993000e-002 0.000000e+000 0 0 Y N N N N 5
10 "Th228" 238.630 0.000 4.494000e-001 0.000000e+000 0 0 Y Y N N N 6
11 "U235" 240.870 0.000 6.984000e-004 0.000000e+000 0 0 N N N N N 6
12 "U238" 258.260 0.000 7.330000e-004 0.000000e+000 0 0 Y N N N N 7
13 "Th228" 583.190 0.000 2.944000e-001 0.000000e+000 0 0 Y Y N N N 8
14 "Th228" 727.300 0.000 6.577000e-002 0.000000e+000 0 0 Y Y N N N 9
15 "U238" 738.000 0.000 2.091000e-005 0.000000e+000 0 0 N N N N N 10
16 "U238" 739.950 0.000 1.165000e-004 0.000000e+000 0 0 N N N N N 10
17 "U238" 742.810 0.000 8.982000e-004 0.000000e+000 0 0 Y N N N N 10
18 "Th228" 763.300 0.000 6.380000e-003 0.000000e+000 0 0 N N N N N 11
19 "U238" 766.360 0.000 3.074000e-003 0.000000e+000 0 0 Y N Y Y Y 11
20 "Th228" 860.500 0.000 4.596000e-002 0.000000e+000 0 0 Y Y N N N 12
21 "U238" 880.450 0.000 2.119000e-004 0.000000e+000 0 0 Y N N N N 13
22 "U238" 883.220 0.000 2.121000e-004 0.000000e+000 0 0 Y N N N N 13
23 "U238" 941.940 0.000 2.851000e-005 0.000000e+000 0 0 N N N N N 14
24 "U238" 945.950 0.000 3.462000e-004 0.000000e+000 0 0 Y N N N N 14
25 "U238" 947.700 0.000 2.215000e-005 0.000000e+000 0 0 N N N N N 14
26 "U238" 994.940 0.000 5.656000e-005 0.000000e+000 0 0 N N N N N 15
27 "U238" 1001.030 0.000 8.371000e-003 0.000000e+000 0 0 Y Y Y Y Y 15

// region information
num_regions: 15
1 119.700 122.100 118.700 119.500 122.400 123.400 0.000 0.000 0.000 0.000 2 "linear"
2 139.200 147.000 136.800 137.700 137.900 139.000 147.100 148.200 148.500 149.600 6 "linear step"
3 160.800 165.000 158.400 159.700 159.800 161.000 166.300 167.400 167.800 169.000 6 "linear step"
4 181.200 187.500 177.000 178.500 180.000 181.000 189.100 190.500 190.800 192.000 7 "bilinear step"
5 198.100 207.000 197.500 198.000 200.000 200.500 207.000 208.000 211.000 212.000 6 "linear step"
6 237.500 242.000 231.000 232.000 243.000 244.000 0.000 0.000 0.000 0.000 2 "linear"
7 256.700 260.000 252.500 254.500 260.500 262.500 0.000 0.000 0.000 0.000 2 "linear"
8 581.000 585.000 579.000 580.000 586.000 587.000 0.000 0.000 0.000 0.000 2 "linear"
9 725.000 729.800 718.100 719.600 734.800 735.800 745.700 746.800 749.300 750.700 6 "linear step"
10 736.400 745.400 718.100 719.600 734.800 735.800 745.700 746.800 749.300 750.700 6 "linear step"
11 762.000 768.600 752.700 754.200 758.600 760.200 770.200 771.600 772.000 773.500 6 "linear step"
12 857.750 862.500 855.750 857.000 862.750 864.000 0.000 0.000 0.000 0.000 2 "linear"
```

APPENDIX C Parameter File Listings

```

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14 940.000 949.000 938.000 939.500 954.000 956.000 0.000 0.000 0.000 0.000 2 "linear"
15 992.500 1006.000 987.000 988.500 990.000 991.500 1008.000 1010.000 1011.000 1013.000 6 "linear step"

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// isotope information
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2 "U235" 7.038100e+008 years 235.04393 0.00006 0.0000 1
3 "U234" 2.446000e+005 years 234.04090 0.18023 0.0000 1
4 "U236" 2.341500e+007 years 236.04556 0.00175 0.0000 1
5 "Th228" 1.913100e+000 years 228.02873 0.00000 0.0000 1

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// appcon information
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8 "ecal_limit[1] (channels)" "3.0"
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26 "eff_abs_name[1]" "Fe"
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28 "eff_abs_max[1]" "6.0"
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30 "eff_abs_min[2]" "0.2"
31 "eff_abs_max[2]" "3.0"
// end

```

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies**APPENDIX D****Plutonium and Americium Branching Ratios and Gamma-Ray Energies
(Gunnink 76a)**

Table D-1. Plutonium and Americium Branching Ratios and Gamma-Ray Energies.

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
237U	26.34	2.43E-02	0.5	2.28E+06
241Am	26.344	2.45E-02	0.1	3.10E+09
239Pu	30.040	2.170E-06	3	4.978E+03
241Am	32.183	1.74E-04	1	2.20E+07
237U	33.19	1.30E-03	1.6	1.22E+05
241Am	33.197	1.26E-03	0.3	1.59E+08
239Pu	38.664	1.050E-04	1.0	2.409E+05
239Pu	40.410	1.620E-06	10	3.717E+03
239Pu	42.060	1.650E-06	3	3.785E+03
237U	43.43	2.40E-04	7	2.25E+04
238Pu	43.477	3.930E-04	0.3	2.489E+08
241Pu	44.20	4.18E-08		1.60E+05
241Pu	44.86	8.36E-09		3.20E+04
240Pu	45.232	4.53E-04	0.2	3.80E+06
239Pu	46.210	7.370E-06	10	1.691E+04
239Pu	46.690	5.800E-07	6	1.331E+03
237U	51.005	3.40E-03	2	3.19E+05
239Pu	51.629	2.700E-04	0.2	6.194E+05
239Pu	54.040	2.000E-06	1.4	4.588E+03
241Pu	56.32	2.50E-08		9.56E+04
241Pu	56.76	9.75E-09		3.73E+04
239Pu	56.838	1.130E-05	1.0	2.592E+04
237U	59.536	3.45E-01	0.2	3.23E+07
241Am	59.536	3.59E-01		4.54E+10
237U	64.832	1.30E-02	0.5	1.22E+06
239Pu	65.741	4.530E-07	4	1.039E+03
239Pu	67.670	1.610E-06	2.0	3.694E+03
239Pu	68.720	5.100E-06	1	1.170E+04

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
241Pu	71.6	2.86E-08	10	1.09E+05
241Pu	77.10	2.22E-07	3	8.49E+05
239Pu	77.607	3.900E-06	0.7	8.947E+03
239Pu	78.420	1.520E-06	1.4	3.487E+03
238Pu	94.658	1.050E-06	1.4	6.650E+05
240Pu	94.658	6.36E-07	5	5.34E+03
241Pu	94.658	3.03E-06	0.5	1.16E+07
239Pu	94.660	4.220E-05	0.25	9.681E+04
239Pu	96.130	2.230E-07	20	5.116E+02
237U	97.071	1.58E-01	0.4	1.48E+07
241Am	97.071	1.18E-05	2	1.49E+06
240Pu	98.442	1.02E-06	5	8.56E+03
239Pu	98.442	6.760E-05	0.3	1.551E+05
238Pu	98.442	1.690E-06	1.0	1.070E+06
241Pu	98.442	4.85E-06	0.5	1.85E+07
239Pu	98.780	1.220E-05	3	2.799E+04
241Am	98.951	2.03E-04	0.5	2.57E+07
238Pu	99.864	7.240E-05	0.2	4.585E+07
237U	101.066	2.52E-01	0.3	2.36E+07
241Am	101.066	1.90E-05	1.4	2.40E+06
241Am	102.966	1.95E-04	0.5	2.47E+07
239Pu	103.020	2.170E-06	1.6	4.978E+03
241Pu	103.680	1.01E-06	0.6	3.86E+06
240Pu	104.244	6.98E-05	0.4	5.86E+05
238Pu	110.421	2.000E-07		1.267E+05
239Pu	110.421	7.950E-06	0.8	1.824E+04
240Pu	110.421	1.18E-07		9.91E+02
241Pu	110.421	5.90E-07	1.5	2.26E+06
238Pu	111.300	3.900E-07		2.470E+05
239Pu	111.300	1.550E-05	0.6	3.556E+04
240Pu	111.300	2.30E-07		1.93E+03
241Pu	111.300	1.09E-06	1	4.17E+06
239Pu	111.890	3.070E-07	10	

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
241Pu	111.89	3.31E-08		1.27E+05
237U	113.300	3.04E-02	0.5	2.85E+06
241Am	113.300	2.37E-06		3.00E+05
237U	114.230	5.85E-02	0.3	5.48E+06
241Am	114.230	4.72E-06		5.97E+05
238Pu	114.333			
239Pu	114.333	6.280E-06	2	1.441E+04
240Pu	114.333	9.32E-08		7.82E+02
241Pu	114.34	1.60E-07		6.12E+05
241Pu	114.56	3.64E-07		1.39E+06
238Pu	114.561	1.580E-07		1.001E+05
239Pu	114.561			
240Pu	114.561			
237U	114.950	3.35E-03	10	3.14E+05
241Am	114.950	2.30E-06		
239Pu	115.380	6.490E-06	1.5	1.489E+04
238Pu	115.400			
240Pu	115.40			
241Pu	115.40	1.34E-07		5.12E+05
239Pu	116.260	5.970E-06	1.5	1.370E+04
237U	117.340	7.90E-03		7.40E+05
241Am	117.340			
237U	117.580	1.56E-02		1.46E+06
241Am	117.580			
237U	118.43	8.23E-03		7.71E+05
241Am	118.43			
239Pu	119.708	3.000E-07	2	6.883E+02
241Pu	121.2	6.85E-09		2.62E+04
241Am	122.994	1.00E-05	0.8	1.27E+06
239Pu	123.620	1.970E-07	6	4.520E+02
239Pu	124.510	6.130E-07	3	1.406E+03
239Pu	125.210	7.110E-07	2	1.631E+03
241Am	125.292	4.08E-05	0.5	5.16E+06

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
239Pu	129.294	6.260E-05	0.2	
241Am	139.53	5.34E-08	20	6.76E+03
239Pu	141.657	3.200E-07	2	7.341E+02
239Pu	143.350	1.730E-07	4	3.969E+02
239Pu	144.211	2.830E-06	0.6	6.493E+03
239Pu	146.077	1.190E-06	0.6	2.730E+03
241Am	146.557	4.61E-06	1	5.83E+05
241Pu	148.567	1.87E-06	0.3	7.15E+06
241Am	150.11	7.40E-07	2	9.36E+04
238Pu	152.680	9.560E-06	0.5	6.054E+06
239Pu	158.100		10	2.294E+01
241Pu	159.955	6.74E-08		2.58E+05
239Pu	160.190	6.200E-08	20	1.422E+02
240Pu	160.280	4.02E-06	0.7	3.37E+04
239Pu	161.450	1.200E-06	0.4	2.753E+03
237U	164.580	1.84E-02	0.5	1.72E+06
241Am	164.580	6.67E-07	3	8.44E+04
241Am	165.93	2.32E-07	4	2.94E+04
239Pu	167.810	2.930E-08	25	6.722E+01
241Am	169.557	1.73E-06	1	2.19E+05
239Pu	171.344	1.105E-06	0.8	2.535E+03
239Pu	173.700	3.050E-08	25	6.997E+01
241Am	175.09	1.82E-07	5	2.30E+04
239Pu	179.190	6.580E-07	1	1.510E+03
239Pu	184.550	2.120E-08	30	4.864E+01
239Pu	188.230	1.090E-07	10	2.501E+02
239Pu	189.320	8.300E-07	2	
241Am	190.40	2.19E-08	20	2.77E+03
241Am	191.90	2.16E-07	4	2.73E+04
239Pu	193.000	8.870E-08	10	2.035E+02
239Pu	195.660	1.064E-06	0.5	2.441E+03
239Pu	196.870	3.700E-08	12	8.489E+01
238Pu	200.980	4.080E-08	2	2.584E+04

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
239Pu	203.537	5.600E-06	0.2	1.285E+04
241Am	203.87	2.90E-08	6	3.67E+03
237U	208.000	2.17E-01	0.2	2.03E+07
241Am	208.000	7.91E-06	0.5	1.00E+06
237U	221.73	2.12E-04	2	1.99E+04
241Am	221.73	4.24E-07	1	5.37E+04
239Pu	225.370		4	3.579E+02
241Am	233.87	4.64E-08	6	5.87E+03
237U	234.24	2.05E-04	2	1.92E+04
241Am	234.33	6.57E-09	40	8.31E+02
239Pu	237.380	1.440E-07	4	3.304E+02
239Pu	242.080	7.310E-08	7	1.677E+02
239Pu		2.530E-07	2	5.804E+02
239Pu	244.920	5.100E-08	10	1.170E+02
241Am	246.70	2.42E-08	10	3.06E+03
239Pu	248.950	7.240E-08	10	1.661E+02
239Pu	255.380	8.050E-07	2	1.847E+03
241Am	260.90	1.21E-08	15	1.53E+03
239Pu	263.930	2.610E-07	3	5.988E+02
241Am	264.85	9.04E-08	4	1.14E+04
239Pu	265.700	1.580E-08	25	3.625E+01
237U	267.54	7.40E-03	0.5	6.93E+05
241Am	267.54	2.63E-07	2	3.33E+04
241Am	271.58	6.37E-09	30	8.06E+02
241Am	275.68	6.57E-08	5	8.31E+03
239Pu	281.200	2.150E-08	15	4.933E+01
239Pu	285.300	1.910E-08		4.382E+01
241Am	291.21	3.08E-08	10	3.90E+03
241Am	292.78	1.42E-07	3	1.80E+04
239Pu	297.490	5.020E-07	2	1.152E+03
239Pu	302.870	5.130E-08	8	1.177E+02
241Am	304.23	1.01E-08	20	1.28E+03
239Pu	307.850	5.470E-08	7	1.255E+02

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
239Pu	311.740	2.580E-07	2	5.919E+02
239Pu	316.410	1.360E-07	3	3.120E+02
239Pu	319.680	4.800E-08	10	1.101E+02
239Pu	320.880	5.360E-07	1	1.230E+03
241Am	322.503	1.518E-06	0.6	1.92E+05
239Pu	323.810	5.420E-07	1	1.243E+03
237U	332.354	1.21E-02	0.3	1.13E+06
241Am	332.354	1.490E-06	0.3	1.89E+05
239Pu	332.838	5.060E-06	0.2	1.161E+04
237U	335.405	9.70E-04	1.0	9.09E+04
241Am	335.405	4.960E-06	0.3	6.28E+05
239Pu	336.107	1.134E-06	0.3	2.602E+03
241Am	337.72	4.29E-08	5	5.43E+03
237U	337.75	8.90E-05	5	8.34E+03
237U	340.45	1.65E-05	20	1.55E+03
239Pu	341.510	6.620E-07	0.4	1.519E+03
239Pu	345.014	5.592E-06	0.2	1.283E+04
241Am	350.56	1.19E-08	20	1.51E+03
239Pu	350.800	1.750E-08	20	4.015E+01
239Pu	354.000	7.310E-09	40	1.677E+01
241Am	358.36	1.20E-08	20	
239Pu	361.890	1.220E-07	5	2.799E+02
239Pu	367.050	8.650E-07	0.3	1.984E+03
239Pu	368.550	9.030E-07	0.3	2.072E+03
237U	368.605	4.29E-04	2	
241Am	368.605	2.17E-06	0.3	2.75E+05
237U	370.934	1.103E-03	1.4	1.03E+05
241Am	370.934	5.23E-07	0.8	6.62E+04
239Pu	375.042	1.570E-05	0.1	3.602E+04
241Am	376.595	1.383E-06	0.7	1.75E+05
239Pu	380.166		0.2	7.000E+03
239Pu	382.751	2.587E-06	0.2	5.935E+03
241Am	383.74	2.82E-07		3.57E+04

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
241Am	390.54	5.90E-08	4	7.47E+03
239Pu	392.530	5.527E-06	0.2	1.268E+04
239Pu	393.140			0.000E+00
239Pu	399.510	6.100E-08	4	1.399E+02
241Am	406.37	1.45E-08	15	1.84E+03
239Pu	406.900	6.350E-09	40	1.457E+01
239Pu	411.150		50	1.560E+02
239Pu	413.712	1.489E-05	0.1	3.416E+04
241Am	419.24	2.87E-07	2	3.63E+04
239Pu	422.586	1.193E-06	0.4	2.737E+03
241Am	426.39	2.46E-07	2	3.11E+04
239Pu	426.680	2.328E-07	1.5	5.341E+02
239Pu	428.400	1.000E-08	10	2.294E+01
241Am	429.84	1.15E-08	20	1.46E+03
239Pu	430.080	4.300E-08	3	
241Am	442.75	3.52E-08	7	4.45E+03
239Pu	445.720	8.700E-08	2	1.996E+02
239Pu	446.820	8.450E-09	15	1.939E+01
239Pu	451.474	1.890E-06	0.3	4.336E+03
241Am	452.21	2.40E-08	10	3.04E+03
241Am	454.62	9.70E-08	3	1.23E+04
239Pu	457.610	1.490E-08	1	3.418E+01
241Am	459.59	3.63E-08	7	4.59E+03
239Pu	461.250	2.270E-08	1	5.208E+01
239Pu	463.900	2.780E-09	10	
241Am	467.98	2.88E-08	7	3.64E+03
239Pu	473.900	5.360E-10	50	1.230E+00
239Pu	481.540	4.600E-08	0.6	1.055E+02
241Am	486.3	1.00E-08	30	1.27E+03
239Pu	487.060	2.650E-09	8.0	6.080E+00
239Pu	493.080	8.680E-09	3.0	1.991E+01
239Pu	497.000	4.610E-10	50	1.058E+00
241Am	514.2	2.58E-08	10	3.27E+03

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
241Am	522.0	9.46E-09	30	1.20E+03
239Pu	526.400	5.720E-10	30	1.312E+00
239Pu	538.800	3.050E-09	6	6.997E+00
239Pu	550.500	4.220E-09	6	9.681E+00
239Pu	557.300	3.820E-10	50	8.764E-01
241Am	574.0	1.25E-08	15	1.58E+03
239Pu	579.400		20	1.968E+00
239Pu	582.890	6.150E-09	3	1.411E+01
239Pu	586.300	1.530E-09	10	3.510E+00
241Am	586.52	1.31E-08	15	1.66E+03
241Am	590.28	2.86E-08	7	3.62E+03
239Pu	596.000	3.900E-10	50	8.947E-01
241Am	597.42	7.41E-08	4	9.38E+03
239Pu	597.990	1.670E-08	3	3.831E+01
239Pu	599.600	1.990E-09	12	4.565E+00
239Pu	606.900	1.200E-09	10	2.753E+00
239Pu	608.900		10	2.661E+00
239Pu	612.830	9.460E-09	5	2.170E+01
239Pu	617.100	1.340E-08	5	3.074E+01
239Pu	618.280	2.040E-08	3	4.680E+01
241Am	619.00	5.94E-07	1	7.52E+04
239Pu	619.210	1.210E-08	6	2.776E+01
239Pu	624.780	4.570E-09	4	1.048E+01
241Am	627.2	5.64E-09	30	7.14E+02
241Am	633.0	1.26E-08	15	
239Pu	633.150	2.530E-08	1.2	5.804E+01
239Pu	637.837		1.2	5.873E+01
239Pu	640.075	8.200E-08	0.6	1.881E+02
241Am	641.42	7.10E-08	4	8.99E+03
240Pu	642.48	1.245E-07	1	1.05E+03
239Pu	645.969	1.489E-07	0.4	3.416E+02
239Pu	649.321	7.120E-09	7	1.633E+01
239Pu	650.529	2.700E-09	15	6.194E+00

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
239Pu	652.074	6.550E-08	0.6	1.503E+02
241Am	652.96	3.77E-07	2	4.77E+04
239Pu	654.880	2.250E-08	1.2	5.162E+01
239Pu	658.929	9.690E-08	0.7	2.223E+02
241Am	662.420	3.64E-06	0.3	4.61E+05
239Pu	664.587	1.657E-08	1.6	3.801E+01
239Pu	668.200	3.930E-10	30	9.016E-01
241Am	669.9	3.80E-09	30	4.81E+02
239Pu	670.800	8.600E-11	50	1.973E-01
239Pu	674.050	5.150E-09	3	1.182E+01
241Am	675.8	6.40E-09	20	8.10E+02
241Am	680.06	3.13E-08	5	3.96E+03
239Pu	685.970	8.730E-09	3	2.003E+01
240Pu	687.7	3.55E-08	1.5	2.98E+02
239Pu	688.100	1.110E-09	10	
241Am	688.77	3.25E-07	1.5	4.11E+04
239Pu	690.810		5	1.278E+01
239Pu	693.200	5.000E-10	30	1.147E+00
241Am	693.49	3.68E-08	4	4.66E+03
241Am	696.44	5.34E-08	3	6.76E+03
239Pu	697.800	7.350E-10	20	1.686E+00
239Pu	699.600	7.910E-10	20	1.815E+00
239Pu	701.100	5.120E-09	3	1.175E+01
239Pu	703.730	3.950E-08	0.4	9.062E+01
238Pu	705.600	5.030E-10	40	
238Pu	708.400	5.000E-09	10	3.167E+03
241Am	709.41	6.41E-08	2	8.11E+03
239Pu	712.960	5.160E-10	12	1.184E+00
239Pu	714.710	7.850E-10	10	1.801E+00
239Pu	717.720	2.740E-08	0.4	6.286E+01
239Pu	720.300	4.850E-10	10	1.113E+00
241Am	721.990	1.96E-06	0.4	2.48E+05
239Pu	727.900	1.240E-09	5	2.845E+00

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
241Am	729.52	1.33E-08	10	1.68E+03
241Am	731.5	4.70E-09	30	5.95E+02
239Pu	736.500		30	6.883E-01
241Am	737.29	8.00E-08	3	1.01E+04
239Pu	742.700	3.750E-10	30	8.603E-01
238Pu	742.820	5.170E-08	1	3.274E+04
239Pu	747.400	8.070E-10	20	1.851E+00
241Am	755.91	7.60E-08	3	9.62E+03
239Pu	756.400	3.470E-08	0.4	7.961E+01
241Am	759.46	1.67E-08	5	2.11E+03
241Am	763.4	1.96E-09	30	2.48E+02
239Pu	763.700	3.240E-10	50	7.433E-01
238Pu	766.410	2.190E-07	0.6	1.387E+05
239Pu	766.600	2.750E-09	5	6.309E+00
241Am	766.92	5.00E-08	3	6.33E+03
239Pu	769.370	1.120E-07	0.3	2.569E+02
241Am	770.58	4.74E-08	4	6.00E+03
241Am	772.13	2.66E-08	5	3.37E+03
239Pu	777.100	2.780E-10	25	6.378E-01
241Am	777.2	6.10E-10	50	7.72E+01
239Pu	779.610	1.360E-09	6	3.120E+00
241Am	780.5	2.50E-09	20	3.16E+02
238Pu	786.300	3.280E-08	1.0	2.077E+04
239Pu	786.900	8.610E-10	10	1.975E+00
239Pu	788.500	3.520E-10	20	8.076E-01
241Am	788.8	3.88E-09	15	4.91E+02
239Pu	792.900	2.000E-10	20	4.588E-01
239Pu	796.900	1.490E-10	20	3.418E-01
241Am	801.9	1.36E-08	10	1.72E+03
239Pu	803.200	6.370E-10	7	1.461E+00
238Pu	805.400	1.290E-09	15	8.170E+02
239Pu	805.900	2.760E-10	15	6.332E-01
238Pu	808.200	8.000E-09	3	5.066E+03

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
239Pu	808.400	1.210E-09	5	2.776E+00
241Am	811.8	6.05E-09	12	7.66E+02
239Pu	813.700	4.510E-10	10	1.035E+00
239Pu	816.000	2.410E-10	15	5.529E-01
241Am	819.3	4.00E-09	15	5.06E+02
239Pu	821.300	5.520E-10	10	1.266E+00
241Am	822.6	2.18E-09	25	2.76E+02
239Pu	826.800	1.800E-10	30	4.130E-01
241Am	828.5	2.43E-09	25	3.08E+02
239Pu	828.900	1.330E-09	6	3.051E+00
239Pu	832.500	2.960E-10	12	6.791E-01
239Pu	837.300	1.910E-10	20	4.382E-01
239Pu	840.400	4.810E-10	10	1.104E+00
239Pu	844.000	1.340E-09	5	3.074E+00
241Am	851.5	3.77E-09	15	4.77E+02
238Pu	851.700	1.290E-08	2	8.170E+03
241Am	854.7	2.00E-09	20	2.53E+02
241Am	859.2	8.16E-10	30	1.03E+02
241Am	862.6	5.34E-09	10	6.76E+02
239Pu	879.200	3.160E-10	10	7.250E-01
241Am	887.5	2.22E-09	20	2.81E+02
239Pu	891.000	7.930E-10	10	1.819E+00
239Pu	895.400	7.490E-11	30	1.718E-01
239Pu	898.100	1.750E-10	20	4.015E-01
241Am	898.4	7.22E-10	40	9.14E+01
241Am	902.5	3.00E-09	15	3.80E+02
239Pu	905.500	7.510E-11	30	1.723E-01
239Pu	911.700	1.370E-10	25	3.143E-01
241Am	912.4	2.50E-09	20	3.16E+02
239Pu	918.700	8.440E-11	35	1.936E-01
241Am	922.2	1.91E-09	20	2.42E+02
241Am	928.8	5.52E-10	50	6.99E+01
239Pu	931.900	1.270E-10	35	2.914E-01

APPENDIX D Plutonium, Americium Branching Ratios and Gamma Ray Energies

Isotope	Energy (keV)	Branching Ratio (photons/dis)	Error (%)	Activity (photons/s/g)
239Pu	940.300	4.960E-10	10	1.138E+00
241Am	945.7	5.60E-10	50	7.09E+01
239Pu	955.600	3.090E-10		7.089E-01
241Am	955.7	5.78E-09	10	7.31E+02
239Pu	957.600	3.200E-10	10	7.341E-01
239Pu	979.700	2.760E-10	15	6.332E-01
239Pu	982.700	1.080E-10	25	2.478E-01
239Pu	986.900	2.090E-10	20	4.795E-01
239Pu	992.700	2.660E-10	15	6.103E-01
239Pu	1005.700	1.780E-10	15	4.084E-01
239Pu	1009.400	1.400E-10	20	3.212E-01

R. Gunnink, J. E. Evans, and A. L. Prindle, A Reevaluation of the Gamma-Ray Energies and Absolute Branching Intensities of ^{237}U , ^{238} , ^{239} , ^{240} , ^{241}Pu , and ^{241}Am , Lawrence Livermore Laboratory report UCRL-52139, October 1976.

Table D-2. Constants.

Isotope	Atomic Mass	Half Life (yr)	Dis/s/g
^{238}Pu	238.049554	87.74	6.33310 E+11
^{239}Pu	239.052157	24119	2.29419 E+09
^{240}Pu	240.053808	6564	8.39468 E+09
^{241}Pu	241.056845	14.348	3.82446 E+12
^{242}Pu	242.058737	376300	1.45220 E+08
^{241}Am	241.056823	433.6	1.26553 E+11
1 year	365.24220	days	
N_0	6.0221367E+23	mol-1	
^{241}Pu - ^{237}U	2.45E-05	branching fraction	

APPENDIX E Americium-241/Plutonium-239 Peak Pairs

APPENDIX E**Americium-241/Plutonium-239 Peak Pairs****INTRODUCTION**

Table E-1 below displays the $^{241}\text{Am}/^{239}\text{Pu}$ concentration ratio for closely spaced (in energy) peak pairs when the two peaks have the same intensity. The calculation neglects differences in relative efficiency between the two peaks. Note, also, that the ratio is taken with respect to ^{239}Pu , not total plutonium. This table can be used in conjunction with simple visual examination of the pulse height spectrum or can be applied to extracted peak area data.

We present ratios only for peak pairs that can be visually separated in the spectrum.

Table E-1. Useful Americium-241/Plutonium-239 Peak Pairs.

Am-241 (keV)	Pu-239 (keV)	$^{241}\text{Am}/^{239}\text{Pu}$ Concentration Ratio for Equal Peak Intensities	Comment
59.54	51.63	1.36 E-05	Can only be used for freshly separated materials.
125.29	129.29	0.0278	Best above 5000 ppm ^{241}Am . Pu-239 interferences to ^{241}Am neglected in ratio.
169.56	171.34	0.0116	
376.59	375.04	0.206	
419.24	413.71	0.942	Best for very high ^{241}Am
662.42	645.97	0.00074	Best for very low ^{241}Am

APPENDIX F

Characteristics of Isotopic Standards

This appendix tabulates the characteristics of the isotopic standards used to characterize the performance of the FRAM software.

Table F-1. Archival Data Set for Coaxial Detector Analysis.

File Name	Accepted Values								Pu Mass (g)	No. runs	Ct. Rate (kHz)	Ct time (h)	Data Date
	wt %					ppm 241 Am	mW/gPu Spec Pow						
	238	239	240	241	242								
ISO03CX-2001	0.006	96.36	3.56	0.054	0.018	736	2.229	3.61	10.97	20	40	0.5	10-Aug-2001
stdiso03_01	0.006	96.36	3.56	0.055	0.018	726	2.228	3.61	11	20	40	0.5	23-Mar-2001
ISO3CX8K	0.006	96.34	3.56	0.076	0.018	518	2.207	3.61	10.97	10	30	2	10-May-1994
SGCOAX8K	0.006	96.34	3.56	0.078	0.018	499	2.205	3.61	100	10	30	2	21-Oct-1993
92COAX8K	0.008	94.63	5.26	0.084	0.014	2004	2.477	5.31	10	10	30	2	18-Oct-1993
86COAX8K	0.010	94.26	5.60	0.106	0.018	2192	2.526	5.66	10	10	30	2	20-Oct-1993
CALX30	0.009	93.92	5.86	0.176	0.029	1987	2.511	5.93	398.2	10	30	1	2-Nov-1994
CALX30PB	0.009	93.93	5.86	0.176	0.029	1995	2.512	5.93	398.2	11	30	1	6-Dec-1994
EUPU7CX8	0.014	93.84	5.86	0.220	0.066	793	2.402	6.01	5	10	30	2	22-Oct-1993
PUEU730	0.014	93.85	5.86	0.209	0.066	898	2.413	6.01	2000	11	30	1	3-Nov-1994
PUEU7PB	0.014	93.85	5.86	0.209	0.066	900	2.413	6.01	2000	11	30	1	8-Nov-1994
STDEUPU7-2001	0.013	93.91	5.86	0.150	0.066	1478	2.475	6.01	5	30	30	0.5	18-Sep-2001
JO01325	0.011	93.93	5.90	0.132	0.028	1694	2.488	5.98	499.6	11	30	1	22-Dec-1994
J1325PB1	0.011	93.93	5.90	0.132	0.028	1693	2.488	5.98	499.6	11	30	1	20-Dec-1994
J1325PB2	0.011	93.93	5.90	0.132	0.028	1693	2.488	5.98	499.6	11	30	1	17-Dec-1994
PIDIE6-1-2001	0.010	93.86	5.99	0.103	0.035	3178	2.657	6.07	0.4	21	40	0.5	8-Aug-2001
PID6_1	0.010	93.83	5.99	0.131	0.035	2928	2.631	6.07	0.4	21	2.9	1	2-Oct-1996
ISO6CX8K	0.013	93.59	6.13	0.206	0.057	1163	2.455	6.26	8.45	10	30	2	6-May-1994
ISO06CX-2001	0.013	93.65	6.13	0.145	0.057	1755	2.517	6.26	8.4	21	40	0.5	8-Aug-2001
STD830	0.009	93.55	6.30	0.116	0.025	1758	2.509	6.37	239.5	11	30	1	10-Jan-1995
STD8PB	0.009	93.55	6.30	0.117	0.025	1755		6.37	239.5	11	30	1	23-Dec-1994
cbnm93_01	0.010	93.53	6.31	0.110	0.040	2150	2.560	6.41	0.6	20	40	0.5	19-Mar-2001
93COAX8K	0.011	93.48	6.31	0.157	0.040	1697	2.512	6.41	6	10	30	2	9-Oct-1993
ISO9CX8K	0.020	92.73	6.89	0.282	0.073	1490	2.570	7.07	11.9	10	30	2	7-May-1994
stdiso09_01	0.019	92.81	6.90	0.202	0.073	2270	2.652	7.07	12	20	40	0.5	
ISO09CX-2001	0.019	92.81	6.90	0.199	0.073	2305	2.656	7.07	11.9	29	40	0.5	8-Aug-2001
2G118CX8	0.025	90.49	9.01	0.374	0.104	3822	2.975	9.25	2.5	10	30	2	23-Oct-1993
PID6_2	0.021	89.48	10.11	0.293	0.094	4148	3.046	10.32	0.4	21	3.2	1	4-Oct-1996
SD4030	0.062	87.34		0.606	0.201	6534	3.638	12.28	869	11	30	1	9-Nov-1994
SD4030PB	0.062	87.34	11.79	0.605	0.201	6543	3.639	12.28	869	11	30	1	21-Nov-1994
2G119CX8	0.036		11.80	0.578	0.168	5919	3.421	12.17	2.5	10	30	2	24-Oct-1993
ISO12C8K	0.055	87.24	11.84	0.645	0.222	4330	3.350	12.35	20.2	10	30	2	8-May-1994
ISO12CX-2001	0.052	87.42	11.85	0.455	0.223	6190	3.544	12.36	20.2	20	40	0.5	9-Aug-2001
PID6_3	0.044	84.88	14.19	0.655	0.235	9569	4.008	14.69	0.4	21	3.2	1	3-Oct-1996
PIDIE6-3-2001	0.043	85.00	14.20	0.519	0.235	10872	4.147	14.70	0.4		17	0.5	6-Aug-2001
84COAX8K	0.067	84.61	14.24	0.724	0.359	5203	3.638	15.01	6	10	30	2	10-Oct-1993
cbnm84_01	0.063	84.80		0.507	0.360	7334	3.859	15.03	0.6	20	40	0.5	21-Mar-2001
ISO15C8K	0.160	82.54	15.48	1.103	0.715	5735	4.290	17.08	12.3	10	30	2	9-May-1994
stdiso15_01	0.152	82.82	15.52	0.794	0.717	8806	4.593	17.11	12	20	40	0.5	27-Mar-2001
ISO15CX-2001	0.152	82.83	15.52	0.780	0.717	8943	4.606	17.11	12.3	26	40	0.5	9-Aug-2001
2G121CX8		82.21	16.53	0.853		7403	3.960	17.27	2.5	10	30	2	3-Nov-1993
LAO225PB	0.058	82.25	16.53	0.809	0.354	7841	4.007	17.27	868.8	11	30	1	15-Dec-1994
LAO22530		82.25	16.53	0.809	0.354	7846	4.008	17.27	868.8	10	30	1	20-Dec-1994
70COAX8K	0.812	74.57	18.60	3.904	2.113	28204	10.722	24.19	6	10	30	2	10-Oct-1989
cbnm70_01	0.776	75.51	18.82	2.759	2.140	40097	11.866	24.37	0.6	20	40	0.5	22-Mar-2001
PID6_4	0.102	78.24	19.89	1.204	0.571	21980	6.047	21.10	0.4	21	6.5	1	4-Dec-1996
PIDIE65	0.123	76.46	21.36	1.352		24409	6.523	22.86		21	15		29-Nov-1996
PIDIE6-5-2001	0.119	76.67	21.41	1.081	0.710	27037	6.798	22.91	0.4	21	26	0.5	7-Aug-2001
PIDIE66	0.884	67.65	24.34		3.627	56522	14.623	32.66	0.4	21		1	30-Nov-1996
61COAX8K	1.154	63.85	25.93	4.791	4.282	34776	13.756	36.03	6	10	30	2	11-Oct-1989
PIDIE67	1.196	63.49	26.20	4.324	4.791	59164	16.779	37.26	0.4	21	29	1	1-Dec-1996
cbnm61_01	1.105	64.83	26.31	3.398	4.349	49504	15.160	36.41	0.6	20	40	0.5	20-Mar-2001
PIDIE6-7-2001	1.164	64.08	26.43	3.482	4.836	68082		37.49	0.4	26	40	0.5	7-Aug-2001

Table F-2. Isotopic Characteristics of Los Alamos Uranium Standards.

Sample	wt %			
	U-234	U-235	U-236	U-238
NBL-0079(93)	0.9800	93.170	0.2937	5.556
C20-8		93.170		
UIISO-91	0.9103	91.336	0.3351	7.419
UIISO-66	0.5781	66.040	0.2590	33.122
NBL-0078 (53)	0.3718	52.488	0.2645	46.876
UIISO-52	0.5306	52.117	0.8676	46.484
UIISO-38	0.2598	37.552	0.2172	61.971
UIISO-27	0.2338	26.752	0.2697	72.745
NBL-0077(20)	0.1486	20.107	0.1973	79.547
UIISO-17	0.1380	17.239	0.1680	82.456
UIISO-13	0.0827	12.954	0.1013	86.862
UIISO-12	0.0719	11.797	0.1152	88.016
A1-323-1	0.0532	10.104	0.0913	89.751
A1-324-1	0.0512	10.086	0.0904	89.772
A1-324-2	0.0522	10.084	0.0904	89.773
NBS-446	0.0359	4.462	0.0069	95.495
A1-1126-2	0.0246	3.027	0.0169	96.931
A1-1126-1	0.0246	3.026	0.0159	96.934
NBS-295	0.0279	2.949	0.0033	97.020
NBS-194	0.0171	1.942	0.0003	98.041
A1-1125-2	0.0157	1.938	0.0089	98.038
A1-1125-1	0.0157	1.937	0.0089	98.039
A1-1127-1	0.0049	0.717	0.0020	99.276
A1-1127-2	0.0049	0.717	0.0020	99.277
A1-408-2	0.0049	0.714	0.0010	99.281
NBS-071	0.0052	0.712	0.0000	99.283
A1-409	0.0049	0.710	0.0010	99.284
NBS-031	0.0020	0.317	0.0146	99.667

Table F-3. Characteristics of the Los Alamos HUA Series of MOX Samples.

Sample	Pu Declared Values (wt %)					ppm ²⁴¹ Am	mW/gPu	wt % ²⁴⁰ Pu _{eff}
	²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu			
HUA 5062	0.0614	87.397	11.831	0.533	0.178	15864	4.7020	12.284
HUA5065	0.0613	87.399	11.831	0.531	0.178	16062	4.7244	12.284
HUA5069	0.0558	87.554	11.693	0.510	0.187	13960	4.4452	12.147
HUA 5301	0.0464	87.629	11.668	0.472	0.185	8180	3.7306	12.095
HUA 8971	0.0549	87.377	11.826	0.533	0.21	9431	3.9297	12.316

Sample	Pu Mass (g)	U Mass (g)	²³⁵ U (%)	²³⁵ U/Pu	²³⁸ U (%)	²³⁸ U/Pu
HUA 5062	241.6	393.8	0.727	0.0118	99.25	1.618
HUA5065	304.9	438.8	0.769	0.0111	99.21	1.428
HUA5069	113.6	679.4	1.073	0.0642	98.91	5.915
HUA 5301	367.8	805.8	0.225	0.00495	99.77	2.186
HUA 8971	234.8	626	1.022	0.0272	98.96	2.638

Table F-4. Characteristics of ARIES NDA Standards and CALEX.

Sample	(g) Pu Mass	wt % Pu-238	wt % Pu-239	wt % Pu-240	wt % Pu-241	wt % Pu-242	μg/gPu Am-241	mW/gPu P-eff	wt % Pu-240eff
CALEX	400	0.0086	93.97	5.86	0.130	0.029	2430	2.558	5.93
MC-005	3000	0.0133	93.83	5.94	0.168	0.054	1300	2.460	6.06
MC-004	1500	0.0133	93.83	5.94	0.168	0.054	1300	2.460	6.06
MC-003	750	0.0133	93.83	5.94	0.168	0.054	1300	2.460	6.06

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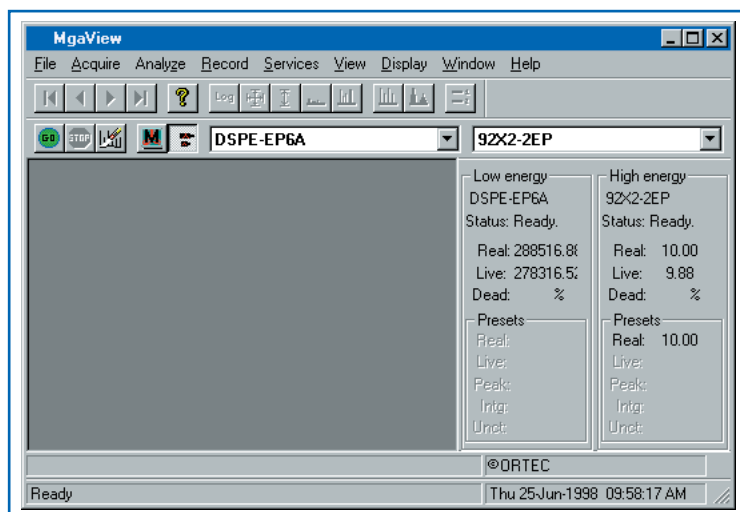
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A full member of the CONNECTIONS-32 software family, MGA++ can display the data being acquired, then rapidly analyze and report results — all from a single, easy-to-use program.

User Interface

For each operational mode, separate “viewer” programs (MGAView, MGAHIView and U235View) and analysis modules (MGA.EXE, MGAHI.EXE and U235.EXE) ensure the integrity of the analytical methods. The Viewer program provides the user interface and the hardware control function. In MGA++ it is possible to suppress all spectral display.

MGAView, MGAHIView and U235View present the same friendly user interface. The MGA mode operator interface is shown in Fig. 1. The current status of the detector is shown on the right. A special count-rate meter mode shows the instantaneous count rate of a selected region. The spectrum may be viewed during acquisition.



The Start/Save/Report feature (Fig. 2) provides one-button collection and analysis — via keyboard or mouse — easing the task for operators in protective suits! When additional counts are deemed necessary, “Restart/Save/Report” continues the current count.

Reanalysis of spectra from disk or in the MCB is easy — just click and select (Fig. 3). All the spectra collected by the MGA++ programs are stored in the ORTEC standard spectrum (SPC) format, which can be read by many programs. The file includes analysis parameters and hardware description records — everything needed to verify the results.

Spectra stored on disk may be analyzed by MGA++ from a wide variety of input file formats in addition to the primary ORTEC SPC file format (Table 1).

The analysis results can be displayed, with zoom function capabilities (Fig. 4), for visual confirmation of the analysis.

Peak fit results may be scrutinized along with fit residuals for visual assurance of analysis quality. To aid comprehension, individual peaks on the display can be turned on or off (Fig. 5).

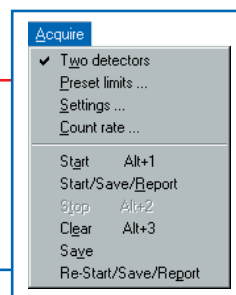


Figure 2.

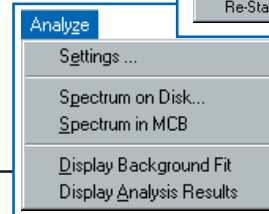


Figure 3.

File Formats Read

LLNL/ACCUDUMP (NCD BINARY)
 ASCII (sequential integer) no header
 Nuclear DATA μMCA (ACCUSPEC) (.CNF)
 Canberra S100
 ORTEC ADCAM (.CHN)
 LLNL ASCII
 SPE ASCII
 “Euro” ASCII
 ORTEC MGA (Integer .SPC)
 ORTEC (Real .SPC)

Table 1.

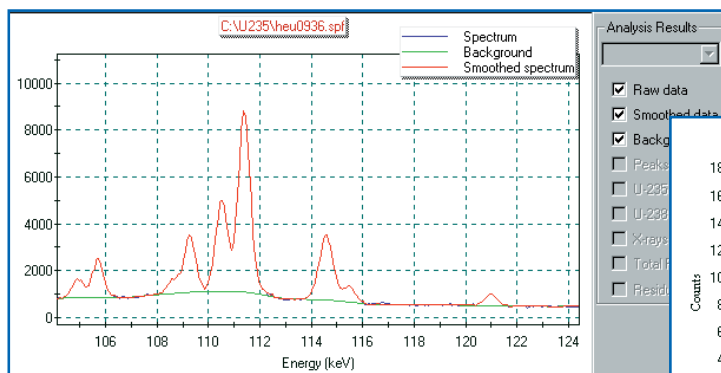
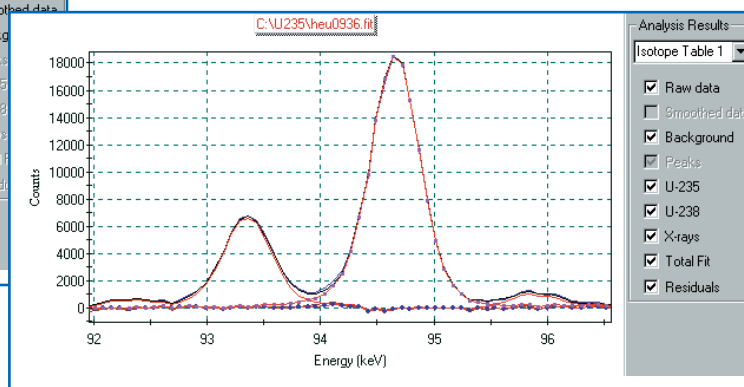


Figure 4.

Figure 5.



Flexible Analysis

Analysis parameters are specified in clear, easy-to-understand dialog boxes. Analysis parameters may be saved to disk for use on similar samples and recalled as required.

The flexibility of the analysis settings options for U235View are shown in Figs. 6–9, for sample type, peak shape parameters, absorption, and source/detector absorption. For MGAView (Figs. 10–13), they are sample type, source geometry, ^{242}Pu calculation, and low-energy detector. Figures 14–16 show sample type, geometry, and Pu-242 dialogs for MGAHView.

At the end of each analysis the results are automatically stored in the Access format database and are also printed or displayed for the operator. The three database tables (Analysis, Acquisition, and Isotope; see, for example, Fig. 17) can be viewed by MGAView (using the record function) or by Access. This powerful data storage method makes summary reports, exception reports, and other useful outputs which are easy to create. The standard reporting options are shown in Figs. 18, 19 and 20.

MGA++

Safeguards Software

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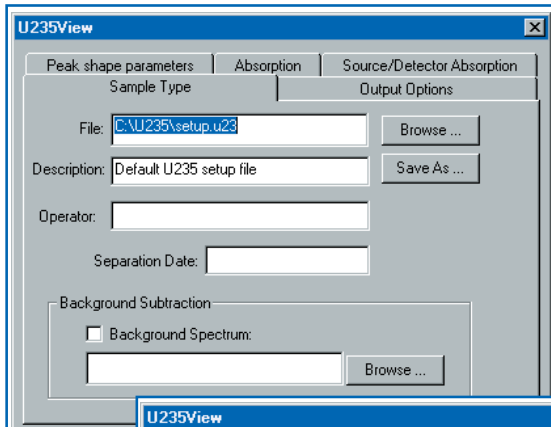


Figure 6.

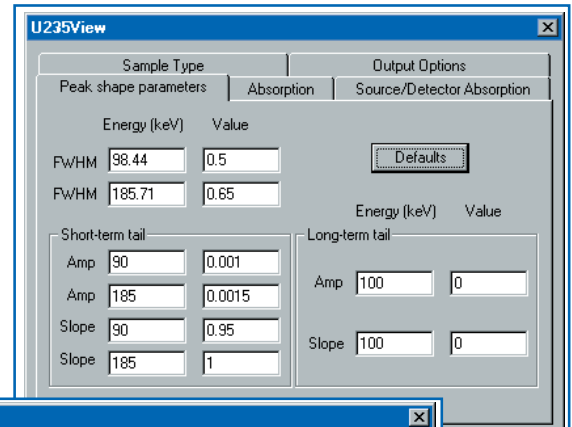


Figure 7.

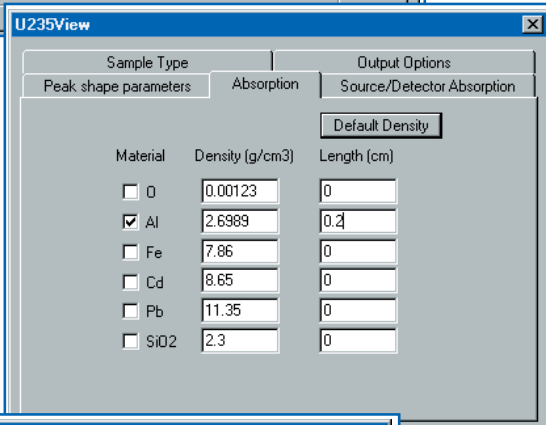


Figure 8.

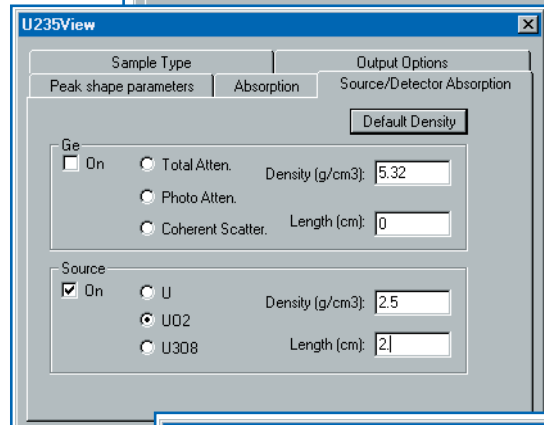


Figure 9.

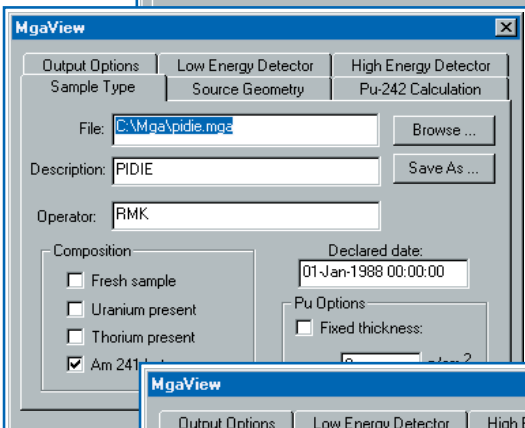


Figure 10.

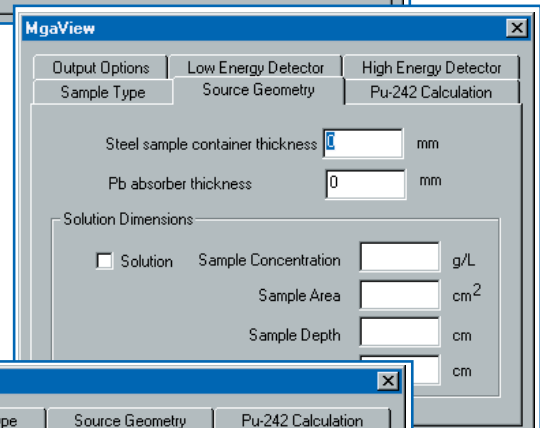


Figure 11.

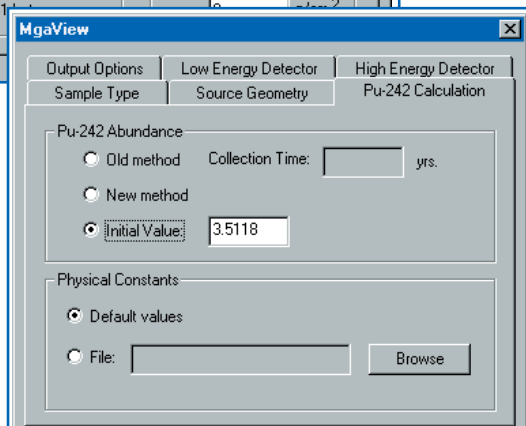


Figure 12.

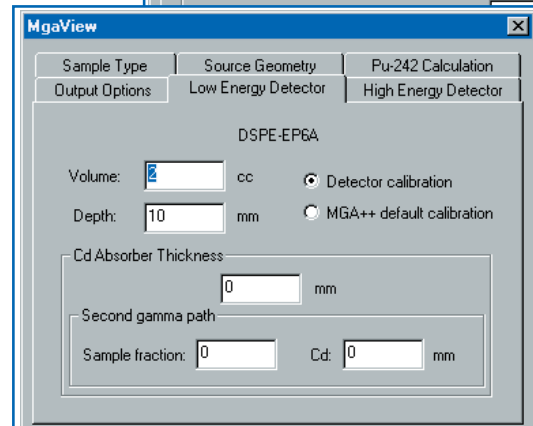


Figure 13.



Figure 14.



Figure 15.



Figure 16.

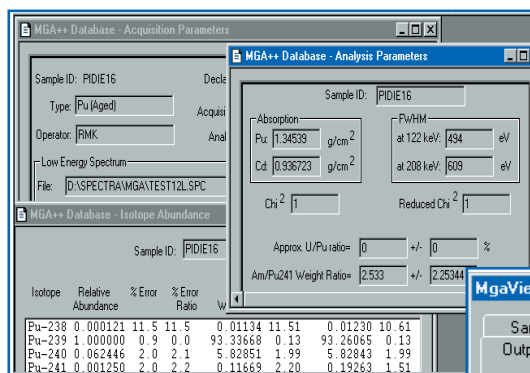


Figure 17.

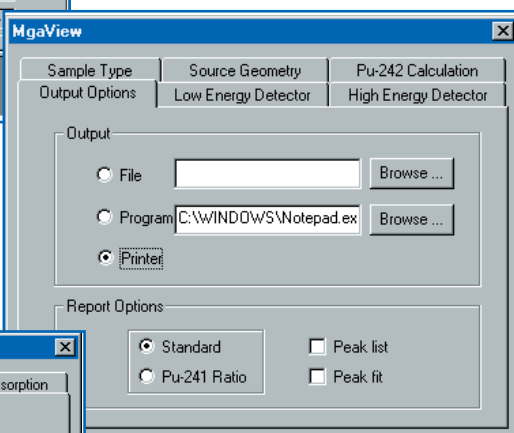


Figure 18.

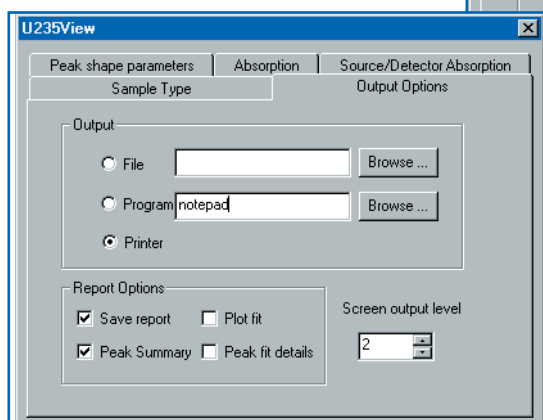


Figure 19.



Figure 20.

MGA++

Safeguards Software

MGA-B32 V1.06

CONNECTIONS Integration

The MGA++ programs, operating under Windows 2000/XP, are completely integrated into the ORTEC *CONNECTIONS*-32 environment. All ORTEC multichannel buffer hardware, including the DigiDART, DSPEC, DSPEC Plus and DSPEC jr MCAs, are supported — whether networked or standalone.

The *CONNECTIONS* structure, common to all 32-bit ORTEC application programs, facilitates development of custom applications, e.g., automated measuring systems. (Developer's toolkits are available from ORTEC to aid this process.)

Common benefits of all *CONNECTIONS* 32-bit products are multitasking, multi-threading support for concurrent analysis processes under Windows 2000/XP, simultaneous support of both locally connected and remotely connected MCAs over Ethernet links, and detector locking by security password.

Prerequisites

MGA++ will operate correctly on any system supporting ORTEC multichannel buffer hardware under Windows 2000/XP. While MGA++ can control compatible MCA hardware directly, MAESTRO-32 is a prerequisite for instrument setup.

MGA Analysis Mode

- Produces weight percent results for ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{241}Am , ^{237}Np , and ^{235}U
- Determines ^{242}Pu
- Operates with a single-planar HPGe detector for 0–300 keV or with a planar and a coaxial HPGe detector for 0–1000 keV
- No calibration standards needed to correct for matrix or container effects
- Automatic energy and peak shape recalibration

MGA mode has two data analysis configurations: one-detector mode and two-detector mode. In one-detector mode, MGA is designed to operate with a planar HPGe detector for the energy range 0–300 keV to obtain the Pu isotopic information. In two-detector mode, intended for highly-attenuated samples, the measurement may be aided by higher energy data up to ~1000 keV obtained from a coaxial HPGe detector. This coaxial detector allows measurement of gamma-ray energies to ~1 MeV. With this additional information, sample homogeneity and isotopic content can be refined. However, in the two-detector mode, the information from the planar detector is required, the coaxial information alone is insufficient. This requirement adds significant limitations when applying the original MGA code to the gamma-ray spectra of heavily shielded samples. This has to some extent been mitigated by the introduction of the ORTEC SGD GEM detectors, which in some cases can be used to perform the function of the planar and coaxial detector in one, by the use of two separate spectra, low and high energy.

There are about ten energy regions in a plutonium gamma-ray spectrum which may be used to calculate isotopic abundances. Those in the 94–104 keV region and the peaks at 129 and 148 keV are the most intense. Although those regions are difficult to analyze, yield precision of 1% or better can be achieved.

Typical MGA Mode Performance



Comparison of MGA Analysis Results, Measured at LLNL with PIDIE Standards–10 Minute Count			
Standard	Std Std Wt % Declared	Std-Calc MGA % Error	Reported MGA % Uncertainty
^{238}Pu			
1	0.0101	0.7	3.87
3	0.0437	3	1.74
5	0.1221	3	1.39
^{239}Pu			
1	93.848	0.064	0.07
3	84.927	0.024	0.08
5	76.534	0.24	0.18
^{240}Pu			
1	5.987	1.02	0.6
3	14.191	0.056	0.49
5	21.381	0.9	0.61
^{241}Pu			
1	0.1206	0.08	0.65
3	0.6049	1.6	0.42
5	1.26	0.8	0.49
^{241}Am			
1	0.3048	0.9	0.39
3	1.012	0.2	0.38
5	2.55	0.27	0.49
Total Specific Power			
Standard	Declared	Std-Calc MGA % Error	
1	2.644	0.22	
3	4.068	0.12	
5	6.639	0.09	

Sample Age Since Processing

MGA handles both freshly-separated and aged samples — important because recently-processed plutonium samples are usually very low in ^{237}U and ^{241}Am . The ^{237}U increases in activity for about 2 months after processing, at which time it reaches equilibrium with the alpha-decay rate of its ^{241}Pu parent. Any analysis method that always assumes an established decay equilibrium between these two isotopes cannot be used on freshly-processed samples.

Presence of Other Radioactive Materials

Other radioactive materials may be present in plutonium samples as decay products, as contaminants from previous processes, or as a result of blending. Uranium is one common radioactive material which is blended with plutonium to form mixed-oxide (MOX) fuels. MGA can accurately determine the relative abundance of ^{235}U in a sample. Other radioactive materials sometimes encountered are ^{237}Np - ^{233}Pa , ^{243}Am - ^{239}Np , and low levels of some fission products such as ^{95}Zr - ^{95}Nb and ^{137}Cs . If a two-detector system is employed, ^{237}Np can be detected down to about 50 ppm by analysis of the 312 keV peak of ^{233}Pa , the daughter of ^{237}Np . MGA automatically recognizes the presence of interference from ^{243}Am and ^{239}Np isotopes, the fluorescence of x-rays of thorium in the sample, and the presence of ^{137}Cs (if the two-detector system is used).

MGAHI Mode

MGAHI uses physical parameters to take into account both attenuation and emission of gamma rays, and does not require a detector efficiency calibration. The gamma-ray information between 50 keV and 200 keV is not required. MGAHI is useful when sources are heavily shielded, and in a high background, space-limited environment. With too much shielding, the 100-keV energy region could be completely attenuated. In a high-background environment, the detector could see gamma rays from other nearby sources. Also, the spectrometry system could have a very high dead time. Lead shielding can be used in this situation to reduce the dead time, but this could also cut out the low-energy gamma rays. MGAHI employs the original MGA methodology in that it: 1) uses physical parameters to take into account both attenuation and emission of the gamma rays, and 2) does not require detector efficiency calibration. However, unlike the "original MGA", the planar information is no longer required. The MGA analysis relies very heavily on the 100 keV energy region detector efficiencies, absorber thickness and Pu thickness are calculated from the spectral data using known gamma-ray peaks from the decay of ^{239}Pu .

MGAHI Mode Performance

MGAHI Pu weight % results of the two Pu (PIDIE) standards. Data was collected using a 75% coaxial detector for 3 hours. Two absorbers (5 mm stainless steel (ss) and 2 mm Pb) were used. Results from destructive analysis (DA) are also tabulated.

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu
PIDIE#1 +ss	0.012 $\pm$ 18%	93.79 $\pm$ 1%	6.02 $\pm$ 4%	0.19 $\pm$ 7%
PIDIE#1 +Pb	0.011 $\pm$ 15%	93.85 $\pm$ 1%	5.98 $\pm$ 3%	0.18 $\pm$ 5%
PIDIE#1 DA	0.01108	93.822	5.969	0.1975
PIDIE#3 +ss	0.042 $\pm$ 14%	84.65 $\pm$ 1%	14.34 $\pm$ 3%	0.97 $\pm$ 4%
PIDIE#3 +Pb	0.044 $\pm$ 13%	84.91 $\pm$ 1%	14.04 $\pm$ 3%	1.01 $\pm$ 3%
PIDIE#3 DA	0.0475	84.835	14.128	0.99

MGA++

Safeguards Software

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U235 Analysis Mode

- Relative ratios for ^{235}U , ^{234}U , and ^{238}U
- Automatically checks for the presence of Pu using the 129 keV peak
- Operates with a single-planar HPGe detector from 0–300 keV
- No calibration standards necessary to correct for matrix or container effects
- Corrects for internal sample absorption and absorbers placed between sample and detector
- Peak shape calibration determined from user-defined spectral peaks, reloadable from file, or from default values

U235 uses a single planar HPGe detector and operates in the energy range 0–300 keV. It determines the relative isotopic ratios for Uranium. In a similar fashion to MGA and MGAHI, no primary calibration is required for efficiency or for absorbers in the matrix or in the sample container.

Typical U235 Mode Performance

U235 gives weight percent results for ^{234}U , ^{235}U , and ^{238}U .

Isotope	Range (wt. %)	Absolute Accuracy (%)
^{234}U	0.02–2	5.0
^{235}U	0.02–0.5	5.0
	0.5–70	0.5
	70–93	1.5
	93–99	5.0
	99–99.5	5.0
^{238}U	99–99.5	5.0

The U235 analysis mode gives relative ratios for ^{235}U , ^{234}U , and ^{238}U ; and when operating in this mode, it can warn the user of the possible presence of Pu.

Absolute accuracy depends on the statistics of the sample.

General Considerations

Sample Size and Matrix

In practical terms, the lower limit on sample size is about 100 mg — determined by count time and required statistical accuracy. While in principle there is no upper limit to the size, only the surface of a large sample is actually measured - because plutonium and uranium have short mean-free-paths for low-energy photons. Increasing the sample thickness beyond the “saturation thickness” will not increase the count rate because photons from the back of the sample are fully absorbed.

The extent of fluorescence from uranium or plutonium by their own alpha or gamma emission is much lower than from solid materials. Entering details about the solution will assist the analysis in dealing with the x-rays.

Shielding

A shield or collimator should be used to reduce or eliminate the counts in the spectrum from nearby materials. Cadmium, copper, lead, or tantalum foils are used to reduce the presence of the low-energy gamma rays, specifically those at 59 keV. This reduces the dead time from unusable counts for plutonium samples. These low-energy gamma rays are hardly ever present in uranium samples. Unless they are present, preferential filtering of low-energy photons is almost never required and is of no value.

MGA++

Safeguards Software

MGA-B32 V1.06

Germanium Detector

For measurements up to 300 keV with either MGA or U235, a planar HPGe detector with a nominal resolution of 550 eV at 122 keV is required. While this requirement may in some cases be relaxed, the 122-keV resolution should not exceed 700 eV.

A thicker planar detector will have a higher peak-to-Compton (p/C) ratio, so that, assuming that it has an area and 122-keV resolution consistent with the other requirements specific to the measurement, it may deliver superior performance at low energies.

To use the higher energy regions in the analysis of samples containing only plutonium, in two detector MGA mode or in MGAHI mode, a coaxial detector with a resolution of less than 2.0 keV at 1332 keV is adequate. For MGAHI, a detector resolution of 1.1 keV or better at 208 keV is required. The 203-keV gamma ray from ^{239}Pu must be visible. Up to 5 mm of Pb absorber can be placed in front of the detector.

ORTEC's Safeguard (SGD) Series of coaxial and planar detectors, specifically optimized for the purpose, are highly recommended for use with MGA++.

Ordering Information

To order, specify:

Model	Description
MGA-B32	MGA++ Safeguards Software
MGA-U32	Update for MGA-B32
MGA-G32	Documentation for MGA-B32

¹It is the subject of a cooperative research and development agreement (CRADA TSV-1368-96) and license (License Number TL-1375-96) between ORTEC and the University of California under which ORTEC is integrating those programs into the ORTEC software environment to enhance usability.

²K. Debertin and R.G. Helmer, "Gamma- and X-Ray Spectrometry with Semiconductor Detectors," p. 185, Elsevier Science Publishers B.V., The Netherlands, 1988.

ORTEC Signs MGA++ Licensing and Development Agreement with LLNL

ORTEC and Lawrence Livermore National Laboratory have entered into licensing and development agreements in the area of specialized software for nuclear safeguards applications. The license covers the existing versions of the MGA ++ suite of codes which analyze HPGe detector gamma-ray spectra from a wide variety of nuclear safeguards samples in order to determine relative plutonium isotopic abundances and/or uranium enrichment. The development agreement (CRADA) relates to further improvements to the code and an improved "seamless" integration within the ORTEC *CONNECTIONS* Windows 2000/XP spectroscopy environment for maximum ease-of-use and reliability.

Specifications subject to change
040306

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PC/FRAM-B32 V4.3

Plutonium and Uranium Isotopic Analysis Software

Advanced Isotopic Ratio Analysis Software for HPGe and CdTe Detector Gamma-Ray Spectra

- Analyzes Pu, and a wide variety of heterogeneous samples containing Pu, Am, U, and other nuclides including ^{242}Pu
- Operates with a single HPGe or CdTe detector
- No calibration standards necessary
- Works with shielded samples
- Select from a large number of supplied sample/geometry conditions or add more types
- Dynamic selection of English or Russian Graphical-User Interface
- ORTEC *CONNECTIONS-32* compliant
- Operates on a variety of hardware platforms and is a 32-bit Windows® 2000/XP application
- Decay Correction for Isotopic fractions
- Significant enhancements over previous versions

The PC/FRAM¹ code has been under evolutionary development at Los Alamos National Laboratory since the mid 1980s. PC/FRAM-B32 Version 4.3, is a 32-bit version for the Windows 2000/XP operating platforms. It operates within the ORTEC *CONNECTIONS-32* network spectroscopy architecture, giving greater flexibility in choice of MCA hardware.

PC/FRAM-B32 analyzes the gamma-ray spectrum taken with a germanium detector, of plutonium-bearing, uranium-bearing, or mixed items and quantifies the distribution of plutonium or uranium isotopes $^{241}\text{Americium}$ and other transuranic isotopes (including uranium in mixed uranium-plutonium oxides) that contribute measurable gamma rays to the spectrum can also be quantified relative to plutonium. In Version 4.3, use of CdTe (Cadmium Telluride) detectors is also supported. PC/FRAM-B32 analyzes spectra from items containing only uranium, and quantifies the uranium isotopic distribution. These measurements are performed on samples of arbitrary size, geometry, and physical and chemical composition.

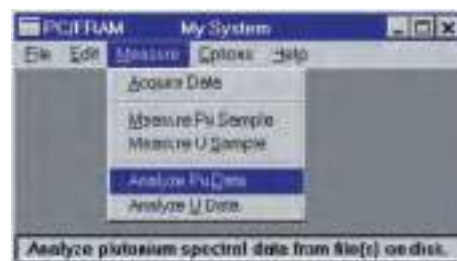


Fig. 1. PC/FRAM V4.3 Main Menu.



Fig. 2. Analyze Plutonium Data Dialog Box.

¹FRAM: Fixed-energy Response function Analysis with Multiple efficiency.

Easy-to-Use Windows 2000/XP User Interface

PC/FRAM-B32 is a member of the ORTEC *CONNECTIONS-32* family of products. The user interface complies with the latest Windows conventions and is very straightforward to use. It provides control of all MCA hardware supported by *CONNECTIONS-32*. The ORTEC MAESTRO®-32 MCA Emulation program is used for hardware system setup prior to use and can be removed from the PC to secure the MCB from changes.

Bilingual Language Support

PC/FRAM-B32 has the capability of supporting two different languages. Currently English and Russian are the two languages, but this can easily be extended to other European languages.



Fig. 3. Change of Language Dialog Boxes.

ORTEC *CONNECTIONS-32* Architecture

The *CONNECTIONS-32* product architecture offers a number of significant benefits: software products are truly multitasking and 32-bit spectroscopy applications, based on Windows 2000/XP. The concept is "see anything, do anything, and be anywhere using any hardware." *CONNECTIONS-32* is secure, standard, and open. Multiple *CONNECTIONS-32* applications may co-exist on a network and interface simply with custom report writers and industry-standard databases; controlling and viewing all attached spectroscopy hardware activity from any workstation. Programmer's toolkits facilitate custom development. *CONNECTIONS-32* hardware support includes all current and past ORTEC MCA devices and also an increasing number of non-ORTEC types.

PC/FRAM-B32 Analysis Capabilities

Sample Type

The versatility of PC/FRAM-B32 and its ability to analyze a wide variety of samples stems from its reliance upon generic analysis algorithms. Specific information needed to guide the analysis is encoded into a set of parameters and stored in a database. This information includes the regions and peaks to be examined, the isotopes to be used in the analysis, and special information for performing a number of diagnostic tests on the spectrum. An "analysis engine library" makes it easy to integrate into specific application situations.

In an improvement over previous versions, separate dialogs now handle analysis of plutonium and uranium samples and data in Version 4.3.

Material Categories are Easily Analyzed:

- 2–38% ^{240}Pu
- 0.01–50% ^{241}Am
- Interferences from ^{243}Am – ^{239}Np , ^{237}Np , and ^{244}Cm
- 80% ^{238}Pu
- Lead-shielded samples
- Heterogeneous Am/Pu
- Nonequilibrium ^{241}Pu – ^{237}U
- MOX: ^{235}U /Pu from 0.005–35%
- Pu with 80–95% ^{242}Pu
- ^{235}U / ^{238}U in pure U (no Pu)
- ^{235}U : ^{241}Am : Pu = 24:1:1

PC/FRAM-B32 V4.3

Plutonium and Uranium Isotopic Analysis Software

Analysis Methods

PC/FRAM-B32 analyzes photopeaks from the spectrum of plutonium (or uranium) gamma rays. The spectrum contains peaks from the plutonium isotopes ^{238}Pu to ^{241}Pu , ^{241}Am , and often other isotopes such as ^{235}U or ^{237}Np . PC/FRAM-B32 combines this information to produce isotopic ratios independent of sample size, shape, physical and chemical composition, measurement geometry, and container characteristics. The results are obtained using only the spectral data and known fundamental nuclear constants. Calibration with standards is NOT necessary.

Peak Area Determination

PC/FRAM-B32 uses response function methods to determine all peak areas, fitting a Gaussian with a single exponential on the low-energy side to model the gamma-ray peak shapes and uses a Lorentzian to model x-ray peaks.

Relative Efficiency

PC/FRAM-B32 uses a separate efficiency curve for each isotope. This allows it to measure the specific power of pyrochemical residues with biases that are reduced by as much as a factor of ten from analyses that do not use multiple efficiency curves.

The multiple efficiency feature of PC/FRAM-B32 may also be used for other heterogeneous samples. The physical and chemical characteristics of the sample may not be uniform or even well known. Items may contain mixtures of solids and powders with no ill effect so long as the plutonium is isotopically uniform. Version 4.3 adds a physical model option for calculating the relative efficiencies to the previously used empirical efficiency model which is also retained.

Analysis for Isotopic Ratios

The approach used is that of finding a least squares solution to a set of linear equations involving peak areas, relative efficiency, and isotope ratios as unknowns. The method allows use of multiple peaks in the analysis with resulting improved measurement precision.

Analysis Parameters Database

The analysis parameters database is important in the power and flexibility of PC/FRAM-B32. These parameters are grouped into five categories: peak fitting parameters, gamma-ray peaks to be searched for, energy regions to be searched, isotopes to be used, and special application constants. Multiple parameter sets can be easily accommodated.

In the latest version of PC/FRAM-B32, it is possible to automatically switch, in a limited way to a more appropriate parameter set depending on analysis results.

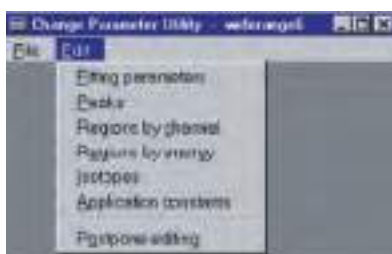


Fig. 4. Parameter Edit Menu.

	isotope	peak energy	line width	branching ratio	fix area to	sum area with	used for eff	used for act	used for cal	used for cal	used for cal
1	Pu239	124.480	0.00	6.0000e-007	1	0	☐	☐	☐	☐	☐
2	Pu239	125.200	0.00	8.0000e-007	4	0	☐	☐	☐	☐	☐
3	Am241	125.292	0.00	4.1240e-005	0	0	☒	☒	☐	☐	☐
4	Pu239	129.294	0.00	6.2900e-005	1	0	☒	☒	☒	☒	☒
5	Pu239	141.657	0.00	1.2410e-007	1	0	☐	☐	☐	☐	☐
6	Pu239	143.350	0.00	1.8000e-007	8	0	☐	☐	☐	☐	☐
7	U235	143.780	0.00	1.1790e-001	25	0	☐	☐	☐	☐	☐
8	Pu239	144.211	0.00	2.0900e-005	1	0	☐	☐	☐	☐	☐

Fig. 5. Edit Peak Information Screen.

Plutonium or Uranium Analysis

A parameter set can be set up for uranium (only) spectra. In this case, different isotopic ratios are calculated and the summary is formatted differently.

Estimation of ^{242}Pu

The estimation of ^{242}Pu is done via a correlation model using an industry-standard formula with user-specified parameters. The values may be stored in any one of the parameter sets used for analysis. This model accommodates most of the commonly-proposed correlations for ^{242}Pu .

Decay Correction of Isotopic Fractions

For samples which are aged on the order of 5 years, the 14.35-year half life of ^{241}Pu can lead to a significant change in the ^{242}Pu fraction, which, if unaccounted for, can lead to (relative) errors on the order of 4% in the ^{239}Pu fraction.

PC/FRAM-B32 can decay correct the isotopic fractions of Pu and Am.

PC/FRAM-B32 V4.3

Plutonium and Uranium Isotopic Analysis Software

Analysis Improvements in Version 4.3

Uranium Analysis: Enhancements for uranium analysis include 1) correction for ^{234}Pa nonequilibrium, 2) correlation to predict ^{236}U , and 3) corrections for coincidence summing.

Plutonium Analysis: Complete capability for plutonium analysis in the 100-keV region and the 40-keV X-Ray region is now present.

Analysis Results Text Window

As well as printing standard reports, analysis results may be displayed in a special text window. Any of the text in this window can be "cut" and "pasted" into a Word® document or an Excel® spreadsheet.

Spectral Graphics

A number of plotting options within PC/FRAM-B32 are available to assist the user. The spectrum itself may be plotted and overlaid with a variety of helpful information, such as parameter files for peak and background regions; energy, peak shape, and efficiency calibration peaks; the efficiency curves themselves; and the peak fit results.

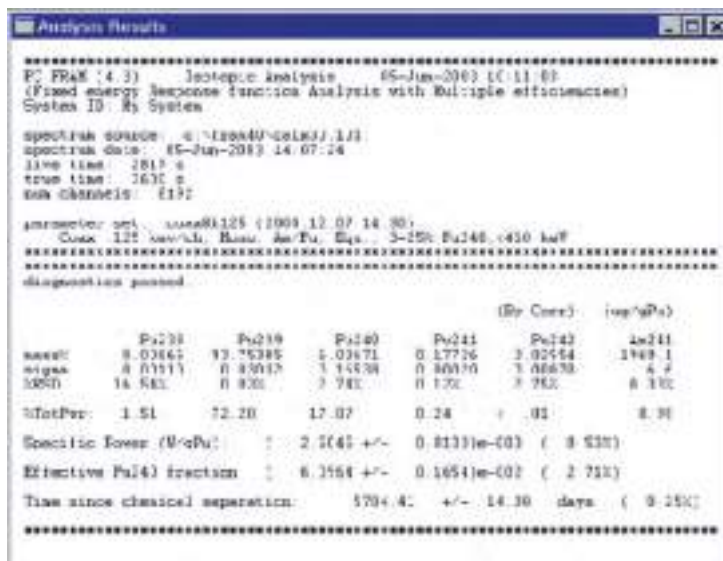


Fig. 6. Short Output Results Text Window.

PC/FRAM-B32 Germanium Detector

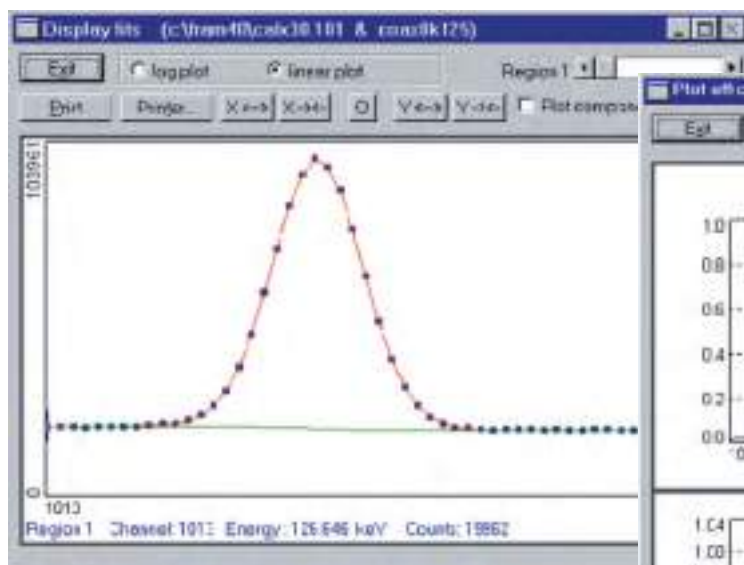


Fig. 7. Display of Peak Results.

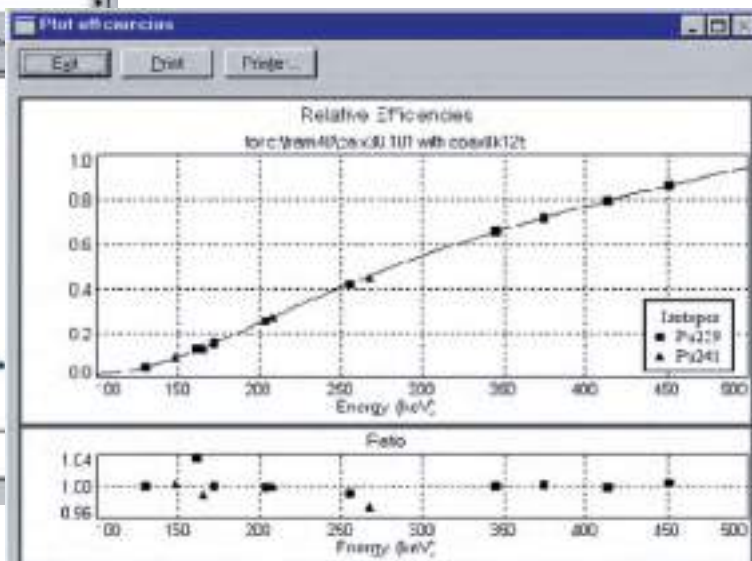


Fig. 8. Plot Efficiencies.

Requirements

PC/FRAM-B32 can perform a complete isotopic analysis using either a single planar or a single coaxial detector. The benefits of being able to operate with a single HPGe detector are obvious: cost, space, convenience, ease of use, and reliability. When used with the "traditional" single planar detector, it is used often (but not always) to collect and analyze data in the 120–420 keV range. The most widely-used energy range used in conjunction with a coaxial detector is 0–1024 keV. Various analysis modes can be used in this wide data range. If the 120–200 keV range is available, PC/FRAM-B32 will work best analyzing in the range 120–450 keV. If this is not possible (for example, if the sample is shielded or in a thick-walled container), PC/FRAM-B32 can still obtain a complete analysis using only those gamma rays above 200 keV from a single coaxial detector.

The optimum choice of detector depends on the applications expected to be encountered. A planar detector is usually the detector of choice if all measured items are unshielded or are in "thin-walled" containers. If shielded containers, thick-walled containers, or a mixture of all container types are encountered, a single coaxial detector is optimum.

The ORTEC SGD series of specifically optimized coaxial and planar geometry Safeguards HPGe detectors are highly recommended.

Password Protection and Security

An access control system within PC/FRAM-B32 stores a list of users, their passwords, and access rights granted to them. Three of the menu items are protected by this mechanism: the Parameters option in the Edit menu, the General Defaults option in the Edit menu, and the User List in the Edit menu. Thus when all these options are in operation, the user will be asked to supply a name and a password. If the security check fails, control returns to the main menu.

In addition to this, as a full 32-bit application, PC/FRAM-B32 may be run under Windows NT 4.0 providing higher level data security and access control. The ORTEC MAESTRO-32 MCA Emulator is also highly secure with password protection on all menu options.

Prerequisites

As a *CONNECTIONS-32* family member, PC/FRAM-B32 will operate correctly on any system supporting *CONNECTIONS-32* compatible hardware. This means ALL ORTEC multichannel buffers, including the latest DSPEC® Plus, DSPEC jr 2.0 and digiDART digital hardware and DART® Portable MCA, Los Alamos M³CA, Rossendorf MiniMCA 166, and various Canberra, Nuclear Data, and Silena hardware systems via the EtherNIM™ MatchMaker™ module. The software will operate on any system already supporting Windows 2000/XP. PC recommendations are a minimum of a 200 MHz Pentium processor with 32 MB RAM. A math coprocessor is required.

PC/FRAM-B32 V4.3

Plutonium and Uranium Isotopic Analysis Software

Ordering Information

To order, specify:

Model	Description
PC/FRAM-B32	PC/FRAM-B32 Version 4.3 Safeguards Software for operation under Windows 2000/XP
PC/FRAM-G32	Documentation for PC/FRAM-B32
PC/FRAM-U32	Update for PC/FRAM-B32

LANL PC/FRAM Nuclear Safeguards Software to ORTEC

ORTEC and Los Alamos National Laboratory have entered into a licensing agreement for specialized software for nuclear safeguards applications. The license authorizes ORTEC to employ the latest version of LANL's PC/FRAM code, which analyzes HPGe detector gamma-ray spectra generated from materials containing plutonium and/or uranium, and thereby determines the isotopic distribution of the plutonium and/or uranium, the ^{241}Am content, and the concentration of certain other radioactive isotopes. The FRAM code will be integrated within ORTEC's *CONNECTIONS-32* spectroscopy environment for ease of use and reliability.

PC/FRAM-B32 V4.3

Plutonium and Uranium Isotopic Analysis Software

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Guide to X-ray inspection by Safeline AVS v1.1

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Guide to X-ray inspection by Safeline AVS v1.1**Principles and applications of automatic X-ray inspection**

For most X-ray inspection systems, the basic principle of operation is the same (see fig 1.). Product is conveyed between an X-ray tube head and a receiver (usually a solid state linear array of X-ray sensitive photo diodes). The photo diodes detect the level of X-rays which pass through the product (the thicker or more dense the product, the fewer X-rays pass through), and generate picture elements (pixels) which correspond to levels of grey. The pixels are then combined, line by line, into a coherent image which is either analyzed by a human operator monitoring the image on a video screen (baggage scanners at airports), or a built-in computer designed for the purpose (industrial applications).

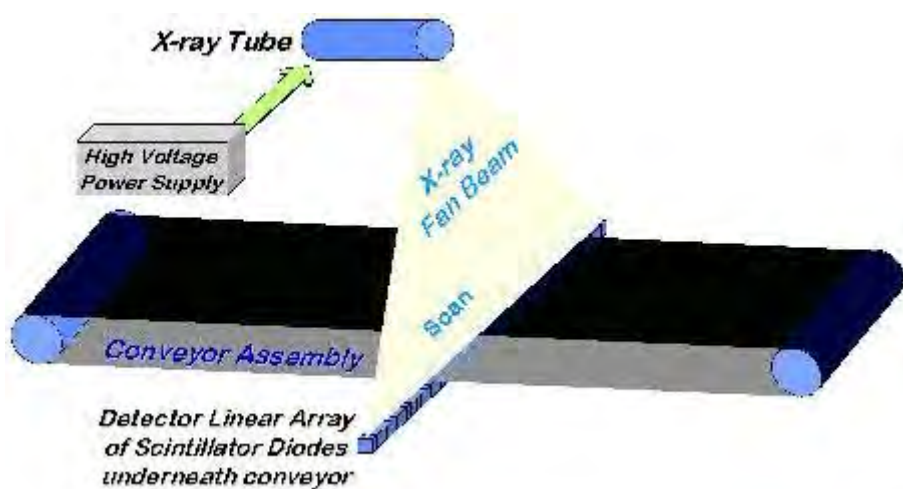


Fig. 1: Basic principle X-ray operation

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What are X-rays? How do they work?

X-rays are a form of electromagnetic radiation (as are microwaves, radio waves, ultraviolet and visible light) which was discovered to have an extraordinarily useful property: X-rays pass through matter in a predictable way. This property opened up a world of applications and, in many ways, revolutionized science and industry.

It was discovered that a sample placed between a source of X-rays and an X-ray sensitive receiver (such as a photographic film) resulted in a picture of the interior of the sample. X-rays passing through the sample are stopped by material in the sample, at a rate which corresponds to the relative density of the sample (the denser the sample, the fewer X-rays reach the receiver). In this way, X-rays allow us to “see” inside not clear objects.

In addition, there is a second effect, whereby X-rays can be scattered by the object. There are two types of scattering:

- 1) Forward or inelastic scatter, in which a small proportion of the X-rays are deflected at a small angle (typically 2 to 4 degrees).
- 2) Back scatter or Compton scatter, where a small proportion of the X-rays are bounced back from the product.

In both of these cases, the amount of scattered radiation is very small, with the result that very high power generators are needed to get a useful image signal. The automatic X-ray systems which are available for the automatic inspection of food, all use the “primary” X-ray beam. These systems use, what is known as, transmission radiography – in other words, it is the X-rays transmitted through the product that are used to create the image.

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Dual energy X-ray systems

There are several methods of implementing dual energy X-ray systems. The major drawback of these systems is the high costs associated with the duplication of circuitry, combined with complexity of extracting additional useful data from the images.

1. Transmission / Compton scatter. In order to generate significant amounts of back-scatter radiation, it is necessary to have a high-energy generator. This type of system will have a conventional transmission detector, which will be used to image the “hard” or high energy X-ray data. In addition, the system will have a collimated array of detectors placed above the object, to detect back scatter radiation.
2. Dual detector systems. When generating high energy X-rays, due to the characteristics of the target material, there will also be a small quantity of soft X-rays generated. If the detector is constructed in two layers one behind the other, the front detector will receive the hard plus the soft X-rays. The X-rays reaching the rear detector will have the soft X-rays filtered out and hence the image will be based only on the “hard” or high energy X-rays. By “subtracting” the data from the two detector layers, the “soft” X-ray data can be extracted.
This technique has been applied in airport security systems, to try to differentiate organic materials such as explosives. In this case, the throughput of the system will be quite low (typically less than 10 objects/minute) and the image is subject to visual interpretation by an operator.
Although, in the past, this method has been applied to automatic on-line industrial inspection systems, the benefits have been very limited.
3. Dual generator systems. In this case, the system will comprise of two independent X-ray generators, each with its own detector. Complex algorithms would compare the result of the two detectors, and this data can be used to resolve softer components in the product.
This method has been used in simple product flows such as ground meat on a conveyor, to determine proportions of components are present, such as fat and lean. However, it has been impractical to apply this method to contaminant detection, due to the difficulty in correlating the image data accurately from the two detectors.

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X-ray energy spectrum:

X-rays are generated by accelerating a stream of electrons towards a target material, within the X-ray tube. The electrons are generated by a heated filament, and being negatively charged, can be accelerated towards an anode with a positive potential (voltage).

When an electron strikes the anode target material, an X-ray photon is emitted. The energy with which the electrons strike the anode, will determine the energy of that photon, and hence its wavelength and frequency. In theory, the energy of the photon can be calculated from the accelerating voltage, and the charge on the electron. However, in practice the energy is somewhat lower due to inefficiencies in the tube and characteristics of the anode target material.

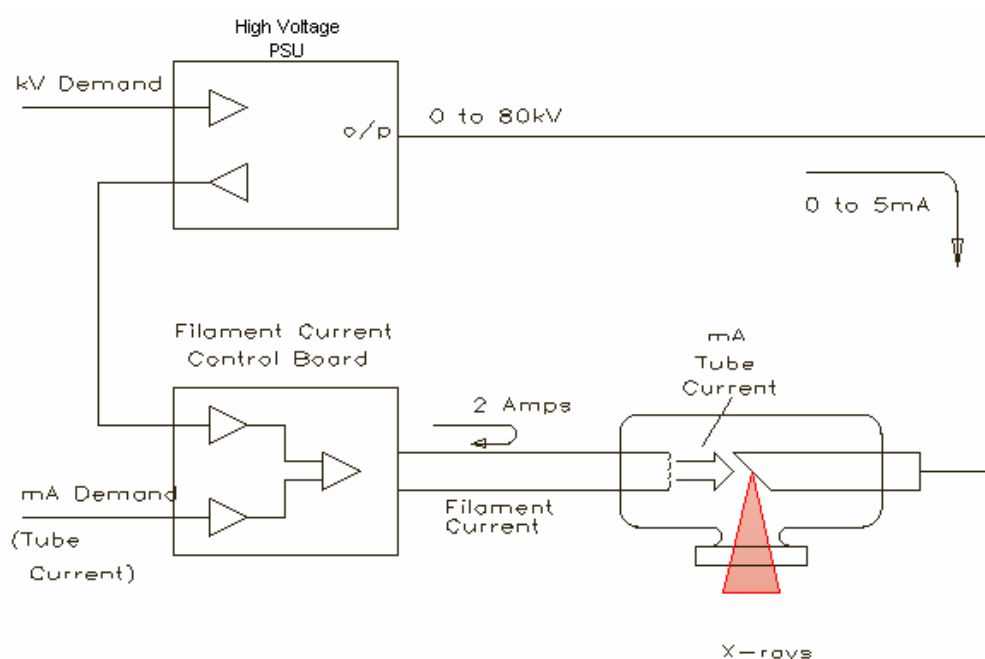


Fig. 2: How X-rays are generated.

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The energy is correctly described in keV (kilo electron-Volts). The frequency and wavelength can be calculated as follows:

$$E = V * e$$

$$E = h * \nu$$

$$c = \nu * l$$

Where:

- E is the energy of the photon.
- V is the accelerating voltage.
- e is the charge on an electron.
- h is Planck's constant.
- c is the speed of light.
- ν is the frequency of the radiation.

Therefore, we can calculate the wavelength of the X-rays to be:

$$l = c * h / (V * e)$$

this gives a value of about $3 * 10^{-11}$ m. This lies between ultra violet light and microwave radiation.

One of the benefits of using X-rays is the fact that the characteristics of the radiation, such as its penetration ability (wavelength) may be controlled over a wide range, just by varying the anode voltage.

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Generating X-rays

For most industrial and scientific applications, X-rays are generated with a device called an X-ray tube (See fig. 3). Electricity is applied to a filament which emits electrons that stream towards an anode, in which is embedded an angled target plate. When electrons bombard the plate, two things are produced:

1. Heat, which is siphoned off by means of a cooling system.
2. X-rays.

X-ray tubes are especially useful because of safety considerations. Since they don't rely on radioactive isotopes to produce X-rays, the tubes are completely inert, and therefore safe to handle, when power is not applied to them.

The material of the target defines the characteristics of the emitted radiation. Tungsten and Copper are two of the materials that are commonly used.



Fig. 3: Example of X-ray tube.

There are several different designs of tubes in use:

1. For standard low cost applications, such as airport baggage scanners, the tube will be constructed in a glass envelope. The X-rays will be emitted through the glass wall on one side of the tube. This is useable for energies of **50kV** and above and at power levels of up to 300W.
2. For low energy applications, the glass of the tube, and the surrounding oil, etc, will attenuate too much of the X-ray beam. In this case a special window, or port, is incorporated into the side of the tube. The window is constructed of Beryllium, which, with an atomic number of 4, is the lightest stable element available. This allows X-rays to be generated at energies down to **5kV** or less.
3. For high power applications, ceramic tubes are used. These generally incorporate water cooling pipes around the anode to take away the large amounts of heat that are generated. Ceramic tubes will operate at power levels of 3000W or higher.

Guide to X-ray inspection by Safeline AVS v1.1**Cooling the tube:**

The X-ray tube has a high potential, or voltage, applied to it. It is usual to immerse the tube in oil, to provide insulation, because the high voltage will flash over in air if the potential gradient exceeds 8kV/cm (20kV/inch). The assembly which contains the X-ray tube and insulating oil is known as the X-ray tank.

Because most of the power applied to the tube is converted to heat, it is necessary to have an efficient cooling system. The insulating oil will also provide a means of taking the heat away, by means of a pump and a radiator. Low power systems (**less than 50W**) will use air cooled tanks, whereas higher powered systems will use a closed circulation system. Over 500W the systems will use a water cooling system, with the water pipes incorporated into the anode of the X-ray tube.

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Detection of X-rays

Image Intensifier

The early systems used a device called an image intensifier, to detect and image the X-rays. An image intensifier is a vacuum tube, which has a large fluorescent screen as its input port, which is typically 9 or 12 inches in diameter. The screen converts the X-ray photons to electrons, which then pass through a series of charged plates which multiply the number of electrons generated. At the back of the device, the electrons strike a second, smaller fluorescent screen, producing a bright image on the output port, which is about 1 inch in diameter. The output port is viewed by means of a conventional CCD camera, and the image is displayed on a monitor or transferred to an image processing system.

Image intensifiers are still used in some systems – in particular, they are used in screening systems where the image is viewed by an operator. Screening systems operate at much lower speeds than automatic systems and the operator will generally have the capability to zoom up the image, modify the contrast or reverse the conveyor to re-inspect the object.

Image intensifiers are also still used in some automatic systems where a formatted image is beneficial, such as down-shoot jar inspection systems. This is in combination with a flash X-ray generator which produces a short pulse of X-rays – about 2 ms – to effectively freeze the motion of the object. However, flash X-ray / Image intensifier systems tend to suffer from high noise levels and high maintenance costs, and are therefore not widely used in current automatic systems.

Linear Detector

A linear X-ray detector is comprised of an array of photodiodes, which are scanned and read-out sequentially. The diodes would be from 0.4mm to 1.6mm in dimension. The image is built up by the movement of the object over the detector, which would normally be scanned between 300 and 2,000 times per second.

The choice of scanning rate would depend on the diode size and the conveyor speed. The objective is to achieve a 1:1 aspect ratio – in other words, the resolution in the direction of the conveyor motion is the same as the resolution across the belt. Therefore, the scan rate would be:

$$S = V * 1000 / (D * 60)$$

Where:

- S is scan rate (scans per second).
- V is belt speed (meters per minute)
- D is diode pitch (mm)

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In low energy systems, the X-ray photons will be absorbed directly by the silicon diodes, generating a current flow, which is picked up by the associated circuitry.

In higher energy systems, the energy of the X-rays is such that most of the X-ray photons pass straight the silicon, rather than being converted. In this case, the diodes will have a phosphor material, or scintillator mounted on the sensitive face. As the X-ray photons hit the scintillator, they are absorbed and emit light photons which are detected by the diodes.

The choice of the scintillator material will affect the sensitivity and response time of the detector. Some of the most sensitive scintillators will give rise to lag or smearing of the image. The scintillator is selected to have a response time faster than the highest scan rate at which the detector is designed to operate.

The various diodes in the array will have differing characteristics, in particular the “dark current” (which is the signal generated when there are no X-rays present) and the “gain” which is a measure of the sensitivity of the diode. In addition, the gain will be affected by the X-ray intensity, which varies across the array due to the geometry of the X-ray beam. The detector incorporates a DSP (digital signal processor), which will calculate the adjustments to the diode signal necessary to linearise the output and give a uniform image. The process of calculating these adjustments is known as “calibration”.

Calibration of the detector normally takes place once per shift, or whenever the product is changed. It is an automatic process and consists of sampling the diode data with the X-rays turned off, and again with the X-rays at a preset level. The entire sequence takes about **40 seconds**. In practice, if the machine is left powered up, it is normally unnecessary, although regular calibration is usually regarded as good operating practice.

The detectability of a contaminant material depends on the energy of X-rays being used to generate the image.

1. At all energy levels, the contrast is a function of the density of the contaminant, compared with the food matrix.
2. When low energy is used, the contrast is enhanced for contaminants where the atomic weight (or atomic number) of the atoms in the contaminant molecules is higher than those in the food matrix.

By using lower energies, additional sensitivity is achieved in stone and glass. In addition, other contaminants produce a contrast difference, such as to make them detectable

The food or other background products, consist primarily of C, H and O. These materials have atomic numbers 6, 1 and 8 respectively. Therefore, materials with atomic numbers significantly higher than eight will be detectable.

Considering the periodic table of elements:

[illegible]

* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
† Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Fig.4: Periodic table of elements.

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It can be seen that typical food matrix components (H, C, O, N) all lie in the top row of the table. As a generality, materials containing atoms in the second row or below will be detectable.

- Second row elements include Aluminium (Al), Silicon (Si), and Chlorine (Cl). These are present in stones, glass and PVC. **Generally these would be detectable at, say, 2 – 2.5 mm.**
- Elements in the third row and below would be including Iron (Fe), Copper (Cu) and most other metals. **These would be detectable at, say, 1.0 mm.**
- Calcium is a third row element, and as such, means that calcified bone would be detected by low energy X-ray systems. Due to the relatively low density of calcium in the bone, **this would be detected at a level of about 2.5 mm**, rather than the greater sensitivity associated with other third row elements.

Detection of plastics

It can therefore be seen that many plastics would normally only be detectable on the basis of density differential. These include:

- Polyethylene – (PE) – this contains C and H atoms.
- Polycarbonate – (Makrolon, Acrylic) – this contains C, H and O atoms, as with the food matrix.
- Polytetrafluoroethylene – (PTFE, Teflon) – this contains C, H and F (Fluorine – atomic number 9)

Where the bulk density of the material is significantly greater than the food, these may be detectable. However, it is important to remember that, in general, contaminants will be embedded within the food, and will therefore displace the equivalent volume of food material. This will have an adverse effect on the detectability, compared with applying the contaminant externally to the product.

In many cases, where a potential source of contamination is known, it is possible to select the materials so that they are detectable. For example, where seals are used in pipelines, it would be desirable to be able to detect parts of a seal. A conventional seal of nitrile rubber will not be readily detectable due to the atomic numbers of the constituents of the molecules. However, seals made from “Viton” are detectable.

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Detection of soft contaminants

Where there is no difference between the bulk density and atomic constituents of the food matrix and the contaminant, it is unlikely that the contaminant will be reliably detected. Examples of these materials are:

- Wood
- Insects
- Hair
- String

In addition, items such as cherry or olive pits would normally be difficult to detect. In the case of a whole cherry pit, there is usually a void, or air pocket in the center of the pit, and this may be seen. However, if the pit is crushed, this would no longer be visible, and this would therefore mean that this application would not be a good candidate for X-ray inspection.

Effect of Salt on inspection

Common salt is sodium chloride (NaCl) and both the sodium and chlorine atoms represent a relatively high atomic number. Therefore, a salt content in a product will make that product appear somewhat denser than normal. Generally, this does not affect the detection of contaminants, since salt content is usually low (<2%) and the salt is in solution or evenly distributed within the product. However, free salt crystals will sometimes be visible, for example, in certain types of crackers. Also, where the application involves mass control, a variable salt content can give rise to errors in the mass measurement.

There is glass and there is glass

There are many types of glass, and the type of glass will affect the detection performance. For example, "lead crystal" glass, will appear to the X-ray system as dense steel. However, it would be relatively rare to find a contaminant of this type in a food product. It would be much likely to find a contamination of soda glass, such as the material the jars or bottles are made of. In some cases, laboratory glass can even be lighter.

There is stone and there is stone

In a similar way, there are many types of stone (rocks). The factors that affect the detectability of stone are the porosity, the specific gravity and the atomic constituents. Most normally occurring rocks would contain silicon, calcium, potassium, sodium and similar materials. These are mainly "second row" elements in the periodic table, and hence would be detectable with "mid sensitivity" i.e. say, 2.0 – 2.5mm. However, material containing metal ores, would appear virtually as dense as metal.

Guide to X-ray inspection by Safeline AVS v1.1*Bone must be calcified*

The mechanism for the detection of bone is the resolution of the calcium atoms in the hard bone. Soft bones, such as the keel bone in a chicken are not normally detectable. However, chicken rib bones, and fan bones can be detected. Generally, land animals (e.g. pork and beef) will have dense, calcified bones.

Again, porosity is a factor in the detection of bones. In some cases, cooked stripped chicken is prepared from older birds, and the poor quality of the feed used can give rise to thin, porous bones that shatter easily. Thus the detection is made more difficult, due to both the density and small dimensions of bone shards.

Guide to X-ray inspection by Safeline AVS v1.1**Product effects**

X-ray inspection differs from other similar contaminant detection technologies in that it is relatively immune to product effects and similar physical interactions. These effects include the following:

- 1) Effects of metalised film and foil packaging. The packaging has no net impact on the X-ray system, because the foils used for trays and packages are very thin (typically less than 60 microns) and packaging is normally uniform over the entire product. In the extreme condition, a successful inspection can be made of products in aluminium and steel cans.
- 2) Presence of metallic items, such as premiums, pouring spouts, etc.
- 3) Effects of conductivity or polarized molecules, and products produced in brine (salt solution) or similar conductive liquids.
- 4) Effects of temperature. X-ray systems are not affected by product temperature. It is quite common for products to be inspected at -20 C or + 90 C (- 10 F to + 200 F).
- 5) Effects of vibrations. X-ray systems are not affected by vibrations from surrounding equipment.
- 6) Proximity of metallic objects or magnetic fields. There is no impact on an X-ray system caused by magnetic or conductive materials.

The only significant factor that affects the detection performance of the X-ray system is the “texture” in the image – for example, a piece of cheese, which is highly homogeneous, can be inspected to a much greater sensitivity than, say, a box of cornflakes.

Guide to X-ray inspection by Safeline AVS v1.1**How small is the contaminant?**

In comparing the performance of systems, it is important to have a consistent standard. It has become traditional in the metal detection industry to use spherical contaminant standards.

In some cases, X-ray systems may be quoted with sensitivities based upon cube contaminant standards. This is because high-energy X-ray systems may “burn through” the edges of small contaminants, due to the excessive penetration capability, resulting in the contaminant to “shrink”.

In order to compare the performance of cube and spherical contaminants, it is necessary to calculate the equivalent volume of the material in the contaminant. Therefore a spherical sample is equivalent to a cube of 80% of the diameter. For example:

$$1.0 \text{ mm sphere} = 0.8 \text{ mm cube}$$

In the case of glass contaminants, there is an argument that the cube is much more likely to occur in the real world. When a piece of glass shatters, it is unlikely to have the smooth edges of a sphere. It is also likely that the inspection algorithm will be tuned to detecting sharp transitions, or regions of high contrast.

Generally, the most important dimension for the contaminant is the “thickness” or dimension in the direction of the X-ray beam. Where a system may, in a certain product, detect a 2 mm. sphere of glass, a shard of glass which may be 20 mm * 20 mm * 1 mm could, lying horizontally, remain undetected.

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Pipeline systems – flow dynamics

A common method of handling products in an on-line X-ray system is to pump it through a pipeline system. The product is usually delivered in a pipe of circular section. However, this does not provide the optimum sensitivity for detection – it is better to convert the section to a rectangular form, to provide a uniform thickness to the product, as it passes through the inspection manifold.

The manifold dimensions are calculated to maintain a constant cross section through the system. For example, typical manifold apertures are:

Diameter (in)	Diameter (mm)	Area (mm ²)	Width (mm)	Height (mm)	Throughput (L / hour) [1]
2.0	51	2043	81	25	3500
2.5	63	3118	90	35	6000
3.0	76	4537	110	40	8500
3.5	89	6222	138	45	11000

Note [1]: Based on scanning rate of 600 scans / sec, and flow rate 30 m / min.

Any fluid passing through a pipe will have non-uniform flow – i.e. the material close to the wall of the pipe will travel more slowly than that in the center of the pipe.

In addition, if the liquid in the pipe has a low viscosity, a large and dense contaminant will naturally sink to the bottom of the pipe, and hence be dragged along more slowly.

The system does not possess any knowledge of the position of the contaminant in the vertical plane, and therefore it is not possible to unambiguously judge whether the contaminant is in the high- or low-velocity part of the flow. Therefore the transit time from the inspection manifold to reject valve is, to degree uncertain.

It is, of course, essential that the contaminant is reliably ejected from the flow. Therefore, the reject valve has to be held open for a sufficient length of time to accommodate contaminants in all positions.

Use of a pump encoder

In many cases, the speed of the pump may be variable. This may be intentional (for example, in the case of a sausage stuffer, where the speed will be dictated by the in feed of product) or unintentionally (for example where product temperatures or viscosity give rise to loading of the pump). In these cases, the timing of the reject signal will be affected by the mean flow rates. In order to compensate for this it is preferable that the reject shift register is clocked by a signal from an encoder, attached to the pump. In this way the reject timing will be compensated for changes in pump speed.

Guide to X-ray inspection by Safeline AVS v1.1*Setting of the reject time*

An approximate value for the reject delay can be calculated from knowledge of the average flow rate, and the physical distance from the manifold to the reject valve. However, this would need to be confirmed by testing.

In order to test the system, an insertion plug would be fitted to the in-feed pipe of the X-ray pipeline system. Such insertion plugs are generally suitable for relatively viscous materials such as ground meat products. However, they are generally not suitable for liquids such as soups and sauces.

Test samples need to be easily recovered, but at the same time pass readily through the system. The test sample would generally be attached to a length of tape, in a contrasting colour such as yellow.

For meat products, when the reject valve is actuated, a slug of meat will be rejected. In the case of ground meat, this will resemble a sausage. The best approach is to set the "reject duration" to be much longer than required. When the slug of meat is rejected, the position of the contaminant can be located, and the necessary adjustments to the optimum reject time can be estimated.

For liquid products, the process is inevitable somewhat more difficult. However, the use of a coarse mesh over the reject bin, aids recovery of the test samples.

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Image processing considerations

The earliest automatic X-ray inspection system achieved reasonable detection results, by using a fixed detection threshold. In this case, the image might typically show that the darkest pixel in the image would be down to grey scale 100. In this case, the operator might set the reject “threshold” to be grey scale 90. The image data from the detector was analyzed by the logic hardware in the system, and if any pixel was less than the reject threshold, a reject condition was immediately signalled.

This approach had the advantage that it was fast – effectively processing data as fast as the detector could deliver it. The disadvantages were however, that the system could normally only detect contaminants that produced a signal denser than the food matrix, and that the system is not tolerant to changes in product – an increase in product thickness or density during production could cause false rejects, and a reduction in thickness or density results in a loss of sensitivity.

Later systems were developed which performed an analysis of the image data by the processor. In this case, the speed of processing becomes critical to the throughput of the system, and minimum product spacing is critical to the reliability of the inspection.

The latest generation of systems uses several methods to resolve the performance limitations, and make the systems much more immune to product spacing. These include:

- Dual bank memory. The system is effectively parallel by collecting the image into one memory bank while performing the analysis of in an alternate bank. Once an image has been fully acquired, the image memory banks swap, to allow the inspection of the new image to proceed.
- Hardware pre-processing. With the advent of flexible high-speed logic arrays, many of the repetitive tasks that formerly consumed a considerable amount of processing resource can be handled by hardware. This means that software is responsible for the tasks of interpretation and decision-making.

Therefore, it is no longer necessary to have extremely high performance processors, which are in general more fragile and less suited to an industrial environment.

Guide to X-ray inspection by Safeline AVS v1.1

Rejecting non-conformant product

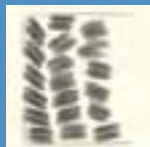
Of course, if we have detected a defective product, it is necessary to eject it from the conveyor or pipeline.

There are a range of different reject mechanisms available, depending on the product, its weight and shape, its susceptibility to damage, the throughput rate, etc. Reject devices include:

- Air blow-off systems. These are generally suitable for packs of up to 200g in weight, but are capable of high speed.
- Pneumatic reject cylinders. This type of reject would typically have a short reject stroke and would be capable of rejecting at high speed (up to 400 packs / minute). It rejects by imparting kinetic energy to the product, and is therefore not suitable where product damage may occur. Also, this type of reject would operate more effectively with square or rectangle packages rather than circular ones, where the pack may be deflected.
- Overhead rodless cylinder. This type of reject will push the product off the conveyor, and is therefore less likely to cause impact damage to the rejected product. The maximum speed would be lower, at about 200 packs / minute. In the case of a long travel, a reject of this type can be configured to eject alternate packs to the left and right. By fitting a profiled actuator to the arm, this overhead rodless cylinder will eject non-rectangular packs.
- Sweep arm rejects. This reject mechanism will have a sweep arm or flipper that will direct the pack off the belt. This is generally suitable for speeds of up to 100 packs / minute and packages of up to 2Kg. It can also be configured as a dual lane reject, with two sweep arms positioned centrally on the conveyor.
- Drop flap rejects
- Retracting conveyor rejects.

Protezione del Vostro Marchio

**POWERx™ Sistemi di Ispezione
a Raggi X ad Alte Prestazioni**



Opzioni Disponibili

Opzioni Software

- Simulazione Contaminanti Virtuali:
Contribuisce a ottimizzare la probabilità di rilevamento simulando il rilevamento di contaminanti in immagini memorizzate
- Impostazione Automatica: determina automaticamente l'impostazione parametrica ideale in base a statistiche raccolte durante l'impostazione della produzione
- Funzionalità di Controllo del Peso (Solo Modelli C): misurazione della massa per correlazione tra densità dei raggi X e peso*

*non conforme allo standard internazionale R51

Opzioni Hardware

- Schermatura contro le radiazioni e nastri trasportatori personalizzati (modelli S e D)
- Corsie di allineamento prodotti (modelli C)
- Dispositivi e contenitori di scarto, con avvisatori acustici e luminosi
- Sfere metalliche e in vetro di prova
- Certificazione di sicurezza UL o CSA
- Misuratore per rilevamento di radiazioni
- Kit pezzi di ricambio

POWERx Modelli S e D

Specifiche di Applicazione

Prodotti Ispezionabili	Prodotti confezionati compresi vasi in vetro, bottiglie, lattine, brick		
Altezza e Larghezza Prodotto (per i dettagli sull'area di ispezione fare riferimento ai diagrammi dei fasci)	S 140: 140 mm x 165 mm	D 165: 165 mm x 185 mm	
	S 230: 230 mm x 185 mm	D 195: 195 mm x 185 mm	
Peso Prodotto Trasportabile su Nastro	Determinato dalla struttura del nastro trasportatore esterno		
Sensibilità di Rilevamento per Metallo	I gradi di sensibilità tipici variano da 1 mm a 2 mm di diametro per il metallo e da 2 mm a 4 mm per il vetro in base alla densità, alla consistenza e al confezionamento del prodotto. In alcuni prodotti è possibile rilevare particelle metalliche di 0,5 mm di diametro e particelle in vetro di 1,0 mm.		
Velocità di Ispezione	≤120 m/minuto		
Tasso di Segnalazione Scarti Standard	2500 contenitori al minuto (cpm); sono disponibili velocità più elevate con hardware esterno		

Caratteristiche Tecniche

Fasci a Raggi X	S 140 e S 230: Singolo D 165 e D 195: Doppio (posizionato a 90 gradi, design brevettato)		
Potenza dei Raggi X	S 140: ≤90 kV e ≤10 mA	D 165: 2 x ≤90 kV e 2 x ≤10 mA	
	S 230: ≤90 kV e ≤20 mA	D 195: 2 x ≤90 kV e 2 x ≤20 mA	
	S 230 opzione LP: ≤90 kV e ≤10 mA	D 195 opzione LP: 2 x ≤90 kV e 2 x ≤10 mA	
Altezza Nastro Trasportatore	(misurata dal pavimento al fondo della confezione controllata)		
	S 140: da 771 a 965 mm	D 165: da 916 a 1110 mm	
	S 230: da 775 a 900 mm	D 195: da 835 a 905 mm	
Algoritmi del Software	Soglie colorimetriche, analisi delle forme, ispezione fotometrica; Sono disponibili routine di ispezione specifiche per varie applicazioni ad un costo aggiuntivo		
Interfaccia Uomo-Macchina	Monitor LCD a colori da 15" a elevato contrasto con schermo tattile		
Lingue Disponibili	Inglese, Francese, Italiano, Tedesco, Portoghese, Spagnolo, Polacco		
Esportazione Dati e Interfacce	Formati file: .mdb, .txt, .tif, .jpg, .bmp; interfacce USB e di rete		
Accesso Remoto	Standard, comprende software e hardware (modem o interfaccia di rete)		
Peso della Macchina	S 140: 600 kg	D 165: 1200 kg	
	S 230: 1100 kg	D 195: 1400 kg	
Struttura	Acciaio inossidabile AISI 304, finitura scotch bright		
Requisiti Elettrici (esclusi i condizionatori d'aria opzionali)	230 VAC ±10%, 50/60 Hz, monofase		
	S 140: 18 A	D 165: 30 A	
	S 230: 28 A; opzione LP: 18 A	D 195: 41 A; opzione LP: 39 A	
Raffreddamento	Refrigeratore esterno ad acqua (tubo a raggi x) e scambiatore di calore (mobile)		

Specifiche Ambientali

Temperatura/Umidità di Esercizio	da +5°C a +35°C; 20-80% senza condensa
Protezione da Acqua e Polveri	IP 65, NEMA 4X
Requisito per l'Alimentazione di Aria	6 bar (87 psi), richiesti per gli otturatori di raggi X in alcuni modelli

Conformità e Certificazioni

Sicurezza delle Radiazioni	Certificato per l'emissione di <0,5 µSv/ora esclusi i tunnel di ingresso/uscita; FDA CFR21 parte 1020.40
Farmaceutica (Modelli Rx)	Conforme alla norma CFR 21 parte 11; convalida IQ/OQ/PQ disponibile

Opzioni Disponibili

Hardware	Refrigeratore ad acqua, schermatura, sistemi di scarto, misuratore della sicurezza delle radiazioni
Software	Impostazione automatica, simulazione contaminanti virtuali
Service	Installazione, assistenza tecnica 24/7, contratti di assistenza, estensioni della garanzia

Vantaggi Dell'ispezione a Raggi x

- **Conformità ai Requisiti:** Agevole conformità ai mandati di ispezione dei clienti e/o alle norme governative
- **Funzionalità Superiori ai Metal Detector:** Rileva molto di più del semplice metallo— identifica altri corpi estranei densi come vetro, pietra e alcuni tipi di plastica
- **Sensibilità Superiore ai Metal Detector:** Sensibilità di rilevamento ottimizzata in applicazioni in cui l'imballo metallico pregiudica le prestazioni dei metal detector
- **Verifica:** Verifica delle condizioni del prodotto (per es., presenza/assenza, conteggio, rottura, disposizione) che garantisce un livello di qualità ottimale e un marchio superiore
- **Conformità:** software di misurazione della massa (opzionale) per mantenere il peso ideale del prodotto
- **Tracciabilità:** Creare e salvare record dettagliati per la tracciabilità e per l'ottimizzazione dei processi, comprese immagini di prodotti respinti ricche di informazioni

Modelli POWERx C

Specifiche di Applicazione

Prodotti Ispezionabili	Prodotti confezionati compresi bag-in-box, buste metallizzate, prodotti in vassoio o cartone, prodotti sottovuoto; prodotti sfusi			
Altezza e Larghezza Prodotto (per i dettagli sull'area di ispezione fare riferimento ai diagrammi dei fasci)	C 200:	160 mm x 160 mm	C 600:	555 mm x 255 mm
	C 300:	275 mm x 130 mm	C 800:	700 mm x 360 mm
	C 400:	360 mm x 270 mm		
Peso Prodotto Trasportabile su Nastro	≤100 kg			
Sensibilità di Rilevamento Per Metallo (Fe, non-Fe e Inox) e Vetro	I gradi di sensibilità tipici variano da 1 mm a 2 mm di diametro per il metallo e da 2 mm a 4 mm per il vetro in base alla densità, alla consistenza e al confezionamento del prodotto. In alcuni prodotti è possibile rilevare particelle metalliche di 0,5 mm di diametro e particelle in vetro di 1,0 mm.			
Sensibilità di Rilevamento per Altri Contaminanti (pietra, osso, plastica ecc.)	Si rende necessario testare l'applicazione; i risultati variano tipicamente da 2 mm a 5 mm			
Velocità di Ispezione	C 200:	≤40 m/minute		
	C 300:	≤60 m/minute		
	C 400/C 600/C 800:	≤70 m/minute		
Corsie di Ispezione e di Scarto	Fino a 8			

Caratteristiche Tecniche

Massima Potenza dei Raggi X	C 200:	≤95 kV, 1.5 mA	C 400 (LP):	90 kV, 10 mA; LP opzione: 5 mA
	C 300:	70 kV, 3 mA	C 600/C 800:	90 kV, 10 mA
Altezza Nastro Trasportatore	C 200:	da 800 mm a 950 mm	C 400:	da 850 mm a 1050 mm
	C 300:	da 860 mm a 1020 mm	C 600/C 800:	da 850 mm a 1050 mm
Larghezza Nastro Trasportatore	C 200:	160 mm	C 600:	585 mm
	C 300:	270 mm	C 800:	850 mm
	C 400:	405 mm		
Lunghezza Nastro Trasportatore	C 200:	1100 mm (compreso sistema di scarto)	C 600:	2530 mm (compreso sistema di scarto)
	C 300:	1840 mm	C 800:	2750 mm
	C 400:	2530 mm; (compreso sistema di scarto)		
Algoritmi del Software	Soglie colorimetriche, analisi delle forme, ispezione fotometrica; Sono disponibili routine specifiche per varie applicazioni ad un costo aggiuntivo			
Interfaccia Uomo-Macchina	Monitor LCD a colori da 15" a elevato contrasto con schermo tattile			
Lingue Disponibili	Inglese, Francese, Italiano, Tedesco, Portoghese, Spagnolo			
Importazione ed Esportazione Dati	Formati file: .mdb, .txt, .tif, .jpg, .bmp; interfacce USB e di rete			
Accesso Remoto	Standard, comprende software e hardware (modem o interfaccia di rete)			
Peso Della Macchina	C 200:	400 kg	C 600:	850 kg
	C 300:	600 kg	C 800:	1100 kg
	C 400:	800 kg		
Struttura	Acciaio inossidabile AISI 304, finitura perlata			
Requisiti Elettrici	230 VAC ±10%, 50/60 Hz, monofase C 300: 13 A			
	C 200:	10 A	C 400/C 600/C 800:	18 A
Raffreddamento	Refrigeratore esterno ad acqua (tubo a raggi x) e scambiatore di calore (mobile)			

Specifiche Ambientali

Temperatura/Umidità di Esercizio	da +5°C a +35°C; 0-80% senza condensa
Livello di Protezione da Acqua e Polveri	IP 65, NEMA 4X
Alimentazione Aria	6 bar (87 psi) solo per il sistema di scarto

Conformità e Certificazioni

Sicurezza Delle Radiazioni	Certificato per l'emissione di <0,5 µSv/ora esclusi i tunnel di ingresso/uscita; FDA CFR21 parte 1020.40
Farmaceutica (Modelli Rx)	Conforme alla norma CFR 21 parte 11; convalida IQ/OQ/PQ disponibile.

Opzioni Disponibili

Hardware	Refrigeratore ad acqua, schermatura, sistemi di scarto, misuratore della sicurezza delle radiazioni
Software	Misurazione massa, impostazione automatica, simulazione contaminanti virtuali
Assistenza	Installazione, assistenza tecnica 24/7, contratti di assistenza, estensioni della garanzia

POWERx

Raggi X a Elevate Prestazioni

I rigorosi standard dell'industria alimentare e delle bevande pongono ai produttori crescenti richieste per livelli di rilevamento dei contaminanti e capacità di ispezione superiori. In passato, semplici metal detector erano in grado di soddisfare questa esigenza. Oggi, i sistemi a raggi X POWERx sorpassano di gran lunga i metal detector per funzionalità e sensibilità.

I sistemi POWERx di Thermo Scientific sono studiati per garantire i massimi livelli di assicurazione qualità. Presentano una tecnologia a raggi X di concezione avanzata e un sofisticato software di analisi delle immagini che ottimizza sensibilità e probabilità di rilevamento.

È disponibile un'ampia gamma di modelli per confezioni con orientamento verticale e orizzontale per offrire tutta la flessibilità applicativa che occorre in un'unica soluzione originata da anni di esperienza nel campo dei raggi X.

POWERx è robusto, affidabile e igienico — studiato per soddisfare o superare i più rigorosi requisiti ambientali e igienici. I componenti modulari interni e il software sono stati sottoposti a test rigorosi per garantire l'affidabilità. Il sistema è espandibile con moduli software opzionali per la simulazione dei contaminanti, la conformità alle normative farmaceutiche e la misurazione della massa.

I prodotti POWERx vantano il supporto della rete di assistenza globale di Thermo Fisher Scientific. La gamma di servizi di assistenza completa comprende una funzionalità di accesso remoto standard che consente ai tecnici certificati Thermo Fisher di collegarsi al sistema POWERx dell'utente e di ottimizzarne le prestazioni in qualsiasi momento.



Ispezione Avanzata a Fascio Singolo per Confezioni o Contenitori Verticali

I sistemi POWERx S a fascio singolo di Thermo Scientific offrono funzionalità di rilevamento d'avanguardia nel settore per lattine metalliche, bottiglie in plastica o altre confezioni a orientamento verticale come scatole o astucci. In tali applicazioni la confezione può essere agevolmente scansionata da un fascio a raggi X per il rilevamento ottimale di eventuali corpi estranei.

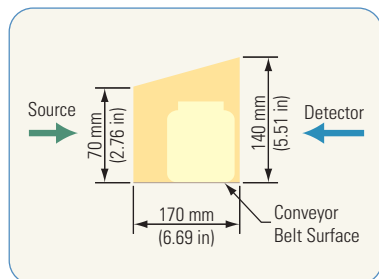
POWERx S models view upright containers from one angle, reliably finding contaminants anywhere inside the package

Modello S140 Sistema a Singolo Fascio Verticale Basso

Idoneo all'ispezione di contenitori verticali bassi.

Studiato per un'ispezione a elevate prestazioni, sebbene economica, di lattine, scatole e astucci di piccole dimensioni con orientamento verticale durante la produzione. Utilizza il medesimo software di analisi delle immagini dotato di numerose funzioni presente in tutti i sistemi POWERx. Le dimensioni contenute e l'integrazione del sistema con i nastri trasportatori esistenti consentono una rapida e semplice installazione. È disponibile anche la versione farmaceutica.

Potenza Raggi X S140: 90 kV e 10 mA



POWERx S140 Geometria del Fascio di Ispezione (vista laterale)

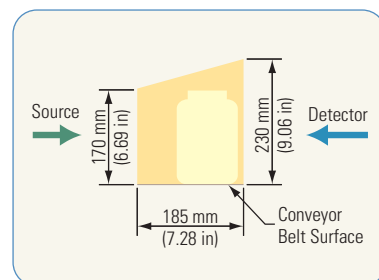


Modello S230 Sistema a Singolo Fascio Verticale Alto

Idoneo all'ispezione di contenitori verticali alti.

Presenta le potenti funzionalità di POWERx S140, con una finestra di ispezione più grande e una potenza superiore per confezioni pesanti e ad elevata densità (è disponibile la versione LP di potenza inferiore).

Potenza Raggi X S230: 90 kV and 20 mA



POWERx S230 Geometria del Fascio di Ispezione (vista laterale)



Ispezione a Doppio Fascio per una Probabilità di Rilevamento pari al 100% in Contenitori di Vetro

Il rilevamento di contaminanti di vetro in contenitori di vetro con un sistema a raggi X può risultare impegnativo. I modelli POWERx D di Thermo Scientific utilizzano una tecnologia brevettata con due fasci radiogeni che effettuano la scansione di ogni contenitore da un angolo diverso, eliminando l'angolo morto riscontrato in altri sistemi. L'architettura a doppio fascio radiogeno è in grado di rilevare anche schegge di vetro difficili da individuare.

I modelli POWERx D visualizzano i contenitori di vetro da due angoli e sono in grado di rilevare contaminanti identificabili in una visualizzazione ma non nell'altra

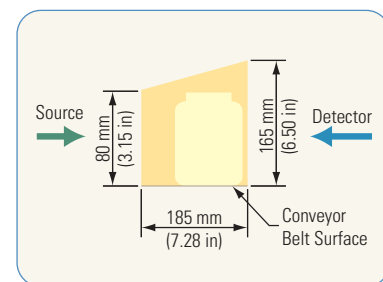


Modello D165 Sistema a Doppio Fascio Verticale Basso

Idoneo all'ispezione di contenitori verticali bassi in vetro.

Sistema a doppio rilevamento brevettato che identifica corpi estranei in vetro in bottiglie e barattoli di vetro. La probabilità di rilevamento di contaminanti sul fondo e sui lati dei contenitori è pari al 100%. Con il sistema a doppio fascio radiogeno è inoltre possibile rilevare frammenti e schegge di vetro sottili e piatte. Il D165 utilizza il medesimo software di analisi delle immagini dotato di numerose funzioni presente in tutti i sistemi POWERx. È disponibile anche la versione farmaceutica.

Potenza Raggi X D165: 2 x 90 kV e 2 x 10 mA



POWERx D165 Geometria del Fascio di Ispezione (vista laterale)

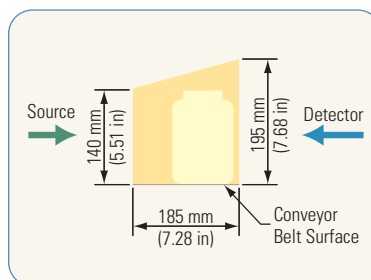


Modello D195 Sistema a Doppio Fascio Verticale Alto

Idoneo all'ispezione di contenitori verticali alti in vetro.

Presenta le potenti funzionalità di POWERx D165, con una finestra di ispezione più grande e una potenza sufficiente a rilevare confezioni pesanti a elevata densità (è disponibile la versione LP di potenza inferiore).

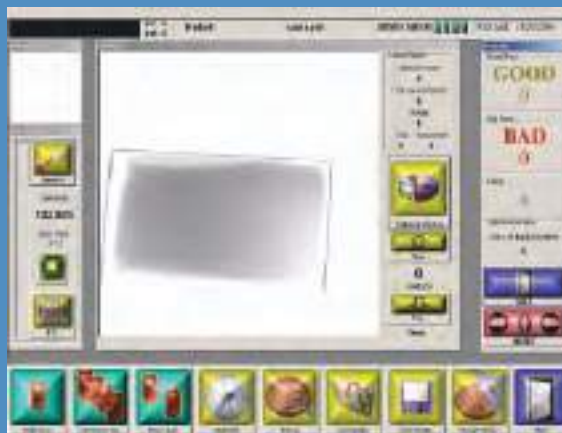
Potenza Raggi X D195: 2 x 90 kV and 2 x 20 mA
D195LP: 2 x 90 kV and 2 x 10 mA



POWERx D195 Geometria del Fascio di Ispezione (vista laterale)

La Potenza Risiede nel Software

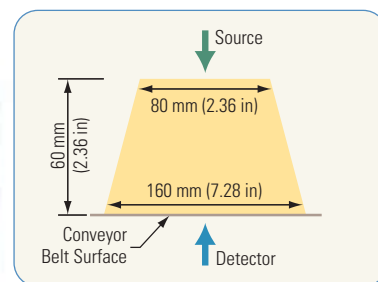
Il software POWERx di Thermo Scientific è stato progettato per agevolare l'utente. L'interfaccia dai pulsanti colorati è intuitiva e semplice da apprendere. Tutti i modelli POWERx presentano numerose funzioni di sistema in comune, nonché una serie completa di strumenti di elaborazione e analisi. La gestione e manutenzione di più sistemi in diverse tipologie di linee di produzione all'interno di un'unica azienda è una cosa da nulla.



Modello C200 Sistema a Nastro Trasportatore Compatto

Idoneo all'ispezione di piccoli contenitori piatti. Progettato per un'ispezione economicamente vantaggiosa e dall'ingombro contenuto di scatole, vassoi e buste di piccole dimensioni manovrate su nastri trasportatori piani. Utilizza il medesimo software di analisi delle immagini dotato di numerose funzioni presente in tutti i sistemi POWERx. È dotato di sistema di scarto integrato. È disponibile anche la versione farmaceutica.

Potenza Raggi X C200: 95 kV and 1.5 mA



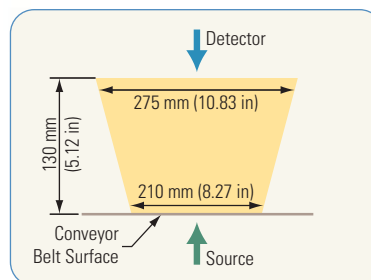
POWERx C200 Geometria del Fascio di Ispezione (vista laterale)



Modello C300 Sistema a Nastro Trasportatore Medio

Idoneo all'ispezione di confezioni di dimensioni moderate. Simile al C200 ma per confezioni più grandi. Il portello ad accesso anteriore consente un rapido ingresso nel tunnel di ispezione a raggi X per la pulitura e la manutenzione. È disponibile anche la versione farmaceutica.

Potenza Raggi X C300: 70 kV e 3,0 mA



POWERx C300 Geometria del Fascio di Ispezione (vista laterale)

Funzionalità Avanzate per Applicazioni Farmaceutiche

Funzionalità Approvata FDA 21 CFR Parte 11

I modelli a raggi X POWERx di Thermo Scientific consentono all'utente di soddisfare i requisiti della norma 21 CFR Parte 11 relativamente alla sicurezza, alla memorizzazione e al recupero di dati elettronici per la ricerca e la tracciabilità. L'accesso degli utenti al sistema è rigorosamente controllato a più livelli e soddisfa i requisiti per le firme elettroniche. Vengono conservati database relativi a lotti e operazioni per la documentazione del corso degli audit e il tracciamento degli eventi.

Pacchetti di Convalida IQ/OQ/PQQ

Documentazione e supporto per installazione, funzionamento e qualifica della produzione che illustrano le specifiche del sistema POWERx e i metodi di analisi a supporto della convalida e della conformità cGMP.

Servizi di Consulenza

Consulenze di Thermo Fisher Scientific per indicazioni sull'implementazione sicura ed efficace dei sistemi di ispezione a raggi X in applicazioni di produzione farmaceutica.



Modelli C400 e C600 Sistemi a Nastro Trasportatore di Dimensioni Standard

Idonei all'ispezione della maggior parte di confezioni dalle dimensioni standard.

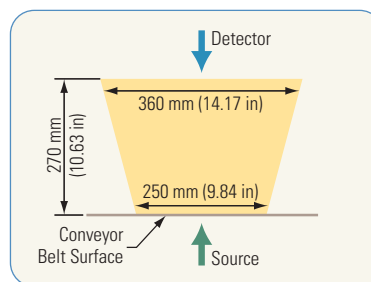
Disponibile in due diverse dimensioni dell'apertura con sorgente radiogena di potenza elevata per prodotti di grandi dimensioni a elevata densità (è disponibile la versione C400 LP di potenza inferiore). Nastro trasportatore di distribuzione di realizzazione unica per un'agevole pulitura e manutenzione. Idoneo all'ispezione di prodotti sfusi disposti su fino a 8 corsie.

Potenza dei Raggi X

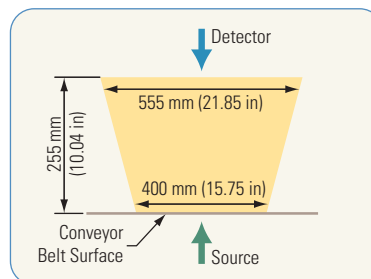
C600: 90 kV and 10 mA

C400: 90 kV and 10 mA

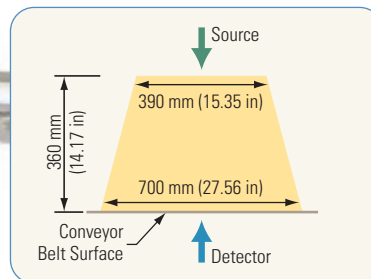
C400 LP: 90 kV and 5 mA



POWERx C400 Geometria del Fascio di Ispezione (vista laterale)



POWERx C600 Geometria del Fascio di Ispezione (vista laterale)



POWERx C800 Geometria del Fascio di Ispezione (vista laterale)



Modello C800 Sistema a Nastro Trasportatore di Grandi Dimensioni

Idoneo all'ispezione di confezioni o casse di grandi dimensioni.

Simile ai modelli POWERx C400/C600, ma realizzato con la massima apertura possibile.

Potenza Raggi X C800: 90 kV and 10 mA



Servizi e Vantaggi

Servizio Priority One™ di Thermo Scientific

Thermo Fisher Scientific fornisce un servizio di assistenza completo per garantire che le prestazioni dei propri prodotti soddisfino i requisiti dei clienti. Dalla garanzia completa, all'assistenza clienti, ai pezzi di ricambio e ai contratti di assistenza l'azienda si impegna a fornire i massimi livelli di servizio per l'investimento effettuato. In qualsiasi momento si presenti la necessità di servizi o assistenza, i tecnici addestrati in fabbrica e certificati saranno pronti a salvaguardare la produzione dei clienti. Per ulteriori informazioni sui servizi e sull'assistenza offerta, visitate il nostro sito web o telefonate al numero verde +1 (800) 227-8891.

Un'Offerta Completa per l'Ispezione dei Prodotti

È disponibile una linea completa di apparecchiature per l'ispezione delle confezioni Thermo Scientific compresi dispositivi di controllo peso, metal detector e sistemi a raggi X. I nostri prodotti proteggono il vostro marchio garantendo sicurezza e qualità per i vostri clienti. Visitate il nostro sito web o telefonate — siamo gli esperti dell'ispezione prodotti.

- Dispositivi di Controllo Peso, visitate www.thermo.com/checkweighers
- Sistemi di Ispezione a Raggi X
 - EZx, visitate www.thermo.com/ezx
 - PROx, visitate www.thermo.com/prox
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ORTEC[®]
ANTECH

QED
Low-Level Waste Assay and Segregation System
Model 3400-210



An Easy to Use, Reliable and Robust Solution to Free Release Sentencing of Containerized Radioactive Waste

- Ideal for low density waste characterization
- Detection limits easily meet free release levels resulting in cost savings
- Intuitively simple user interface with flexible reporting options
- Tried and tested analysis software algorithms
- High sensitivity LN₂-Free HPGe detectors with advanced digital signal processing electronics
- Supports 208 liter (55 gal.) containers and smaller boxes
- Container weighing up to 725 kg (1600 lbs) via load cell
- Automatic Drum Handling Conveyor options

QED is a tool for radioactive waste generators and assay professionals with the task of identifying, quantifying, and sorting radioactive wastes. The high disposal cost of low-level waste makes QED the most cost effective tool to sort and demonstrate that 'non-radioactive' wastes are free release candidates. (The definition of what waste is non-radioactive varies, but for most facilities, QED can make the determination in a single count of a few minutes.)

QED Benefits

- Rapidly and reliably verifies waste activity is at "free release" levels.
 - Ultra-low MDA (~10 nCi) for 'No Activity'
 - Performs TRU sorting at 100 nCi/g over a wide density range (0.1 to 1.5 g/cc)
 - MDA of less than 370 Bq for 208 liters of drummed low density waste for most nuclides
- Naturally occurring radioactive materials (NORM) activities may be excluded from results
- Determination of non gamma emitters by correlation.
- Corrects for matrix material density
- All new modular shield design:
 - Easy installation/reinstallation, especially in restricted spaces or waste storage areas
 - Easily decontaminated
 - Easily reconfigured from drums to smaller boxes

Mechanical Description

QED features a unique, modular shield design. The shield is shipped as individual pieces, and can be easily installed by two people in a matter of hours. It is fabricated from 4 inches of low background steel checked for contamination by ^{60}Co . Each lot of low background steel is individually analysed before fabrication to ensure there is no extraneous contamination. An easily cleanable lacquered copper inner liner suppresses lead x-rays.

The drum is manually loaded with a conveyor and rotated on a platform inside the low background shield in order to average out matrix attenuation effects. Automatic conveyor options are available on request.

A high degree of attention has been paid to operator safety in the design of the QED. The heavy shielded door is electrically controlled. A "light curtain" coupled to an interlock system eliminates any possibility of an object or a person being injured by a moving door. Two emergency interrupt buttons are located on either side of the door and a third is located on the operator console.

For counting of 208 liter drums, the HPGe detectors are installed in the "top", "middle" and "bottom" positions. A fourth intermediate position, with removable plug, is provided between the bottom and middle positions to facilitate the counting of smaller waste packages, for example cardboard boxes.

Generally, smaller containers will result in lower detection limits than larger containers filled with the same material. QED handles small paper or plastic bags of waste as well as carboys containing liquids up to a standard 55 gallon (208 litre) drum weighing up to 1600 lb (750 kg).

QED Spectroscopy Electronics

The latest generation ORTEC DSPEC jr 2.0 (Ref. 1) USB family DSP spectroscopy electronics provide ultra-stable operation over a wide range of count-rate and temperature.

Ethernet communications can be provided to allow the operator console to be located remotely from the measurement point, particularly useful in areas of high ambient radiation. The ORTEC *CONNECTIONS*™ spectroscopy architecture means that the QED is easily interfaced with other systems, e.g. for record keeping/reporting; live spectral data and results may be viewed on other network PC's if required.

QED Software

QED Waste assay software employs the tried and tested ORTEC GammaVision-32 (Ref. 2) algorithms to process the spectra and extract the peak areas. A unique interpolative attenuation correction method is used to correct for the effects of container and matrix.

QED

Low-Level Waste Assay and Segregation System Model 3400-210

Standard QED HPGe Detectors

QED employs three ORTEC Large Area PROFILE Series GEM detectors that 'view' the drum in three vertical slices or segments without collimation. This method provides high-efficiency and high-resolution at high and low energies and maximizes sensitivity for reliable nuclide identification. All HPGe detectors are supplied as "SMART-1™", which monitor and store their own state-of-health (SOH) (Ref. 3). Use of the X-COOLER II cryo-cooler eliminates the need for liquid nitrogen (Ref. 4).

Standard HPGe detectors offered with the QED are ORTEC PROFILE GEM-F7040 (Ref. 5) with the following specifications:

Nominal Crystal frontal area: 36 sq cm, length 40 mm

FWHM resolution at 122 keV: 750 eV (Ref. 6),
at 1.332 keV: 1.95 keV

Nominal Relative efficiency: 40% (Ref. 7)

Peak Shape FWTM/FWHM typical: 1.9
FWFM/FWHM typical: 2.65

Peak To Compton ratio: 50:1

Standard Performance Specifications

The following are typical performance data for the standard GEM-F7040 detector option. These are detection limits for a 55 gallon drum, with matrix densities as specified, in a 30 minute count according to the NUREG4.16 detection limit methodology. These detection limits assume homogeneous source and matrix distribution. NUREG4.16 is a very conservative detection limit formalism. It is not uncommon for vendors to specify detection limits using the simple "1-sigma Currie limit".

High Performance QED Detector Option

For improved sensitivity, QED can be supplied with PROFILE GEM-FX8530 detectors which provide ~45% greater frontal area and an ultra thin entrance window for enhanced low energy response (recommended for ²⁴¹AM determination.) (Compatible with PC/FRAM (Ref. 8) for determination of Pu and U Isotopic ratios.)

GEM-FX8530 Specifications:

Nominal Crystal frontal area: 54 sq cm, length 30 mm

FWHM resolution at 14.4 keV: 600 eV (Ref. 6),
at 122 keV: 650 eV (Ref. 6), at 1.332 keV: 1.90 keV

Nominal Relative efficiency: 50% (Ref. 7)

Peak shape FWTM/FWHM typical: 1.9
FWFM/FWHM typical: 2.9

Peak to Compton ratio: 55:1

High Performance Specifications

The following are typical performance data for the high performance GEM-FX8530 detector option. These are detection limits for a 55 gallon drum, with matrix densities as specified, in a 30 minute count according to the NUREG4.16 detection limit methodology. These detection limits assume homogeneous source and matrix distribution. NUREG4.16 is a very conservative detection limit formalism. It is not uncommon for vendors to specify detection limits using the simple "1-sigma Currie limit".

Nuclide	Energy keV	Detection Limit (pCi/g)				
		Matrix Density g/cc				
		0.1	0.2	0.3	0.8	1.8
CS-137	662	0.07	0.04	0.03	0.02	0.02
CO-60	1173	0.06	0.03	0.02	0.01	0.01
CO-58	810	0.08	0.05	0.04	0.02	0.02
Th-232	911	0.23	0.13	0.10	0.06	0.05
Th-228	583	0.10	0.06	0.04	0.03	0.03
TH-234	93	3.04	2.03	1.47	0.79	0.68
BI-214	609	0.22	0.13	0.09	0.06	0.05
U-235	185	0.14	0.09	0.06	0.05	0.04
U-238	1001	6.06	3.48	2.51	1.57	1.32
PU-239	414	4506	2737	2035	1483	1198

Typical Performance Data, Standard HPGe Detector Option.

To compare the performance data shown here with Currie limit data, divide the data here by ~2.83. For example, for a matrix density of 0.3 g/cc, the high performance detection limits for ¹³⁷Cs and ²³⁹Pu become 0.01 and 720 pCi/g respectively.

Nuclide	Energy keV	Detection Limit (pCi/g)				
		Matrix Density g/cc				
		0.1	0.2	0.3	0.8	1.8
CS-137	662	0.05	0.03	0.02	0.01	0.01
CO-60	1173	0.05	0.03	0.02	0.01	0.01
CO-58	810	0.06	0.03	0.03	0.01	0.01
Th-232	911	0.17	0.10	0.08	0.04	0.04
Th-228	583	0.06	0.04	0.03	0.02	0.02
TH-234	93	1.60	1.07	0.77	0.41	0.36
BI-214	609	0.14	0.08	0.06	0.04	0.03
U-235	185	0.07	0.05	0.03	0.03	0.02
U-238	1001	4.84	2.78	2.01	1.26	1.05
PU-239	414	2575.11	1564.17	1162.64	847.22	684.49

Typical Performance Data, High Performance HPGe Detector Option.

To compare the performance data shown here with Currie limit data, divide the data here by ~2.83. For example, for a matrix density of 0.3 g/cc, the high performance detection limits for ¹³⁷Cs and ²³⁹Pu become 0.007 and 410 pCi/g respectively.

QED

Low-Level Waste Assay and Segregation System

Model 3400-210

QED Ordering Information

QED is delivered, installed and commissioned following full factory testing.
The system comes complete with operator station, ready to work.

Model No.	Description
3400-210-F70	QED equipped with ORTEC PROFILE GEM-F7040 detectors
3400-210-FX85	QED equipped with ORTEC PROFILE GEM-FX8530 detectors

Contact the Factory for the following options:

Automated conveyor system

"In line" (pass through) systems with automatic conveyors

Additional detector configurations (including plastic and NaI(Tl) scintillators)

- 1) ORTEC DSPEC jr 2.0 spectrometers digitally process the signal from each HPGe detector. Ultra stable temperature and count-rate performance is the result. The patented LFR filter reduces the effect of low frequency environmental noise. The innovative "ZDT" Loss-free counting mode eliminates measurement bias, should hot spots produce wide fluctuations in count rate. High speed USB 2.0 data communications are provided. See http://www.ortec-online.com/pdf/dspjr_20.pdf.
- 2) See <http://www.ortec-online.com/pdf/a66.pdf>.
- 3) See http://www.ortec-online.com/detectors/photon/a3_7.htm.
- 4) X-COOLER, exclusive to ORTEC is the leading non-LN₂ refrigerator for HPGe detectors. Since 2000 it has been proven in many hundreds of installations, and is by far the pre-eminent cooler of its type. In combination with ORTEC patented PopTop detector capsules, the system is reliable and in the unlikely event of a failure, either the detector capsule or the cooler may be swapped out on site for easy repair. See <http://www.ortec-online.com/detectors/xcool.htm>.
- 5) See http://www.ortec-online.com/detectors/photon/b2_1_1.htm.
- 6) This specification may be relaxed by up to 10% because of the use of the X-COOLER refrigerator.
- 7) Specified according to IEEE-325. PROFILE F detector crystals are "over square" (diameter>length), leading to much improved sensitivity in applications such as drum scanning compared to conventional detectors of similar relative efficiency but closer to 1:1 d/l. For more detail see http://www.ortec-online.com/pdf/best_choice_det.pdf page 5.
- 8) PC/FRAM is licensed form Los Alamos National Laboratory, more detail on request.

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RadScan® 800 4pi Gamma Imager

- Saves cost by supporting optimisation of maintenance, refurbishment and decommissioning strategies
- Saves operator dose uptake by reducing the requirements for manual area monitoring
- Rapid deployment by a single operator achieved through comprehensive re-engineering and re-packaging
- Deployment horizontally and inverted in addition to upright to satisfy a greatly increased application area
- An improved lower energy limit which enables the detection of ^{241}Am
- In-situ analysis of gamma overlay images of all surveyed areas from a single automatic scan, even whilst a subsequent scan is in progress, or remotely from an office based computer

The BIL Solutions RadScan® 800 4pi Gamma Imager remotely locates and efficiently characterises gamma hotspots in a wide variety of environments including building surfaces, cells, in or on gloveboxes and process vessels.

The instrument maps and records the distribution and intensity of measured radiation using radiometric data and real-time colour video images which are viewed from a safe distance.

Applications

The RadScan® 800 is a planning tool which saves cost and dose uptake by reducing project risk, supporting optioneering studies and reducing the requirements for manual area monitoring, particularly in unknown or high dose fields.

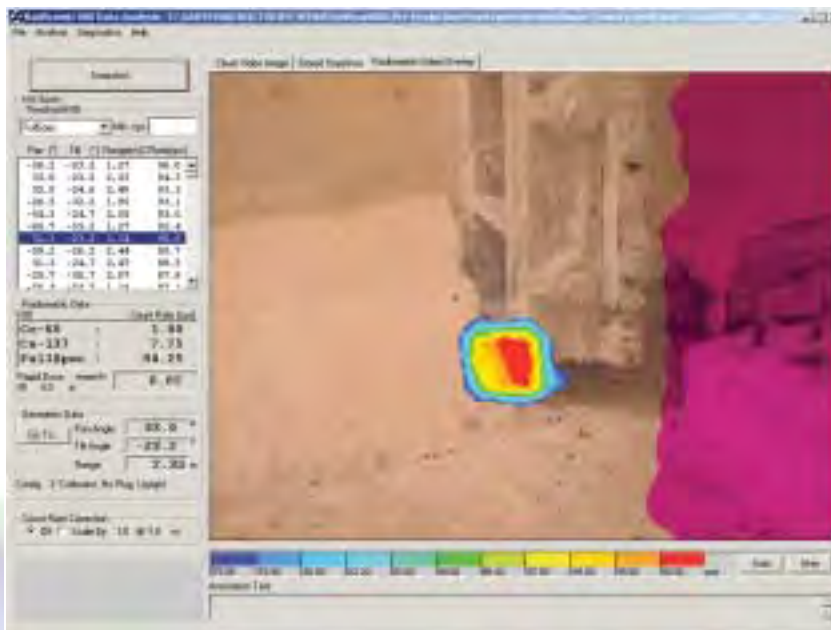


The system saves cost and dose uptake in any environment in which the spatial distribution or intensity of gamma emitting radioactive material is needed.

The main users are Health Physicists, Decommissioning, Project and Planning Engineers or their staff. A typical application is in support of the radiological characterisation of a contaminated building or cell prior to maintenance, refurbishment, decommissioning or clean out.

Deployment and operation

The Inspection Head can be deployed rapidly by a single operator on a lightweight, collapsible and height-adjustable tripod supplied as standard. It can be mounted on many other platforms including fixed or mobile stand, crane and Remote Operated Vehicle (ROV).



Alternatively, it may be mounted directly to a wall, floor or roof using its integral quick release coupling and flange. Deployment is achieved manually or remotely depending on the application.

The detachable Detector Head is optimised for americium, uranium, plutonium, fission product and activation product gamma energies through the use of efficient tungsten shielding.

Set-up is achieved within a few seconds of the Inspection Head being deployed and system self-checking is automatic. Almost the entire environment is capable of being surveyed from a single deployment.

RadScan® 800 is operated from a remote, safe location using a PC-based Remote Workstation. On-screen information is presented using Windows XP® compatible software and includes a high definition colour video picture of the area being surveyed. A circle, which represents the Field Of View (FOV) of the detector, is overlaid on to the video picture using colour software graphics. During an automatic scan, all frames of video are recorded and compressed on to the PC's hard disc. All associated geometrical and radiometric data is recorded in a Microsoft Access® database. All spectra are also recorded.

The system is controlled using the keyboard's cursor keys and hula point. Communication and electrical power for and between the Inspection Head and Remote Workstation is via a single cable.

Software architecture

The software comprises a Data Acquisition package and a Data Analysis package which run as fully independent tasks. The Data Acquisition package requires all RadScan® 800's hardware to be present and is used to collect and record all data. The Data Analysis package is used to recall, display and analyse this data. It is invoked on the Remote Workstation from the Data Acquisition package and can be run whilst a subsequent automatic scan is in progress. Alternatively, as an option, the Data Analysis package can be used on a desk-top PC running under Windows XP®.

Data acquisition package

All measurement parameters are configured from the Data Acquisition package. These include such options as the orientation of the deployed Inspection Head, the size of collimation and the Region(s) Of Interest (ROIs) within the energy spectrum.

Some important parameters, such as constants defining the system's energy calibration, are password protected to prevent unauthorised access.

Data can be acquired manually or automatically. At any time during manual scanning the operator can toggle between a display of the current video picture with circle representing the detector's FOV, and the current acquired spectrum from the detector's FOV. All status, geometric and radiometric data is permanently displayed and updated every second. Measurement data and its associated configuration is recorded to the PC when the user selects the 'Snapshot' facility.

Automatic scans are set up in one of two ways; driving the Inspection Head to the start and stop positions, or by defining its size and position by the currently displayed video picture. Upon entering the time of acquisition of data at each measurement position, an estimate for the duration of the scan is displayed. If accepted, the entire scan is performed automatically. At each measurement position, the count rate(s), angles and distance are recorded to a unique database. The acquired spectrum and video picture from each measurement position are also recorded to the hard disc.

Data analysis package

The Data Analysis package accepts, as its input, and post-processes the databases generated by the Data Acquisition package. Once a valid database is loaded, the operator can toggle at will between the display of a colour overlay image of the current scene, the original captured video frame of the same scene and the acquired spectrum from the measurement position in the detector's FOV. Status, geometric and radiometric data from the measurement position are also displayed.

The display is updated and repeated for all scanned measurement positions by the operator driving the system as if the hardware were present.

Data is retrieved from the database and presented to the operator in the form of a 'Virtual Scan' which shows an overlay image of every scanned video frame. The Virtual Scan is controlled using the keyboard's cursor keys.

The operator can choose to display data from any one of up to three, overlapping ROIs as configured in the Data Acquisition package.

A threshold for a selected ROI can be requested and the system will display a list of radiometric and geometric data for all measurement positions at which the count rate data in the ROI exceeds the threshold. The operator is able to select any measurement point within the list. Upon doing so, the display presents the colour overlay image of the selected point. The operator may continue with a Virtual Scan from this point or select another point.

The operator can also create new ROI(s) and post-process the acquired data to form new ROI count rate(s). These may be used to search for previously unidentified hot spots.

The thresholds of the displayed count rate data of any overlay image can be set automatically or manually. The overlay image, video frame, radiometric, geometric and associated configuration data for any measurement position is recorded permanently using the 'Snapshot' facility. A two dimensional, angular contour plot of an entire scan for a selected ROI is performed by a Microsoft® Excel spreadsheet from the Data Analysis package when requested by the operator.

Radiometric output modes

RadScan® 800 displays the count rate(s), corrected for dead-time, at the detector from objects within the detector's FOV from up to three, overlapping ROIs as configured in the Data Acquisition package. The count rate(s) is updated every second.

An operator can opt to correct the count rate(s) to what it would be if the object was at a range specified by the user. The operator can also scale the range corrected count rate(s) to assess whether a FOV contains more or less activity relative to another

FOV. An estimate of the dose rate, Rapid Dose, at a range specified by the user from an equivalent point source at the centre of the FOV is permanently displayed.

Energy calibration

Periodic energy calibration or calibration check is quickly and easily performed using common, sealed sources.

Anti-contamination PVC hoods

Disposable, purpose-designed PVC hoods are supplied as standard for use with the Inspection Head in contaminated environments.

Tripod

A lightweight, collapsible and height-adjustable tripod is supplied as standard.

Shipping crates

The RadScan® 800 is supplied with four re-usable and lockable, shipping crates as standard.



Specification

Detector Head size:	H 285 mm x W x 205 mm x D 425 mm
Detector Head mass:	25 kg
Inspection Head size:	H 600 mm, rotates within a 670 mm diameter
Inspection Head mass:	45 kg (rapidly disassembles into components of 25 kg, 14 kg and 6 kg)
Deployment orientation:	Upright, inverted, horizontal downwards, horizontal upwards
Deployment mechanism:	13 kg, collapsible, height-adjustable tripod as standard (H 790/1040 mm, 865/1040 mm diameter footprint at min/max extension during use, H 830 mm x W 330 mm x D 300 mm when fully collapsed for ease of transportation) Wall, floor or roof mounted via standard flange
Remote Workstation size:	H 460 mm x W 515 mm x D 285 mm
Remote Workstation mass:	25 kg
Remote Workstation monitor:	Rugged 15" colour TFT
Scanning angle:	340° pan, -60° to +90° tilt
Scanning speed:	0.5°/sec pan/tilt (slow), 4°/sec pan/tilt (fast)
Detector:	NaI(Tl) scintillator with miniature photomultiplier tube
Camera:	3 lux, high definition colour CCD with 16x optical zoom lens, auto/man iris, auto/man focus
Range finder:	Red laserdiode (IEC 825-1:1993, Class 2; FDA 21CFR Ch.I §1040:1988, Class II)
External data storage media:	CD-RW; 1.44 MB, 3.5" floppy disc drive
Operating system:	Windows XP®
Operating voltage:	110 or 230V AC, 50/60 Hz, configured at shipment

Performance

Detection limits:	<1 µCi for ¹³⁷ Cs in FOV at 1 m (whole spectrum) <0.2 µCi for ¹³⁷ Cs in FOV at 1 m (photopeak) <50 mg for Pu (~20 % ²⁴⁰ Pu) in FOV at 1 m <1 g for ²³⁵ U in FOV at 1 m <2.5 µCi for Am-241 in FOV at 1 m
Energy resolution (FWHM):	~6/9.5/28/36 % at 1332/662/186/60 keV
Operating range:	<1 µCi to 0.5 Ci for ¹³⁷ Cs in FOV at 1 m
Energy range:	~30 keV to ≥ 1500 keV
Dynamic range in a single image:	~300 for ¹³⁷ Cs
Dose rate envelope:	0-500 mGy/hr for Cs-137
Detection range:	Camera focal length; 0.01 m (wide)/1.0 m (tele) - ∞ Range finder; 0.3 - 30 m (natural surfaces)/100 m (brown reflector), ±5 mm or better Detector; 0 - ∞ (useful upper limit determined by FOV)
Angle of view:	4°, 3° screw-on collimator extension, 2° screw-in collimator insert
Collimator additions:	Screw-in background correction plug
Environmental:	Inspection Head rated to IP65 once assembled; purpose designed PVC hood fitted over head to prevent contamination (3°, 2° collimators and background plug can be installed/removed in-situ without removing hood) Remote Workstation rated to IP31 (keyboard to IP65)
Remote operation:	Up to 40 m from Inspection Head as standard via a single cable with option of longer cable lengths

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**DETECTION AND
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SOLUTIONS**

A BNFL Group Company

The Next Generation Tomographic Gamma Scanner

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Abstract

The goal of Non-Destructive Assay (NDA) of radioactive waste is to accurately identify and quantify the radionuclides present in the waste stream. Gamma ray scanning instruments such as the Segmented Gamma Scanner (SGS) have found widespread use in the NDA community. The Tomographic Gamma Scanner (TGS) aims to improve the accuracy of assay results for difficult cases such as a non-uniform distribution of radioactivity in a heterogeneous matrix. The TGS combines high resolution gamma ray spectrometry with 3-dimensional single photon attenuation coefficient images (Transmission image) and single photon Emission images.

Canberra Industries developed its prototype TGS in collaboration with Los Alamos National Laboratory (LANL). The prototype Canberra TGS was used as a Research and Development tool to conduct an in-depth study of the TGS technique. The results of these studies have been reported elsewhere.

Recently, Canberra has built its next generation of TGS systems implementing many advanced features. The new features include an automated variable collimator aperture, an automated detector slide mechanism for adjusting the sample to detector distance, automated attenuator mechanism, and an automatic selection of assay geometry based on the dose rate and density of the assayed sample. The collimator aperture is formed by interleaved layers of tungsten that can be opened and closed to change either the spatial resolution of the TGS measurement or to switch over to an SGS measurement mode. The automated slide mechanism allows the detector to move further back from the high activity drums extending the dynamic range of the system. Alternately, for use with small samples such as cans, the can can be placed on sample pedestal to allow the detector to move closer to the container for improved spatial resolution in either the SGS or TGS modes. The automated attenuator assembly is intended to allow system operation for drums with high surface exposure rates. The assembly is mounted to the front face of the detector shield and collimating aperture.

The paper discusses the features and performance of the next generation TGS.

1. Introduction

The Non Destructive Assay (NDA) of special nuclear materials in waste containers for inventory and safeguards purposes is challenging because of the potentially high degree of variability from item to item. This variability may allow the deliberate addition or removal of special nuclear materials to be made to waste containers to go undetected. These materials could be used in a clandestine nuclear weapons program. The Tomographic Gamma Scanning (TGS) technique combines transmission and emission reconstructive tomography techniques in an effort to improve the accuracy of high resolution gamma-ray spectroscopic measurements. In particular the goal is to reduce the uncertainties associated with the unknown material and density distribution of the waste matrix and also with the unknown distribution of SNM and other radioactive materials present. HRGS is retained in order to unravel the complex spectrum and in order to provide 'good geometry' results - that is peak areas which are relatively insensitive to coherent and small angle scattering

In addition to improving the quality of the assay results the intermediate transmission (linear attenuation map as a function of energy) and emission (by nuclide or line) images, although only of low spatial resolution, can provide powerful additional visual verification and confirmation information about the items.

Reconstructive tomography involves scanning the item in a series of layers or slices from many different orientations or views and using the information to reconstruct a picture of the interior of the object free from the interference effects from underlying and overlying planes. The idea is that if we know the attenuating properties of the interior along with the distribution of activity that a better matrix attenuation correction factor can be derived. The objective is to improve the accuracy of the assay while still retaining a useful detection limit and throughput at reasonable cost. Thus for a 200 liter drum, say, a representation of the item comprising 16 layers each of 88 volume elements (or voxels) is used. This contrasts with the familiar segmented gamma scanner approach which may use 8 to 16 segments, say, with each individual segment being treated as distinct but as homogeneous in matrix and uniform in activity (on a per unit mass of matrix basis). The TGS scan sequence generates a series of data grabs or views which over determine the contents of the voxel grids. Algebraic reconstruction in real space is used to extract a best fit solution consistent with the data and as free from spurious features as possible. The quality of the reconstructed images may be judged by the correspondence between the measured and actual distributions of test cases. The reconstruction model takes into account the changing collimation, attenuation and inverse square law affects at each view. These physical processes acting together provide the modulation and contrast in pattern of view data that allow the images, free from cross talk, to be formed.

The experimental realization of the TGS discussed here has been outlined elsewhere^[1-3]. Here we wish to concentrate on the next generation of TGS that has incorporated in it, many new features. These improvements make the instrument suitable for assaying waste streams with a wider range of matrices and activities. We include some preliminary results generated from the new system.

2. The Next Generation TGS

Canberra industries has designed and built the next generation of TGS with the objective of making the instrument applicable to waste streams with a wider range of activities and matrices and as well as with a wider range of nuclides that is not restricted to just plutonium isotopes. Figure 1 shows a picture of the system. The TGS system can be operated in the Segmented Gamma Scanner (SGS) mode, if desired. The selection of TGS or SGS mode of operation is decided based upon dose rate and density measurements of a given waste drum. Canberra has

developed a special software package called the "Supervisor" for automatically deciding the assay mode (TGS or SGS) based on the density and dose rate measurements. Alternatively, the Supervisor software may also be used by the system's operator to manually set an assay mode for drums in a given waste stream. A highly collimated ^{152}Eu source (15 mCi, 555 MBq) is used to perform the transmission scan.

A Canberra Model BEGE 5030 High Purity Germanium (HPGe) detector is used in the TGS system that has been built. The pulse processing electronics consists of an RC pre-amplifier, a Canberra Model 2060 Digital Signal Processor (DSP), and an Accuspec B Board to facilitate high speed data transfer, and a Canberra Model 1654 NIM Reference Pulser. Rate loss corrections were performed using the reference pulser counts. Data acquisition and analysis was performed using Canberra's NDA2000 software platform.

Some of the salient features of the next generation TGS are discussed in the following sections.



Figure 1. The Next Generation TGS with fully automated features

The local PLC control pedestal is to the right and the transmission source assembly is to the left. A 300-liter drum is shown on the rotator/translator. The attenuator mechanism is visible in front of the HPGe detector. Between the attenuator(s) and the dewar is located the variable aperture collimator. The dosimeter is mounted on the front of the detector lift and is therefore, not visible in the picture.

When the system is installed at a waste assay facility, the in-feed and out-feed conveyor stubs shown in the picture can be readily integrated with an automated conveyor system that loads and unloads a stream of waste drums.

The sequence of events is as follows. A waste drum is loaded on to a conveyor using a crane or a fork lift. Upon receiving the signal from the PLC, the drum moves along the conveyor and eventually reaches the in-feed portion of the TGS conveyor. The drum is then transferred to a palette centrally located on a translator/rotator platform. The drum is weighed. The platform then moves towards the center-line of the detector-transmission source. The palette is raised up so that the bottom of the drum clears the side rails of the conveyor. The drum is then rotated. The dosimeter located at the front of the detector lift measures the average and maximum dose rates of the drum contents. Based on the bulk density of the drum matrix and the maximum dose rate, the Supervisor software selects either the TGS or the SGS assay mode. Once the assay mode has been selected, the NDA2000 software proceeds to set the geometry which is a combination

of the detector distance, collimator aperture, and the presence or absence of one or more lead attenuators. After the geometry is set, data acquisition is performed followed by data analysis and printing of the reports. In the case of TGS mode, the report includes images of the source distribution.

2.1 Detector Shield and Automated Collimator Assembly

The detector shield minimizes the impact of background gamma radiation and surrounds the sides and extends behind the detector. The shield provided is a minimum of 50 mm thick lead with a low-Z inner liner to minimize the effects of the lead X-rays on the measurement. The collimating aperture consists of lead and tungsten components. The aperture is formed by interleaved layers of tungsten that can be opened and closed to change either the spatial resolution of the TGS measurement or to switch over to an SGS measurement mode. Closing the tungsten leaves forms a diamond shaped aperture from 12.7 mm to approximately 60 mm in diameter. For SGS mode the aperture opens to a height of approximately 95 mm and width of 400 mm. The width of the opening is controlled via the system PLC and operating software.

2.2 Automatic Detector Slide Mechanism

The detector slide mechanism allows the detector to move towards or away from the sample rotator. The slide mechanism provide for a travel of +/- 355 mm from the normal detector position. The slide mechanism is automated to allow the detector to move further back from the high activity drums extending the dynamic range of the system.

For use with small samples such as cans, the can can be placed on sample pedestal to allow the detector to move closer to the container for improved spatial resolution in either the SGS or TGS modes.

2.3 Automated Attenuator Assembly

The automated attenuator assembly is intended to allow system operation for drums with high surface exposure rates. The assembly is mounted to the front face of the detector shield and collimating aperture. The assembly is controlled by the system PLC with the appropriate thickness of attenuator selected based on the measured dose rate for the sample drum.

The attenuator consists of 4 individual attenuators, 3 of lead and 1 of low-Z material. The inner most attenuator is the low-Z attenuator shutter. This shutter is included primarily to shield the detector from the lead X-rays generated in the three lead shutters. The lead attenuating shutters have thicknesses of 9, 8, and 7 mm respectively. Prior to the beginning of an assay, all of the lead attenuators are closed, thus protecting the detector from a potential high activity drum. Depending on the measured dose rate for a given sample drum, the lead attenuating shutters will be opened sequentially. The collimator aperture and the horizontal position of the detector are also automatically adjusted based on the measured dose rate.

These attenuator assembly can be used in either the SGS or TGS modes of operation.

3. Performance Test Results and Discussion

The TGS system was calibrated by placing a set of six mixed gamma rod source standards inside an empty 208-liter drum and performing a TGS assay. The rod sources were inserted at specific radial positions in the drum, with the radii ranging from 50mm to 280mm. The radial positions were arranged in a spiraling fashion. The rod sources consisted of the nuclides ¹³³Ba, ¹³⁷Cs, and

^{60}Co . The calibration results included in this paper are for the assay geometry where the TGS collimator aperture is set to a value of 50.3 mm, the detector horizontal position is set at the mid-position of the +/- 355.6 mm range, and all of the attenuators are open.

The output of a given TGS analysis is a quantity known as the “TGS Number” and the uncertainty associated with it. The TGS number and its uncertainty are determined at each emission energy, and represents values proportional to the activity or mass of an assayed radionuclide inside the drum. For a calibration count, the activity of the nuclides in the standard sources are known from the certificates. The calibration parameter is then determined as Activity per unit TGS number for a specific nuclide and a specific gamma ray of that nuclide. The raw TGS numbers for empty drum calibration measurement are given in Table 1.

Table 1. TGS Calibration Results ($1\ \mu\text{Ci} = 3.7 \times 10^4\ \text{Bq}$)

Gamma Energy (keV)	TGS Number	Uncertainty	μCi per TGS Number	Uncertainty
276	0.9722	0.0166	191.188	6.646
303	2.1725	0.0233	85.554	2.750
356	6.3186	0.0470	29.416	0.918
383	0.8815	0.0103	210.858	6.844
662	0.9407	0.0125	34.228	1.186
1173	0.7319	0.0143	42.226	1.619
1332	0.6571	0.0147	47.037	1.876

Several measurements were performed to verify the accuracy of the TGS calibration. Two such measurements are discussed below.

3.1 Uniform activity distribution inside a homogeneous matrix

In this assay, the six rod sources were inserted in radial holes drilled through a Homosote matrix ($0.43\ \text{g}\cdot\text{cm}^{-3}$) drum. The assay was performed for a total time of 1 hour. The assay results are given in Table 2. The transmission and emission images for ^{137}Cs and ^{60}Co gamma rays are given in Figure 2 and 3.

Table 2. TGS Accuracy for a Uniform Activity Distribution

Nuclide	Measured Activity		True Activity		Ratio (Meas/True)	
	Activity (μCi)	Uncert (μCi)	Activity (μCi)	Uncert (μCi)	Ratio	Uncert
Cs-137	33.18	1.23	32.04	1.03	1.036	0.051
Co-60	31.04	0.90	30.05	0.99	1.033	0.045

For all of the results presented in this paper, the uncertainty values are quoted at 1σ standard deviation. In each case, the measured uncertainty includes the statistical component evaluated using the Monte Carlo Randomization (MCR) method^[4]. The measured activities are in excellent agreement with the true activities of the nuclides.

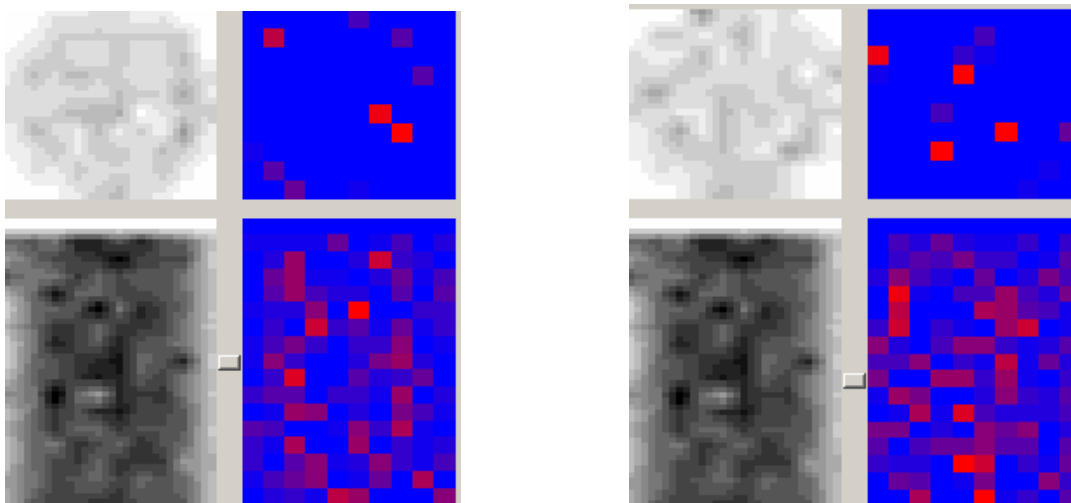


Figure 2. Uniform distribution of ^{137}Cs (662 keV) Figure 3. Uniform distribution of ^{60}Co (1173 keV)

The images on the left (in black and white) are the transmission images, and the images on the right (in colour) are the emission images. The transmission images shown are a 2-dimensional projection of the linear attenuation coefficient map (μ) at the given gamma ray energy. The emission images are a 2-dimensional projection of a voxel by voxel distribution of the nuclide activity. In figures 2 and 3, the transmission images show that the matrix is a homogeneous matrix. The emission images indicate the presence of nuclide activity throughout the drum volume, which is consistent with a uniform distribution of activity. In each figure, the top portion is the cross-sectional view of a given layer (layer 8 in Figures 2 and 3).

3.2 Three Point Sources of ^{137}Cs distributed in a homogeneous matrix

A TGS assay was performed by distributing 3 point sources of ^{137}Cs of approximately same activities inside a 208 liter Homosote matrix (0.43 g.cm^{-3}) drum. The results are given in Table 3. The transmission and emission images are shown in Figure 4.

Table 3. TGS Accuracy for 3 point sources inside a Homogeneous Matrix

Nuclide	Measured Activity		True Activity		Ratio (Meas/True)	
	Activity (μCi)	Uncert (μCi)	Activity (μCi)	Uncert (μCi)	Ratio	Uncert
Cs-137	187.5	6.56	178.40	5.35	1.051	0.048

The measured activities are in excellent agreement with the true activities at the 1σ level of uncertainties.

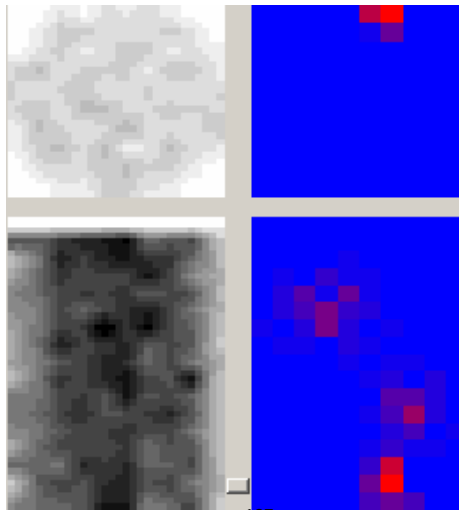


Figure 4. Three point sources of ^{137}Cs in a homogeneous matrix

The transmission image shows the uniform nature of the Homosote matrix. The emission image shows the presence of three regions with elevated levels of source activity. The source at the interface of layers 1 and 2 towards the edge of the drum is clearly seen in the cross-sectional view of the emission image.

3.3 Single Point Source of ^{137}Cs inside a Non-Homogeneous Matrix

A single point source is located inside a non-homogeneous matrix represents a difficult assay situation, with regards to the accuracy of the results. For such situations, the assay results from a non-imaging method might suffer from significant biases (for example a factor of 2). This is especially true if the matrix density is high. For an imaging method such as the TGS technique, the assay results might be more accurate. To explore this, TGS assays were performed by locating a single point source inside non-homogeneous drum matrices with moderate to high densities. The example discussed in this paper is one such typical assay of a ^{137}Cs point source inside a scrap steel drum with a bulk density of 1.0 g.cm^{-3} . The source was located at a radius of 220 mm and at a height of 390mm from the bottom of the drum.

Table 4. Single point source of ^{137}Cs inside a Non-Homogeneous Matrix (1.0 g.cm^{-3})

Nuclide	Measured Activity		True Activity		Ratio (Meas/True)	
	Activity (μCi)	Uncert (μCi)	Activity (μCi)	Uncert (μCi)	Ratio	Uncert
Cs-137	132.1	4.62	108.43	3.25	1.218	0.037

This is a difficult assay scenario from many respects. There is only a single point source, the matrix is non-homogeneous, and the density is fairly high. Considering these mitigating factors, the accuracy of TGS seems fairly reasonable. The images are shown in Figure 5.

In view of the encouraging results that we have obtained for a matrix density of 1.0 g.cm^{-3} we are exploring a variety of analysis methods to further extend the density range of TGS assays. These methods include the “Uniform Layer” and the “Bulk Density” approaches. In the Uniform Layer approach, the linear attenuation coefficient μ is calculated for a few voxels in a given drum layer for which transmission data is available and then averaged. All of the voxels of the given layer are then populated with this average value of μ . The Uniform Layer approach will be useful in assay

situations where the transmission beam is too weak to penetrate the drum matrix, while the drum contents are active enough to register non-negligible count rates in TGS views. In the “Bulk Density” approach, all the voxels in all the drum layers are populated with a value of μ derived based on the bulk density, assuming a matrix composition. This will be useful for drum matrices with very high densities (2 to 3 g. cm⁻³). The Bulk Density approach will be useful in situations where the operator may only have TGS data available for a high density drum. Also, Bulk Density TGS assays generate confirmatory emission images that will be useful in assaying conditioned waste.

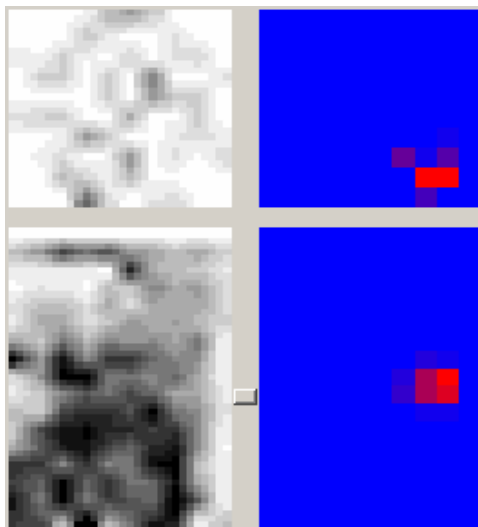


Figure 5. A single point source of ¹³⁷Cs inside a non-homogeneous matrix

The transmission image depicts the non-homogeneous nature of the scrap steel matrix. The emission image shows the presence of the single point source inside the drum. The image is remarkably constrained within four neighbouring voxels.

4. Conclusions

Canberra Industries has built and tested four fully automated enhanced TGS systems for waste assay. The salient features of this next generation of TGS systems were discussed. The performance of the system was evaluated using results from assays involving homogeneous and non-homogeneous matrices, and uniform and non-uniform source distributions. The design provides qualitative gamma assay capability over the surface dose rate range of up to 100 R/h (1 Sv/hr) and over the density range up to about 3 g.cm⁻³ in a fully automated industrial environment. The TMU estimates for the TGS system are being evaluated and will be reported elsewhere in the near future.

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U-Pu InSpector

- An integrated, portable instrument to measure the isotopic composition of plutonium or the enrichment of uranium without prior efficiency calibration
- Multi-Group Analysis for plutonium (MGA) and for uranium (MGA-U) integrated into a single operating software shell
- Complete procedures for counting, calibration, QA and system maintenance
- Comes standard with special LGe detector:
 - Optimized for high dynamic activity range
 - Built-in high Z collimator shell with filters
 - Multi-Attitude Cryostat, two day holding time
 - Quick and easy filling with special fill device
 - System carrying case





Waste Crate Assay System (WCAS)

Features

- Combines multiple assay techniques
 - Passive neutron multiplicity coincidence counting
 - High resolution isotopic gamma-ray analysis
- Crate sizes up to 1660 L (1.4 x 1.4 x 1.2 m)
- Scalable to larger containers
- Fully automated operation and analysis
- 18% efficiency for ^{240}Pu fission neutrons
- MDAs of less than 6 mg ^{240}Pu
- Multiple HRGS detectors
- ^{252}Cf Add-A-Source moderator correction
- NDA-2000 Non-Destructive Analysis Software

Description

The Waste Crate Assay System (WCAS) is a passive neutron coincidence counter designed for low level waste assay to determine the transuranic (TRU) activity of contaminated solid waste in containers up to 1.43 x 1.43 x 1.20 m crates. The WCAS provides simultaneous passive neutron coincidence and high resolution gamma isotopic analysis allowing rapid characterization of plutonium wastes.

The WCAS is based on the Canberra Waste Drum Assay System (WDAS) design with integrated High Resolution Gamma-Ray System. Results from individual neutron and gamma-ray assays are combined automatically by the NDA-2000 software. Because the assays are performed in the same system in a single assay sequence there is no confusion over item ID or modification of sample contents between assays.

The system is designed to be operated as an automated counting system which can process batches of drums, or can be incorporated in a facility process line. The following sections describe the various assay sub-systems, hardware, software and indicate typical performance characteristics.

Components of the system include the neutron counter with ^3He detector, Amptek based fast preamplifier/discriminator circuit boards (Model JAB-01), coincidence electronics, computer hardware, high resolution gamma detectors, digital signal processing for the gamma-ray analysis and application software.

The WCAS shield assembly provides a 4π , 20 cm thick High Density Polyethylene (HDPE) moderator/shield as a measurement chamber for the drums and crates. The neutron shield provides an assay chamber that minimizes the effects of outside neutron radiation levels. As configured the neutron shielding is also effective for reducing the gamma-ray background levels (equivalent to a 1 in. thick steel shield) enhancing the performance of the MGA isotopic analysis at low Pu mass loadings.

The software converts the correct neutron coincidence rate to ^{240}Pu effective. The plutonium isotopic abundances are then calculated and used to convert the measured ^{240}Pu effective mass to a total plutonium mass.



Figure 1.
Waste Crate Assay System (WCAS).

Operation of the Counter

The WCAS counter automatically loads and unloads drums into the assay chamber. The general sequence of events for the system in analysis mode is as follows:

1. The sliding door opens and the conveyor moves the crate into the assay chamber.
2. The sliding door closes.
3. Operator enters the pertinent information on the sample.
4. Add-A-Source movement is automatically controlled by the PLC and the matrix correction measurement is controlled by the software.
5. Passive neutron and gamma isotopic measurements are run simultaneously.
6. Upon completion of the assay the door opens and the sample automatically exits the counter.

Crate loading and unloading is provided by a trolley/conveyor mechanism. The trolley/conveyor system accommodates crates weighing up to 2000 kg and the cavity door is controlled by a Process Logic Controller (PLC) interfaced to the system computer.

Passive Neutron Assay System

The WCAS utilizes the same basic design parameters for passive neutron assay analysis as Canberra's High Efficiency Neutron Counter (HENC)¹. The passive neutron counting system uses 96 ^3He proportional tubes arranged in a 4π counting geometry providing a total neutron detection efficiency of 18% for ^{240}Pu spontaneous fission neutrons and a coincidence sensitivity of 13.4 cps/g ^{240}Pu effective. This corresponds to a detection level of 64 mg weapons grade Pu (6% ^{240}Pu) in 3600 seconds.

Add-A-Source (AAS) Matrix Correction

The Add-A-Source (AAS) technique provides a means of measuring the impact of the waste matrix on the neutrons emitted within the drum. In practice a small ^{252}Cf source (about 100 000 n/s) is introduced into the assay cavity with no sample in the counter. The measurement is repeated after the sample is

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loaded and the results compared. The difference in the measured count rates can be used to correct the measured sample rate. The WCAS includes a dual position AAS matrix correction module. An illustration of the AAS measurement is shown in Figure 2. The ^{252}Cf source is normally stored in a shield module located to one side (or above) the counter. The source is automatically moved through a guide tube to the interrogation position and then retracted.

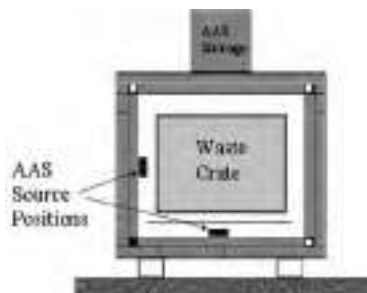


Figure 2.
Relative location of the Cf-252 source interrogation position for the WCAS Add-A-Source measurement.

For homogeneous distributions of Pu in the drum the AAS correction results in a typical error of $\pm 5\%$ from the expected values. Without the correction the errors can exceed 50%. The effectiveness of the AAS correction is illustrated in Figure 3.

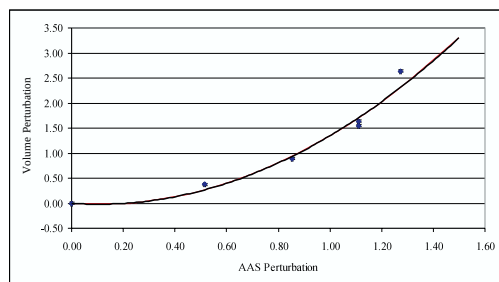


Figure 3.
AAS correction calibration results for the WCAS counter for a series of homogeneous matrix crates with a simulated uniform source distribution.

The assay cavity's neutron response was tailored to minimize variations in detection efficiency as a function of source location in the cavity. In order to provide a uniform neutron response within the assay cavity the counter door extends below the assay cavity floor. The linearity in response is illustrated in Figure 4.

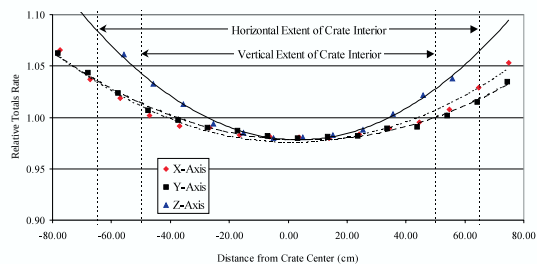


Figure 4.
Axial response profiles for the WCAS.

Passive Neutron Analysis Background Corrections

The coincidence neutron background has two primary sources, the presence of nearby fission sources and cosmic-ray induced neutron events. The WCAS shielding is sufficient to remove

much of the ambient neutron background but can not eliminate the neutrons generated by cosmic-rays interacting with the counter's body or the contents of the sample. Crates containing lead or steel have an associated cosmic-ray induced coincidence background (or interference) that results in a positive bias in the reported mass if not corrected. Conversely, highly moderating matrices (e.g. plastics) tend to attenuate the cosmic-ray induced coincident neutrons potentially resulting in a negative bias. The WCAS can correct for these effects using the NDA-2000 software.

The NDA-2000 software has a suite of correction algorithms available. The Matrix Based Background Correction (patent pending) will adjust the background rates based on the moderator content of the drum determined from the AAS measurement. The cosmic-ray rejection (CCR) algorithms include the typical truncation techniques but also a more sophisticated multiplicity analysis that can determine the high-Z material content of the drum and correct the measured coincidence rates (patent pending) for this effect and eliminate the bias.

Gamma-Ray Assay System

The gamma-ray assay system is based on Canberra's Q^2 concept. Two high resolution germanium detectors are mounted on each side of the assay chamber protruding through the HDPE shield. The HDPE shielding serves to reduce the gamma-ray background improving the performance of the gamma isotopes measurement.

Plutonium Isotopics Measurement

The WCAS would typically be provided with Canberra's Broad Energy Germanium (BEGe) detectors. These detectors provide efficiency required for quantitative gamma measurements and the resolution required for the most sensitive plutonium isotopics codes such as the Multi-Group Analysis (MGA) software. MGA was developed at Lawrence Livermore National Laboratory by Dr. Ray Gunnink. Canberra's MGA code has been enhanced for waste assay applications and the complications resulting from poor counting statistics. This package can provide plutonium isotopics for very small sources in waste containers. In addition to the plutonium isotopics, it will determine other actinides such as ^{235}U , ^{238}U , ^{237}Np , and ^{241}Am . (Note: other isotopics codes such as the Los Alamos FRAM code are available upon request).

Physical

The overall dimensions of the passive active neutron counter are 422 x 486 x 286 cm (L x W x H). This foot print includes the requirements for the door in open position and the 240 cm long load conveyor. Overall weight of the counter is approximately 8000 kg.

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2. "Q2 – A Very Low Level Quantitative And Qualitative Waste Assay And Release Certification". F. Bronson, Proceedings of Waste Management '90, February 25-28, 1990, University of Arizona, Tucson, AZ.





Features

- Complete quantitative gamma analysis for fission products or TRU (alpha) radionuclides
- Modular design permits system to be optimized for customer's measurement application
- Non-Destructive Assay Software (NDA-2000) provides extensive setup analysis, calibration, and QA capabilities
- PLC-based electromechanical control system
- Many optional capabilities available including:
 - Automatic weighing system
 - Surface dose rate measurement
 - Inline automated conveyor system

WM2200 Series Segmented Assay System



Introduction

Canberra's WM2200 Segmented Assay System is designed to perform accurate quantitative assays on gamma emitting nuclides found in fission product, activation product, and Transuranic (TRU) waste. With the optional ASTM algorithms it is also designed for use in safeguards applications. The system provides very accurate assays through the use of a collimated high purity germanium detector. The container is divided into a number of vertical segments and the activity is quantified in each vertical segment using matrix correction techniques which calculate the average matrix density for each segment.

The system is designed to assay drums with volumes up to 320 L (85 gal) and weights up to 900 kg (2000 lb) in its standard configuration. Optional configurations have been provided for larger or heavier containers.

The standard system is designed to assay radionuclides such as ^{60}Co or ^{137}Cs with drum activities ranging from approximately 100 nCi up to approximately 20 mCi. For transuranic waste the system is optimized for assaying drums containing 0.1 gram up to 1000 grams of ^{235}U or ^{239}Pu . Detector size and collimation can be used to modify the dynamic range of the system.

The following sections describe the system hardware and software as well as the typical system performance.

Description

The waste assay system utilizes Canberra's modular mechanism design. This design provides the flexibility to easily add features such as transmission correction or to upgrade from a manual to an automatic system. This design can also be adapted for a variety of container sizes and weights.

Phone contact information

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WM2200 Series Segmented Assay System

Model 2442 Mechanism

The mechanism is a modular design and consists of one or more of the following modules: 2442 detector vertical drive module, 2442R-24 turntable rotation module or optional inline conveyor rotator, 2442T transmission vertical drive module, 2442S single transmission source shield and shutter. These are described in detail on the following page.

The 2442 detector vertical drive unit is a stepper motor driven vertical drive platform which will raise and lower the germanium detector, collimator, and optional dose measurement system over a vertical range of 114 cm (45 in.). The unit is designed to handle operational weights up to 680 kg (1500 lb). This permits use of large collimators if necessary when measuring high activity containers. A variety of collimators and detector shields are available. The drive is designed for use with any of the following detector cryostats: horizontal integral, cryoelectric, or 7935-7 Big MAC cryostats.

The 2442R is the manual turntable module. This module can be equipped with a variety of turntable sizes depending on the measurement requirements. The turntable module is designed to handle a maximum diameter of 76 cm (30 in.) and weight of 900 kg (2000 lb). The turntable uses a dc motor which can be set up to rotate at speeds from 1 to 10 rpm.

The inline conveyor/rotator (shown in picture) is an optional drum rotator module which can be used to automatically load, assay, and unload drums from infeed and outfeed conveyors.

An optional digital scale can be interfaced into the PLC system to automatically weigh the drum and enter this weight into the application software during the assay. The accuracy of the weighing system is ± 1 kg for the manual turntable and ± 2 kg for the conveyor/rotator.

Transmission Correction (optional)

If transmission correction is specified, the transmission vertical drive and transmission source shield and shutter must be added to the system. This option is also shown in the picture above. The vertical drive is similar in design to the detector vertical drive.

The transmission source shield and shutter is designed to shield a transmission source with activities up to 370 MBq (10 mCi) to minimize worker radiation exposures.

Model 2445 Control System

The Model 2445 control system is a PLC-based controller with associated contactors, stepper motor controllers, I/O modules, drivers, etc. The PLC utilized is a GE/Fanuc Series 90 PLC. The PLC interfaces to the application software through an RS-485 interface. The flexibility of this design permits it to be easily modified to interface to a customer's process line. The control system is mounted in a locking NEMA 12 enclosure to ensure security, safety, and environmental control.

Detector and Electronics

A high purity germanium detector is used for detection of the gamma emitting nuclides from the drums. The detector provided with the standard WM2200 system is a 30% relative efficiency "P" type coaxial detector with a resolution of 1.9 keV at 1332 keV. The detector is housed in a horizontal integral cryostat. As an option, an electrically cooled detector can be provided. Other detector sizes can be specified to improve low level sensitivity or to improve the high activity performance.

The counting electronics utilizes Canberra's high count rate Instrument Control Bus (ICB) NIM electronics. This is necessary to handle the wide dynamic range of activities which are typically found in waste measurements.

Waste Assay Application Software

Canberra's Genie 2000 based Non-Destructive Assay Software (NDA-2000) is used for WM2200 applications. The application software is designed to run under Windows® NT®/2000 and utilizes all of the standard Genie 2000 high resolution gamma spectroscopy techniques. In addition, some of the features included in the software are:

- A high level menu structure for ease of use.
- Multiple matrix correction techniques including:
 - Average Density.
 - Differential peak analysis.
 - Transmission Correction.
- Extensive QA and measurement control routines.
- Automated calibration routines.
- Archiving capabilities.
- User editable report templates.
- Compliant with NQA2 and ISO9001.
- And much more.

A more detailed description is included in the NDA-2000 spec sheet.

WM2200 Series Segmented Assay System

Performance

System performance will depend on actual measurement conditions. Under the following conditions the standard WM2200 waste assay system has an MDA of approximately 0.1 μCi for ^{137}Cs or 0.2 gm for ^{239}Pu :

- Standard 200 L (55 gal) drum.
- Density less than 0.3 gm/cc.
- Background less than 0.02 mR/hr.
- No other significant nuclides present.
- 30 minute assay time.

This sensitivity can be modified by detector size, assay time, and geometry.

The typical dynamic range is five to six orders of magnitude.

The accuracy of the measurement is based on the uniformity of the activity distribution and the density and homogeneity of the waste material. Typical accuracies are $\pm 20\%$ with maximum errors being in the range of 50% for drums with densities up to 1 gm/cc.

Table 1.

Nuclide	Daughter	Energy (MeV)	LLD (μCi)	LLD (kBq)	LLD (g)
^{137}Cs	^{137}Ba	0.662	0.1	3.7	
^{134}Cs		0.796	0.1	3.7	
^{60}Co		1.173	0.1	3.7	
^{152}Eu		1.408	0.4	14.8	
^{235}U		0.185	0.2	7.4	0.1
^{238}U	$^{234\text{m}}\text{Pa}$	1.001	20.0	740.0	59.0
^{239}Pu		0.414	12,000	4.4E5	0.2

Table 2.
Physical Specifications

MODULE WEIGHTS (approximate)	
Detector Drive Module	550 kg (1200 lb)
Detector and Drive Collimator Add	365 kg (800 lb)
Rotator Module	160 kg (350 lb)
Conveyor/Rotator Module	230 kg (500 lb)
Transmission Drive Module	230 kg (500 lb)
FOOTPRINT	
Detector Drive Module	81 cm (32 in.) x 137 cm (54 in.)
Rotator Module	81 cm (32 in.) x 81 cm (32 in.)
Transmission Drive Module	81 cm (32 in.) x 81 cm (32 in.)
POWER REQUIREMENTS	
Counting Electronics	15 A at 110 V
Mechanical System	
Manual	30 A at 110 V
Automated	60 A at 110 V

WM2200 Series Segmented Assay System

Related Systems

- Segmented Can Scanner – Segmented Gamma Assay System (SGS) assay system optimized for waste and scrap materials in containers less than 30 cm in diameter.
- High Activity SGS – SGS assay of Intermediate Level Wastes in 200 liter and larger drums with surface exposure rates in excess of 100 R/hr.
- High Throughput SGS – SGS assay of drums using multiple HPGe detectors for increased throughput.
- Shielded Multi-Detector SGS – Segmented Gamma Analysis system using multiple HPGe detectors and a 4π low background steel shield provides both the accuracy of the SGS analysis and low detection levels.
- Tomographic Gamma Scanner (TGS) – Provides improved accuracy over the standard SGS along with images of the drum contents.





Features

- Complete quantitative gamma analysis for fission/activation products or TRU (alpha) radionuclides
- Modular design permits system to be optimized for customer's measurement application
- Large coaxial or Broad Energy Detector for optimal performance
- Non-Destructive Assay Software (NDA 2000) provides extensive setup analysis, calibration, and QA capabilities
- Los Alamos NIS-6 based tomographic analysis algorithms
- MGA/MGAU U-Pu isotopes software
- Fully integrated software
- Full spectral acquisition and storage at each grab
- Storage of all 16k spectral data from each grab (position correlated measurement)
- Region of Interest based gamma-line analysis
- Storage of all acquisition parameters
- Full re-analysis capability
- Ability to alter Regions of Interest for Post Acquisition Analysis
- Automated image reconstruction
- Interactive Graphics Package
- PLC-based electromechanical control system
- Many optional capabilities available including:
 - Automatic weighing system
 - Surface dose rate measurement
 - In-line automated conveyor system

WM2900 TGS

Tomographic Gamma Scanner



Introduction

The WM2900 TGS is Canberra's Tomographic Gamma-ray scanning system for Safeguards and Waste Assay applications. The system is designed to accurately quantify plutonium, uranium, fission and activation products in a variety of containers from 20 L pails to 200 L drums in overpacks.

The TGS uses high purity germanium detection and low spatial resolution transmission and emission imaging to obtain improved measurement accuracy over non-imaging gamma-ray techniques. The container is divided into a number of vertical and radial volume elements. The activity is quantified in each of these voxels using matrix correction techniques based on the activity content and matrix properties of each voxel.

Data is acquired by scanning hardware with high resolution HPGe detector electronics. Matrix mapping is performed by applying Beers Law to rays from the center of each voxel to the center of the detector face. Special image reconstruction software is used to allow for the response of the collimator in combination with the properties of the waste. A comprehensive graphics package allows the attenuation map and emission image to be visualized from different perspectives.

The system is designed to assay drums with volumes up to 340 L and weights up to 1000 kg (2200 lb) in its standard configuration. Optional configurations can be provided for larger or heavier containers. A detector horizontal drive option is also available to allow assay of smaller containers (e.g. 20 L pails).

The standard system is designed to assay radio-nuclides such as ^{60}Co or ^{137}Cs with drum activities ranging from approximately 500 nCi up to approximately 100 mCi. For transuranic waste the system is optimized for

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WM2900 TGS Tomographic Gamma Scanner

assaying drums containing 0.4 g up to 1000 g of ^{235}U or ^{238}Pu . Detector size and collimation can be used to modify the dynamic range of the system.

The following sections describe the system hardware and software as well as the typical system performance.

Description

The waste assay system utilizes Canberra's modular mechanism design. This design provides the flexibility to easily add features such as an upgrade from a manual to an automatic system. This design can also be adapted for a variety of container sizes and weights.

TGS Mechanism

The mechanism is a modular design and consists of one or more of the following modules: 2442 detector vertical drive module, 2942R-27 turntable rotation module or optional in-line conveyor rotator, 2442T transmission vertical drive module, and 2942S single transmission source shield and shutter. These are described in detail below.

The 2442 detector vertical drive unit is a stepper motor driven vertical drive platform which will raise and lower the germanium detector, collimator, and optional dose measurement system over a vertical range of 1100 mm (43.5 in.). The unit is designed to handle operational weights up to 680 kg (1500 lb). This permits use of large collimators if necessary when measuring high activity containers. A variety of collimators and detector shields are available. The drive is designed for use with any of the following detector cryostats: horizontal integral, cryoelectric, or 7935-7 Big MAC cryostats.

The 2942R is the manual turntable module. This module can be equipped with a variety of turntable sizes depending on the measurement requirements. The turntable module is designed to handle a maximum diameter of 686 mm (27 in.) and weight of 1000 kg (2200 lb). The turntable module is mounted on a motorized track to provide the translational movement required for the tomographic imaging analysis. The rotator platter can be easily replaced to accommodate larger items.

The in-line conveyor/rotator is an optional drum rotator module which can be used to automatically load, assay, and unload drums from infeed and outfeed conveyors.

An optional digital scale can be interfaced into the PLC system to automatically weigh the drum and enter this weight into the application software during the assay. The accuracy of the weighing system is ± 2.3 kg (5 lb) at full scale.

Transmission Correction

The transmission correction module requires that the transmission vertical drive and transmission source shield and shutter be present on the system. The transmission module is also shown in the picture on

the front page. The vertical drive is similar in design to the detector vertical drive. The transmission source shield and shutter is designed to shield a transmission source with activities up to 370 MBq (10 mCi) for higher energy sources such as ^{152}Eu to minimize worker radiation exposures.

Mechanism Control System

The mechanism control system is a PLC-based controller with associated contactors, stepper motor controllers, I/O modules, drivers, etc. The PLC utilized is a GE/Fanuc Series 90 PLC. The PLC interfaces to the application software through an RS-485 interface. The flexibility of this design permits it to be easily modified to interface to a customer's process line. The control system is mounted in a locking NEMA-12 enclosure to ensure security, safety, and environmental control.

A touch screen control panel is provided with the system to allow local or remote control of the mechanism. The panel provides a convenient interface for control of the mechanism during testing or maintenance without going through the host computer.

Module Weights (approximate)	
Detector Vertical Drive, Detector and Collimator	998 kg (2200 lb)
Rotator Module	590 kg (1300 lb)
Transmission Drive Module and Shield	335 kg (734 lb)
System Foot Print	
Width	2920 mm (115 in.)
Depth	1830 mm (72 in.)
Height	2670 mm (105 in.)
Power Requirements	
Counting Electronics	15 A at 110 V
Mechanical System	60 Hz, 220 V ac, 20 A

Detector and Electronics

A high purity germanium detector is used for detection of the gamma emitting nuclides from the drums.

The detector provided with the standard WM2900 system is a 60% relative efficiency "P" type coaxial detector with a resolution of 2.0 keV at 1332 keV. The detector is housed in a horizontal integral cryostat. As an option, an electrically cooled detector can be provided. Other detector sizes can be specified to improve low level sensitivity or to improve the high activity performance.

The counting electronics utilizes Canberra's Digital Signal Processing electronics. This is necessary to handle the wide dynamic range of activities which are typically found in waste and safeguards measurements and to cope with high data transfer demands.

WM2900 TGS Tomographic Gamma Scanner

Visual Representation

The primary purpose of the tomographic analysis is improved accuracy while the images are generated to facilitate data review. NDA 2000 is provided with a number of powerful imaging tools. The images can be displayed interactively and in a variety of modes. Vertical and horizontal slices for both transmission and emission measurements (Figures 1 and 2) provide information on source positioning and matrix uniformity. 3-D projections (Figure 3) and continuous rotation modes are provided to allow easier visualization of relative source positions.

The NDA 2000 TGS analysis will also generate a series of vertical drum slices that can be printed with each analysis report.

Performance

System performance will depend on actual measurement conditions. Under the following conditions the standard WM2900 waste assay system has an MDA of approximately 0.2 μCi for ^{137}Cs or 0.4 g for ^{239}Pu :

- Standard 200 L (55 gal) drum.
- Density less than 0.3 g/cc.
- Background less than 0.02 mR/hr.
- No other significant nuclides present.
- 60 minute total assay time.

This sensitivity can be modified over a wide range by detector size, assay time, and geometry – both distance and collimator. The typical dynamic range is five to six orders of magnitude. The accuracy of the measurement is based on the uniformity of the activity distribution and the density and homogeneity of the waste material.

Spatial Resolution

For a typical 200 L drum analysis, a grid of 10 x 10 horizontal and 16 vertical segments are used to provide a voxel size of 56 mm (2.2 in.). The number of horizontal and vertical divisions can be varied by the user to provide improved resolution or decreased assay time.

Typical accuracies obtained are $\pm 20\%$ for 200 L drums with densities up to 1 g/cc. Both non-self attenuating sources in heterogeneous waste forms and non-uniform activity distributions can be measured accurately.

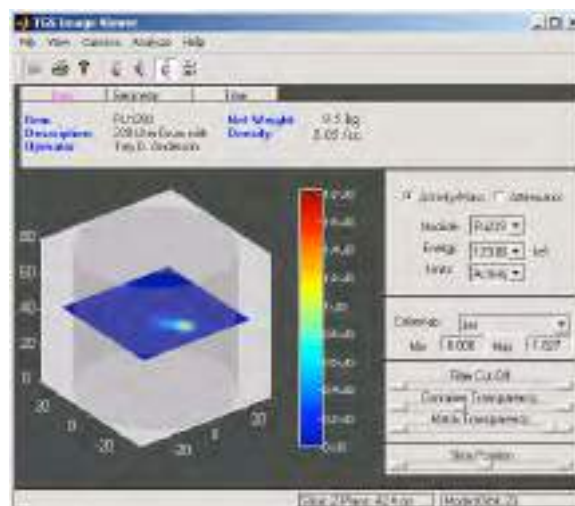


Figure 1.
Typical TGS vertical slice showing a hot spot near the center of the drum.

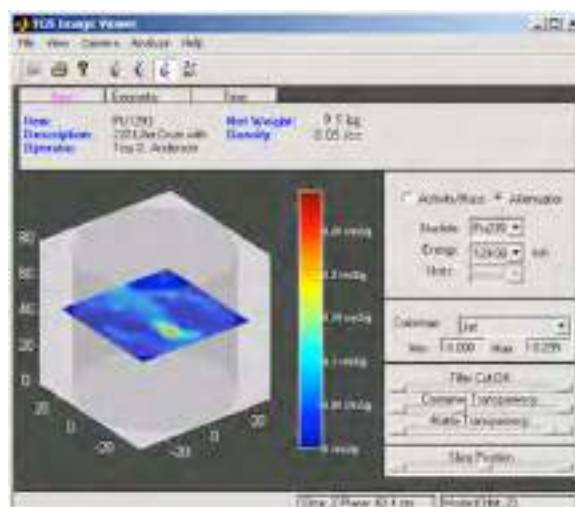


Figure 2.
Typical TGS vertical slice showing a high density object at the same location as the hot spot shown in the Figure 1.

WM2900 TGS Tomographic Gamma Scanner

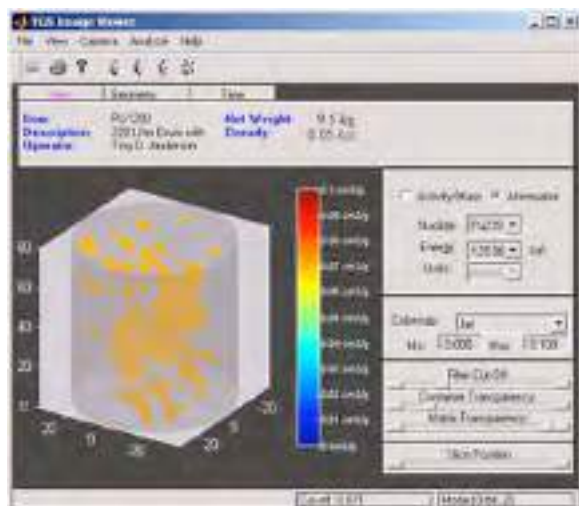


Figure 3.

3-D projection from the transmission measurement. The high density portions of the drum matrix are displayed in this screen.

Waste Assay Application Software

Canberra's Genie 2000 based Non-Destructive Assay Software (NDA 2000) is used for WM2900 applications. The application software is designed to run under Windows® NT®/2000 and utilizes all of the standard Genie 2000 high resolution gamma spectroscopy techniques. NDA 2000 seamlessly combines assay results from complimentary assay techniques when a suite of equipment is demanded.



A variety of collimating apertures are available to provide the desired resolution and sensitivity.

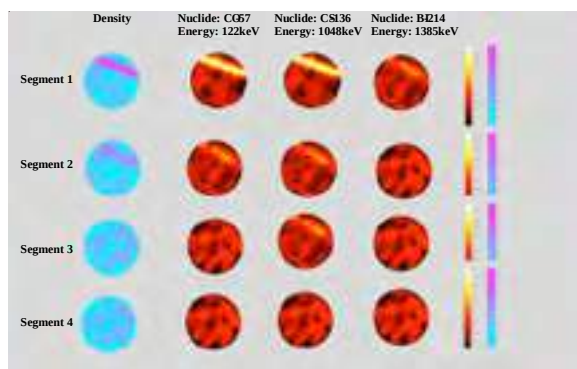


Figure 4.

Partial TGS summary printout showing a summary of the transmission and emission images.

In addition, some of the features included in the software are:

- A high level menu structure for ease of use.
- Multiple matrix correction techniques including:
 - Average Density.
 - Differential peak analysis.
 - Transmission Correction.
- Tomographic imaging and analysis.
- Integrates measured plutonium isotopics (MGA analysis).
- Total Measurement Uncertainty (TMU) Analysis.
- Extensive QA and measurement control routines.
- Automated calibration routines.
- Archiving capabilities.
- User editable report templates.
- Compliant with NQA2 and ISO 9001.
- And much more.

A more detailed description is included in the NDA 2000 (S529C) spec sheet.

ISO 9001
SYSTEM
CERTIFIED



Model WM3210 Passive/Active Neutron Cf-252 Shuffler System

Features

- Unique ^{252}Cf Shuffler mechanism for both Active and Passive neutron coincidence counting of 200 L drums.
- Active mode sensitivity¹, 1000 second count time:
 - Fast neutrons: 300 mg ^{235}U .
 - Thermal neutrons: 3 mg ^{235}U .
- Passive mode sensitivity¹, 1000 second count time: 4 mg ^{240}Pu .
- Rugged mechanical design for in-plant use.
- Fast Teleflex source shuffling mechanism with 400 ms transfer time.
- Three rpm turntable for barrel rotation.
- Sixty-four ^3He tubes for 17.5% detection efficiency.
- PC-based control and analysis system.

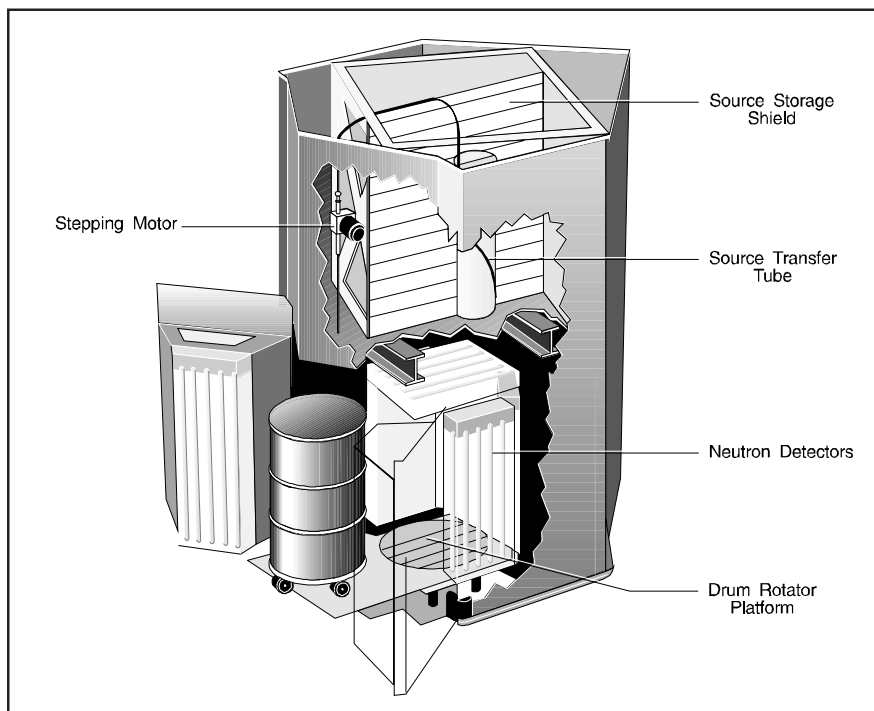


Figure 1
The WM3210 PAN Counter and Shuffler¹.

Description

The WM3210 is based upon a design by Los Alamos National Laboratory¹, and is available commercially from Canberra's Applied Systems Division through a technology transfer agreement with LANL. The Model WM3210 Passive/Active Neutron (PAN) Shuffler uses a high speed transfer mechanism to shuffle a ^{252}Cf interrogation source between a source shield assembly and the counting chamber, giving it the ability to be used for both passive and active neutron coincidence counting of fissionable materials.

Because shuffler-type instruments can be used for the non-destructive assay (NDA) of small amounts of both uranium and plutonium in a wide variety of forms and matrix materials, they are ideal for analyzing waste materials produced by facilities which handle fissile material and for safeguards accountability measurements. In addition, the design of the WM3210 allows it to also be used for samples as large as spent fuel assemblies, where

the presence of large amounts of activation products make gamma assay impractical.

The Counting Chamber

The counting chamber, shown in Figure 1, has an interior cavity large enough to comfortably contain a 200 L (55 gal) drum. The drum sits on a turntable, which rotates at 3 rpm while the count is in progress. When the door to the counting chamber is closed the drum is surrounded by a shield of tungsten, high-density polyethylene, and boron-loaded polyethylene weighing approximately 3600 kg (8000 lb). Imbedded in the shielding are 64 ^3He tubes, giving the system a high counting efficiency.

The Source and Shuffler

The ^{252}Cf interrogation source, which nominally provides 8×10^8 n/s, is housed in its own 1800 kg (4000 lb) shield located above the counting chamber. A Teleflex cable, which is driven by a computer-controlled

stepper motor, is used to rapidly transfer the source between its shielded housing and the counting chamber. Less than 400 ms are required to insert or remove the source, and safety interlocks insure that the counting chamber door is closed before the source is transferred into its sample interrogation position.

The Shuffler Counting Method

When the WM3210 is used as an active counter, the shuffler mechanism is typically used as follows to count a sample:

1. The source is sent to the counting chamber, where it spends 11 seconds irradiating the sample.
2. The source is removed, and a delay of approximately 3.5 seconds is allowed to elapse.
3. A 7 second count cycle is then initiated to count the delayed neutrons from the sample.

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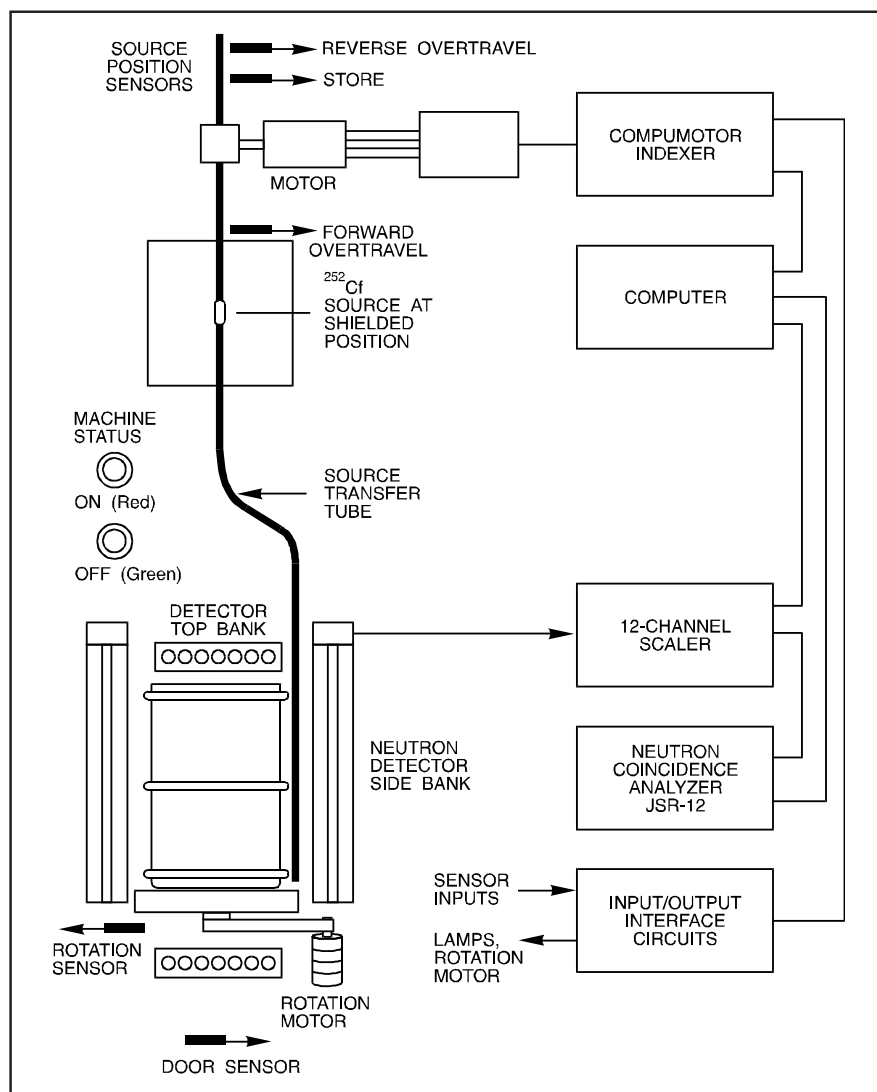


Figure 2
System Block Diagram¹.

This irradiation/delay/count process is then continuously repeated until sufficiently good counting statistics have been achieved.

When the WM3210 is used as a passive counter, the ^{252}Cf source remains in its shield. In this mode the WM3210 operates in a manner similar to the WM3100 Series.

Typical Results

While the nature of the sample and exact shuffle/count times used will

impact the results, 1000 second measurement times have yielded sensitivities (at 3 s above background) of 300 mg of ^{235}U contained within a 200 L drum. By removing the cadmium liner from the counting chamber and counting the thermal neutrons which are produced, sensitivities down to 20 mg of ^{235}U have been obtained. When operated in areas with lower ambient backgrounds or with a larger ^{252}Cf source, the sensitivity levels improve.

When used as a passive counter for the even isotopes of plutonium, results of 4 mg ^{240}Pu -eff are typical of what can be expected.

The Electronics Subsystem

A block diagram of the control and analysis system required to perform the shuffle counting and analysis is shown in Figure 2. Overall supervision and data analysis is performed via an industry PC. A JSR-12 Neutron Coincidence Counter is used for data acquisition, and the remaining components for motion control and safety interlocks.

Specifications

^{252}Cf SOURCE AND SHIELD

- **Source Strength** – 8×10^8 n/s.
- **Source Half Life** – 2.6 years.
- **Radiation Shielding** – 1800 kg (4000 lb).
- **Radiation Level** – 1 mR/h at 1 m from the shield.

COUNTING CHAMBER

- **^3He Tubes** – 64 each.
- **Detector Efficiency** – 17.5%.
- **Radiation Shielding** – 3600 kg (8000 lb).
- **Liner** – Cadmium.
- **Inside Diameter** – 76 cm (30 in.).
- **Barrel Rotation** – 3 rpm.

PERFORMANCE

- **Active mode sensitivity** – 1000 second count time:
 - **Fast Neutrons** – 300 mg ^{235}U .
 - **Thermal Neutrons** – 3 mg ^{235}U .
- **Passive mode sensitivity** – 1000 second count time: 4 mg ^{240}Pu -eff.
- **Accuracy** – 15% for waste barrels.

REFERENCE

1. Los Alamos National Laboratory Application Note *The $^{252}\text{Californium}$ Shuffler*, March, 1990.



Features

- Designed for quantitative passive neutron analysis
- Suitable for go/no-go measurement of plutonium
- Flexibility geometry for assay of pails, drums or large objects
- Expandable – additional slabs can be connected to improve performance with large samples
- Fast Amptek electronics
- High efficiency >19%
- Sensitivity – detection levels of <50 mg W.G. Pu
- All HDPE moderator enclosed in stainless steel skins
- Transportable
- Free standing detector assemblies
- Operated using JSR-12 or JSR-14 shift registers
- Available with NDA 2000 software

WM3500 Curved Slab Passive Neutron Counter



Description

The curved slab neutron coincidence slab counter measures the plutonium content of the sample by detecting coincidence neutrons from the spontaneous fission of the even numbered isotopes of plutonium. The counter is designed to make either quantitative or go/no-go measurements. A JSR-12 or JSR-14 Neutron Coincidence Analyzer is required for coincidence counting (ordered separately).

The counter is comprised of four separate slab counters. These counters are curved through 90° and may be fitted together to form a passive well counter. Each section of the counter contains eight 91 cm (35.8 in.) ³He proportional tubes forming a single detector bank. The output from each of these detector banks is daisy chained, providing a single TTL signal out to the shift register. When configured in its smallest sample geometry (i.e. the four slabs are in contact) the WM3500 provides an overall efficiency of 19.4%. As the sections are positioned further apart, the efficiency decreases. The full counter has a height of 114 cm (44.9 in.) and forms a circle with inner diameter of 54 cm (21.3 in.) and has an outer diameter of approximately 86 cm (33.9 in.). For the most accurate results the sample should be placed on a pedestal to center it vertically within the counter. Since this counter does not have end plugs, the axial response will fall quickly as the source is moved near the ends of the counter.

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WM3500 Curved Slab Passive Neutron Counter



The WM3500 can be used with larger objects by separating the pillars.

Specifications

DETECTOR ASSEMBLY

- The detector assembly consists of a curved high-density polyethylene (HDPE) moderator with embedded ^3He proportional tubes.
- ^3He detectors are threaded into a conductive junction box containing a JAB-01 pre-amplifier/amplifier/discriminator board to provide low noise signal processing.
- Inputs/outputs from each slab are daisy chained together to provide a single output.
- The assembly is by a 0.81 mm (0.032 in.) cadmium liner to eliminate thermal neutron background.
- Each slab is free-standing.

SHIELDING

- Primary Shield: 5 cm (2 in.) HDPE – Detector slab is fixed in a minimum within the shield surrounding the entire detector except for the active front/face.

- Peripheral Shield: 5 cm (2 in.) HDPE – Counter and primary shield fit into the peripheral shield for added shielding (total of four inches).

CAVITY DIMENSIONS

- Inner diameter (smallest configuration) – 54.0 cm.
- Outer diameter (smallest configuration) – 86.0 cm.
- Height to top of junction box – 114.0 cm.

NEUTRON DETECTION

- Eight (8) ^3He proportional tubes per slab.
- Active length 91.0 cm (36 in.).
- Outer diameter 2.5 cm (1 in.).
- ^3He partial pressure – 4 atm.

DETECTION EFFICIENCY

- 19% in smallest configuration.
- Die-away time – 75 μs .

COINCIDENCE COUNTING DETECTION LEVELS

<3 mg ^{240}Pu effective (<50 mg weapons grade plutonium) under the following conditions:

- 20 minute acquisition time.
- Source located at the center of the detector cavity in smallest configuration (all slabs touching).
- Operation at sea-level.
- Neutron background – natural sources only.

INPUTS

- +5 V LVPS (BNC connector).
- +1700 V HVPS bias supply (SHV connector).
- TTL out from adjacent slab (BNC connector).

OUTPUTS

- TTL pulse (BNC connector).
- +5 V LVPS to adjacent slab (BNC connector).
- +1700 V HVPS bias supply to adjacent slab (SHV connector).

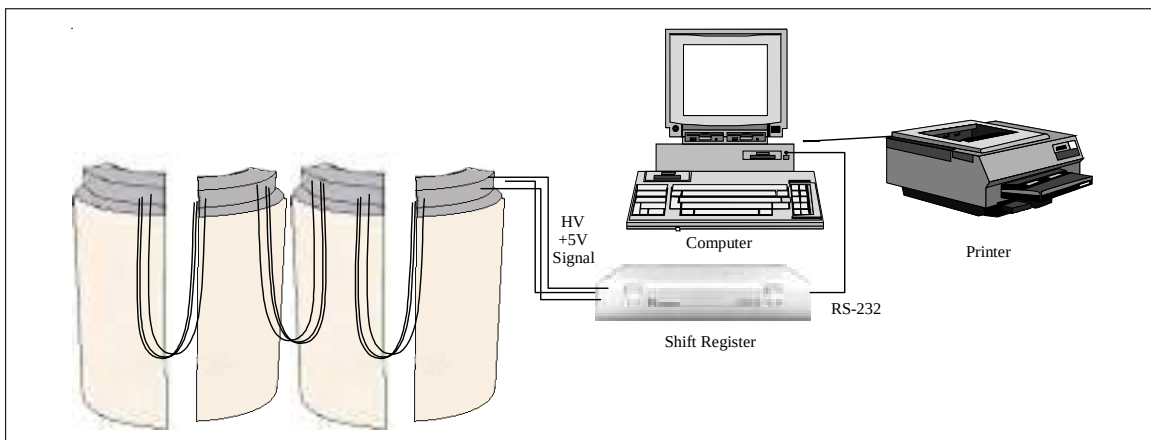


Figure 3.
Illustration of the set-up of the WM3500 slabs, shift register and computer.