



Ricerca di Sistema elettrico

Raccolta delle Lecture del Workshop Tematico “LFR-Gen IV: Stato attuale della tecnologia e prospettive di sviluppo”

Mariano Tarantino

RACCOLTA DELLE LECTURE DEL WORKSHOP TEMATICO “LFR GENERATION IV STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO”

Mariano Tarantino (ENEA)

Settembre 2016

Report Ricerca di Sistema Elettrico

Accordo di Programma Ministero dello Sviluppo Economico - ENEA

Piano Annuale di Realizzazione 2015

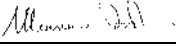
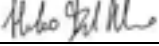
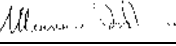
Area: Generazione di Energia Elettrica con Basse Emissioni di Carbonio

Progetto: Sviluppo competenze scientifiche nel campo della sicurezza nucleare e collaborazione ai programmi internazionali per il nucleare di IV Generazione.

Linea: Collaborazione ai programmi internazionali per il nucleare di IV Generazione

Obiettivo: Comunicazione e diffusione dei risultati

Responsabile del Progetto: Mariano Tarantino, ENEA

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Titolo RACCOLTA DELLE LECTURE DEL WORKSHOP TEMATICO Î LFR GENERATION IV STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPOÏ							
Descrittori Tipologia del documento: Rapporto Tecnico Collocazione contrattuale: Accordo di programma ENEA-MSE su sicurezza nucleare e reattori di IV generazione Argomenti trattati: Generation IV reactors							
Sommario Presso il CR ENEA Brasimone dal 19 al 20 novembre 2015 si è svolto il Workshop tematico dal titolo ÎLFR-GEN IV STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPOÏ, organizzato da ENEA in collaborazione con le principali università italiane che svolgono attività di ricerca in campo nucleare. Il Workshop, promosso nell'ambito delle attività, inerenti la Linea Progettuale 2 ÎCollaborazione internazionale per il nucleare di IV generazioneÏ dell'AdP MSE-ENEA, assume il duplice obiettivo di condividere lo stato dell'arte dei sistemi LFR tra gli stakeholder italiani definendo al contempo, in maniera condivisa e sinergica con il contesto Europeo, le linee di intervento future in ambito LFR							
Note Autori: M. Tarantino							
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0	EMISSIONE	26/09/16	NOME	M. Tarantino	A. Del Nevo	M. Tarantino	
			FIRMA				
REV.	DESCRIZIONE	DATA		REDAZIONE	CONVALIDA	APPROVAZIONE	

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1 LFR-GEN IV Stato attuale della tecnologia e prospettive di sviluppo

Dal 19 al 20 novembre 2015, presso il CR ENEA Brasimone, si è tenuto il Workshop tematico dal titolo **LFR-GEN IV STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO**, organizzato da ENEA in collaborazione con le principali università italiane che svolgono attività di ricerca in campo nucleare.

Il Workshop, promosso nell'ambito delle attività inerenti la Linea Progettuale 2 **Collaborazione internazionale per il nucleare di IV generazione** dell'AdP MSE-ENEA, è stato finalizzato ad:

- Analizzare lo stato progettuale della tecnologia dei sistemi LFR partendo dal lavoro svolto in ambito ADP;
- la programmazione delle attività future, definendo le priorità di intervento in ambito italiano in maniera che siano sinergiche al contesto europeo ed internazionale (l'entrata della Cina nel settore);
- armonizzazione le strategie di sviluppo mediante l'incontro di tutti gli stakeholder italiani.



Fig. 1: Ingresso al CR ENEA Bologna

L'Italia, grazie all'ENEA, ANSALDO NUCLEARE e con il contributo fondamentale del CIRTEN, continua a conservare la leadership internazionale sulla progettazione e sullo sviluppo tecnologico dei sistemi LFR, nonostante il sempre più ampio interesse (accompagnato da ingenti investimenti economici) di altri Paesi quali ad esempio la Cina.

Ciò è stato possibile grazie ai continui sforzi fatti da ENEA (che ha sfruttato efficacemente i fondi dell'ADP), sia per accrescere e migliorare le proprie infrastrutture di ricerca (Brasimone e Casaccia), sia per rafforzare le proprie capacità e competenze sulla progettazione dei sistemi nucleari innovativi. (es. gruppo core design di Bologna).

Facenti parte del comitato organizzatore troviamo M. Tarantino, responsabile della divisione di Ingegneria sperimentale del dipartimento di fusione e tecnologie per la sicurezza industriale (FSN-ING), A. Del Nevo responsabile del laboratorio di

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progettazione e analisi nucleari (FSN-ING-PAN), I. Di Piazza responsabile del laboratorio di termoidraulica sperimentale (FSN-ING-TESP) ed infine A. Masinara, amministrativa gestionale presso l'ente di ricerca ENEA Brasimone.

I 65 rappresentanti (Allegato 1) di cui 35 rappresentanti delle più prestigiose università italiane (Bologna, Firenze, Milano, Pisa, Torino, Treviso), 20 rappresentanti dell'Agenzia Italiana per le Nuove Tecnologie l'Energia e lo Sviluppo Economico Sostenibile e 10 rappresentanti delle eccellenze industriali presenti sul territorio nazionale (Istituto Italiano di Tecnologia, Ansaldo Nucleare, CSM s.p.a. Hydromine Inc.), sono stati accolti presso la sala conferenze del Centro Informazione ENEA (Figura 2) ubicato sulle rive del lago Brasimone.



Fig. 2: Centro informazioni ENEA

L'agenda del Workshop (Allegato 2) è stata suddivisa in 6 sessioni. All'interno della sessione di apertura sono state presentate le strategie e prospettive nazionali sui reattori di quarta generazione refrigerati a piombo liquido (P. Agostini). Inoltre, è stata fornita un'ampia panoramica sullo stato attuale e sulle problematiche ancora aperte relative alla progettazione del reattore dimostratore ALFRED (Advanced Lead Fast Reactor Demonstrator). A seguire le sessioni Progettazione di Sistema e Analisi di Sicurezza, Materiali strutturali e Controllo della Chimica. Il giorno seguente, sono state trattate le tematiche inerenti alla Termoidraulica del refrigerante e lo sviluppo e applicazione di codici di calcolo per sistemi LFR.

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2 ALLEGATI

1. LISTA DEI PARTECIPANTI AL CONGRESSO
2. AGENDA
3. CONTRIBUTI PRESENTATI NELLE VARIE SESSIONI

ALLEGATO 1

Lista dei partecipanti

Allegato 1

NOME	COGNOME	ISTITUTO
Mariano	Tarantino	ENEA
Francesca	Lamastra	UNITV
Massimiliano	Polidori	ENEA
Francisco	Garcia Ferrè	IIT
		Hydromine
Luciano	Cinotti	Inc.
Mario	Bragaglia	UNITV
Daniele	Martelli	UNIFI
Stefano	Lorenzi	POLIMI
Mario	Carta	ENEA
Augusto	Gandini	UNIROMA-1
Francesca	Nanni	UNITV
Valentina	Fabrizio	ENEA
Ranieri	Marinari	UNIFI
Marica	Eboli	UNIFI
Massimo	Angiolini	ENEA
Patrizio	Console Camprini	ENEA
Alessandro	Venturini	UNIFI
Alessandra	Bellucci	CSM
Stefano	Lionetti	CSM
Emanuela	Martelli	UNIROMA-1
Francesco	Lodi	UNIBO
Gioacchino	Micichè	ENEA
Andrea	Giovinazzi	UNIFI
Fabio	Di Fonzo	IIT
Matteo	Vanazzi	IIT
		Hydromine
Giuseppe	De Antoni	Inc.
Saverio	Nitti	ENEA
Antonio	Cervone	ENEA
Simone	Mannori	ENEA
Davide	Rozzia	UNIFI
Gianfranco	Caruso	UNIROMA-1
Francesco	Edemetti	UNIROMA-1
Vincenzo	Narcisi	UNIROMA-1
Alessandro	Tassone	UNIROMA-1
Paolo	Balestra	UNIROMA-1
Antonio	Naviglio	UNIROMA-1
Carlo	Cristalli	ENEA
Paola	Parente	ENEA
Carlo	Cerminara	UNIFI
Roberto	Da Via	UNIBO
Filippo	Menghini	UNIBO
Daniele	Cerroni	UNIBO
Sandro	Manservigi	UNIBO
Marco	Beghi	POLIMI

Edoardo	Besozzi	POLIMI
Laura	Savoldi	POLITO
Roberto	Zanino	POLITO
Alessandro	Del Nevo	ENEA
Ivan	Di Piazza	ENEA
Pietro	Agostini	ENEA
Elena	Macerta	POLIMI
Mario	Mariani	POLIMI
Stefano	Cervino	POLIMI
Mauro	Cappelli	ENEA
Morena	Angelucci	UNIP
Luigi	Lepore	UNIROMA-1
Dominic	Caron	POLITO
Fabio	Moretti	UNIP
Paride	Meloni	ENEA
Felice	De Rosa	ENEA
Marco	Utile	ENEA
Dario	Diamanti	ENEA
		Hydromine
Giovanni	Corsini	Inc.
Piero	Gaggini	
		Hydromine
Leonardo	Presciuttini	Inc.

ALLEGATO 2

Agenda



WORKSHOP TEMATICO

LFR-GEN IV

STATO ATTUALE DELLA TECNOLOGIA E

PROSPETTIVE DI SVILUPPO

ADP ENEA-MSE (PAR2014-LP2)

Brasimone, 19-20 Novembre, 2015

Centro Ricerche ENEA Brasimone

Presso il CR ENEA Brasimone si terrà, dal 19 al 20 Novembre 2015, un Workshop tematico dal titolo “LFR-GEN IV STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO”, organizzato da ENEA in collaborazione con le principali università italiane che svolgono attività di ricerca in campo nucleare.

Il Workshop, promosso nell’ambito delle attività inerenti la Linea Progettuale 2 “Collaborazione internazionale per il nucleare di IV generazione” dell’ AdP MSE-ENEA, è finalizzato a :

- *analizzare lo stato attuale della tecnologia dei sistemi LFR partendo dal lavoro svolto in ambito ADP;*
- *supportare la programmazione delle attività future, definendo le priorità di intervento in ambito italiano ed europeo;*
- *armonizzazione le strategie di sviluppo mediante l’incontro di tutti gli stakeholder italiani.*

Il Workshop assume quindi il duplice obiettivo di condividere lo stato dell’arte dei sistemi LFR tra gli stakeholder italiani definendo al contempo, in maniera condivisa e sinergica con il contesto Europeo, le linee di intervento future in ambito LFR.

Comitato Organizzatore

M. Tarantino
A. Del Nevo
I. Di Piazza
D. Martelli
A. Masinara

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daniele.martelli@ing.unipi.it
annamaria.masinara@enea.it

GIOVEDÌ 19 NOVEMBRE, 2015

	Ora	TITOLO	SPEAKER
A	9,00	SESSIONE DI APERTURA	Chair: M. Tarantino
A-1	30'	Sviluppo dei Sistemi LFR: strategie e prospettive	P. Agostini
A-2	30'	DEMO-LFR ALFRED: Technical Overview	M. Iamele
1	10,00	PROGETTAZIONE DI SISTEMA E ANALISI DI SICUREZZA	Chair: A. Del Nevo
1-1	20'	TAPIRO Fast Reactor. Feasibility study of minor actinides irradiation campaign	M. Carta
1-2	20'	Il codice ERANOS per le analisi perturbative e di sensitività in supporto allo sviluppo dei reattori veloci	A. Gandini
1-3	20'	Characterization of the ALFRED core configuration and on the viability of In-Vessel Storage	F. Lodi
	11,00-11,30	Coffe Break	
1-4	20'	Supporto alla progettazione del combustibile nucleare per il reattore LFR.	S. Lorenzi
1-5	20'	Influenza della conducibilità nella simulazione del fuel MOX con il codice TRANSURANUS	D. Rozzia
1-6	20'	Sviluppo e validazione di un approccio e di modelli per l'analisi di sicurezza di reattori veloci di IV generazione	E. Martelli
1-7	20'	Verifica di fattibilità di sonde commerciali per la misura dei flussi neutronici. Proposta di studio teorico-sperimentale di SPND innovativi ottimizzati per reattori LFR.	L. Lepore
1-8	20'	Studio delle interazioni tra combustibile, prodotti di fissione e refrigerante in sistemi LFR	E. Macerata
1-9	20'	Valutazione degli effetti dinamico-strutturali indotti dal fenomeno del "core compaction"	R. Lo Frano
	13,30-15,00	Pranzo	
2	15,00	MATERIALI STRUTTURALI E CONTROLLO DELLA CHIMICA	Chair: M. Angiolini
2-1	20'	Qualifica coating e materiali strutturali per sistemi LFR	M. Angiolini
2-2	20'	Sviluppo di ricoperture a base di FeCrAl per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo	A. Bellucci
2-3	20'	Sviluppo di ricoperture per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo mediante tecniche di ablazione laser	F. Di Fonzo
2-4	20'	Report sulla caratterizzazione di rivestimenti mediante prove di irraggiamento con ioni pesanti	F. Garcia Ferrè
2-5	20'	Report sulla caratterizzazione di materiali strutturali ricoperti per applicazioni nucleari	F. Lamastra
	16,40-17,00	Coffee Break	
2-6	20'	Prove di corrosione in piombo stagnante e fluente e controllo dell'ossigeno in impianti a piombo	S. Bassini
2-7	20'	Characterization of mechanical properties and corrosion behavior in lead of DS4 steel	C. Cristalli
2-8	20'	Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante	A. Coglitore
	18,00	Fine dei Lavori	

Cena (ore 20,00)

VENERDÌ 20 NOVEMBRE, 2015

	Ora	TITOLO	SPEAKER
3	9,00	TERMOIDRAULICA DEL REFRIGERANTE	CHAIR: M. TARANTINO
3-1	20'	ALFRED-SGTR. HERO Test Section on CIRCE facility.	D. Rozzia
3-2	20'	Leak before break in HLM steam generator	A. Del Nevo
3-3	20'	Flow Blockage experimental studies in HLM systems	R. Marinari
3-4	20'	Experimental tests on the HLM facility NACIE-UP	M. Angelucci
	10,20-10,50	Coffee Break	
3-5	20'	Mixing and Stratification in HLM large pool	M. Tarantino
3-6	20'	Preliminary analysis of CIRCE by CFD codes	D. Martelli
3-7	20'	Pre-test CFD analysis of the rod bundle experiment in the HLM facility NACIE-UP	R. Marinari
3-8	20'	Pre-test Analysis of SGTR event on large scale experimental facility by SIMMER-IV code	A. Pesetti
4	12,10	SVILUPPO E APPLICAZIONE DI CODICI DI CALCOLO PER I SISTEMI LFR	CHAIR: P. MELONI
4-1	20'	Advances in the development of the code FRENETIC for the coupled dynamics of lead-cooled reactors	D. Caron
4-2	20'	System codes applications to HLM nuclear systems	G. Caruso
	13,20-14,30	Pranzo	
4-3	20'	Verifica e validazione preliminare sull'accoppiamento del codice di calcolo RELAP5-3D e il codice CFD CFX	F. Moretti
4-4	20'	Verifica e validazione preliminare sull'accoppiamento del codice di calcolo RELAP5/Mod.3.3 e il codice CFD Fluent	D. Martelli
4-5	20'	FEMLCORE-CATHARE coupling on SALOME platform	S. Manservigi
4-6	20'	Revisione della validazione del codice T/HCATHARE2 attraverso il benchmark LACANES	M. Polidori
		CONCLUSIONI E SVILUPPI FUTURI	Chair: P. Agostini
	16,30	Fine del Workshop	

ALLEGATO 3

Contributi presentati nelle varie sessioni



Sviluppo dei sistemi LFR: strategie e prospettive

P.Agostini

Brasimone, 20 Novembre 2015

Strategia per ALFRED

European frame: ALFRED in ESNII

2025

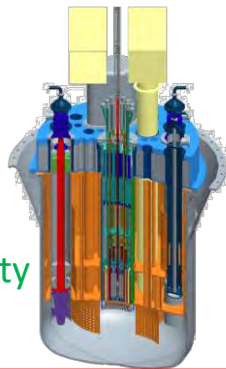
ASTRID
SFR
Prototype



Reference Technology
Design, Construction &
Commissioning

MYRRHA

Irradiation Facility



Supporting Infrastructure
Design, Construction &
Commissioning

ALFRED

LFR Demonstrator



Short-term alternative Technology
Conceptual design, siting, & supporting R&D

ALLEGRO

GFR Demonstrator

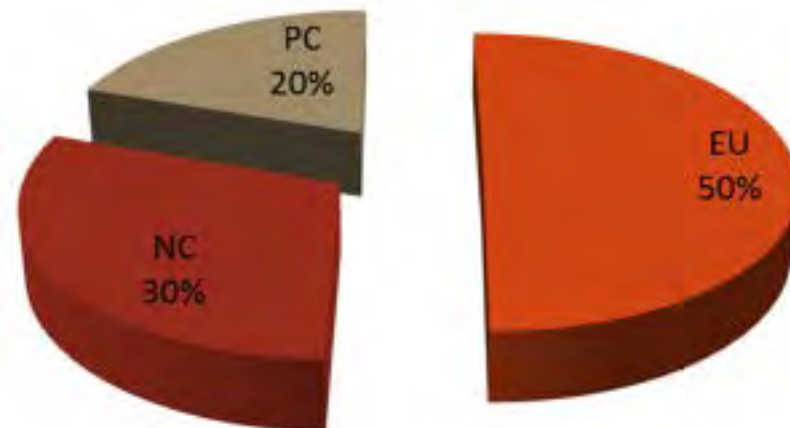
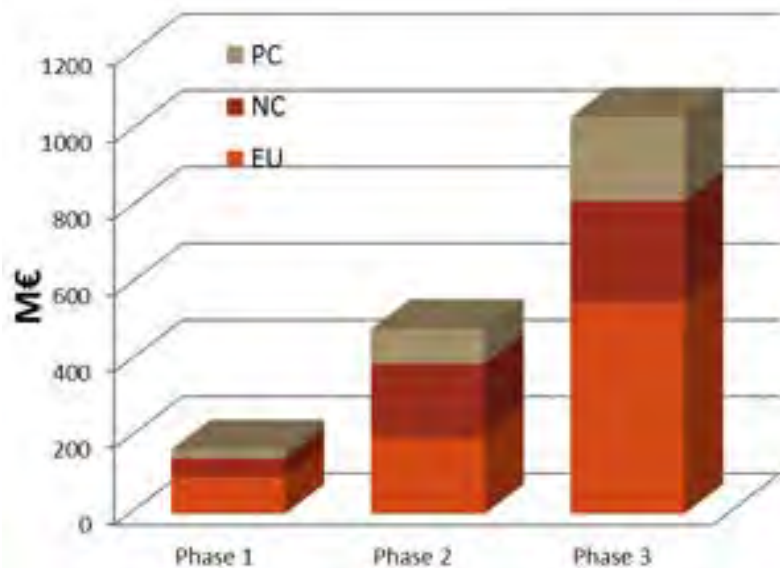
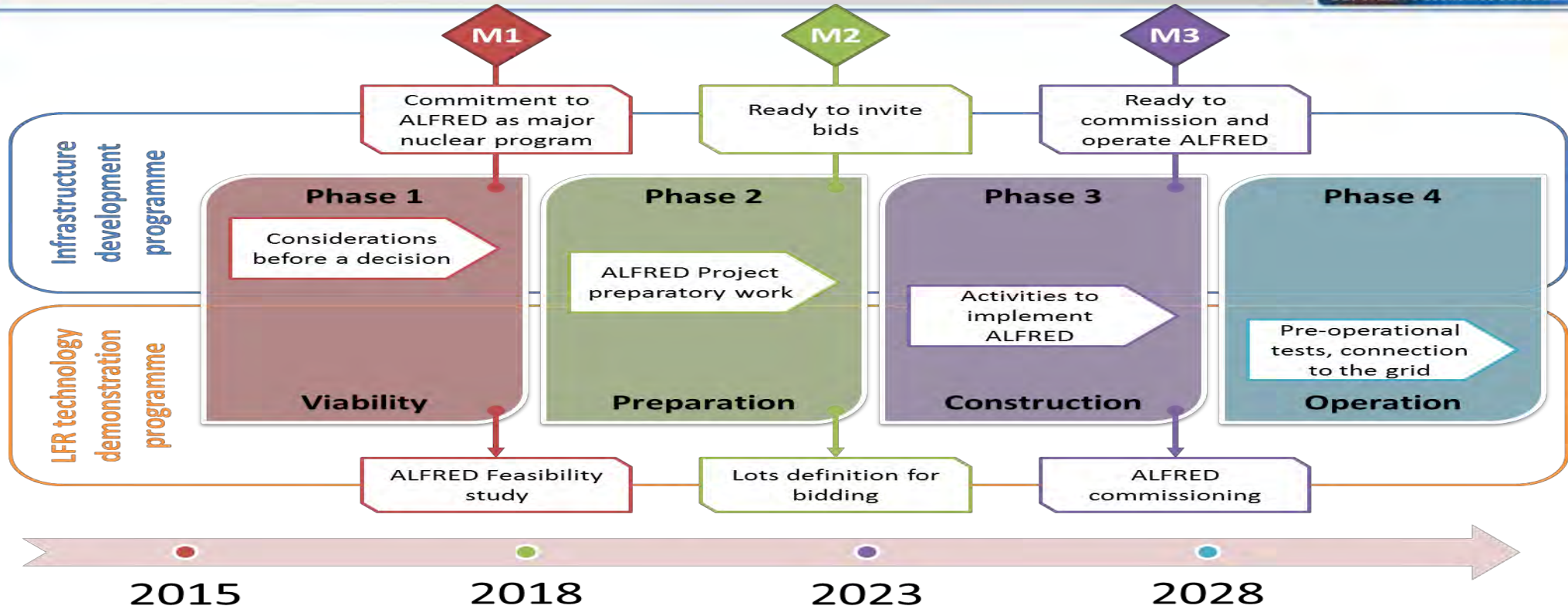


Long-term alternative Technology
Conceptual design, siting, & supporting R&D

ESNII is the European
Sustainable Nuclear
Industrial Initiative

Participation to EU projects
in GEN IV is facilitated by
the participation to ESNII

ALFRED ROADMAP



THE FALCON CONSORTIUM



Fostering **AL**fred **CON**struction



Signature ceremony
Dec 18th 2013

PHASE
1

- 30 months
- Unincorporated consortium
- In-kind contributions
- Optimize the cooperation
- Areas: strategic, management governance, financial and technical aspects

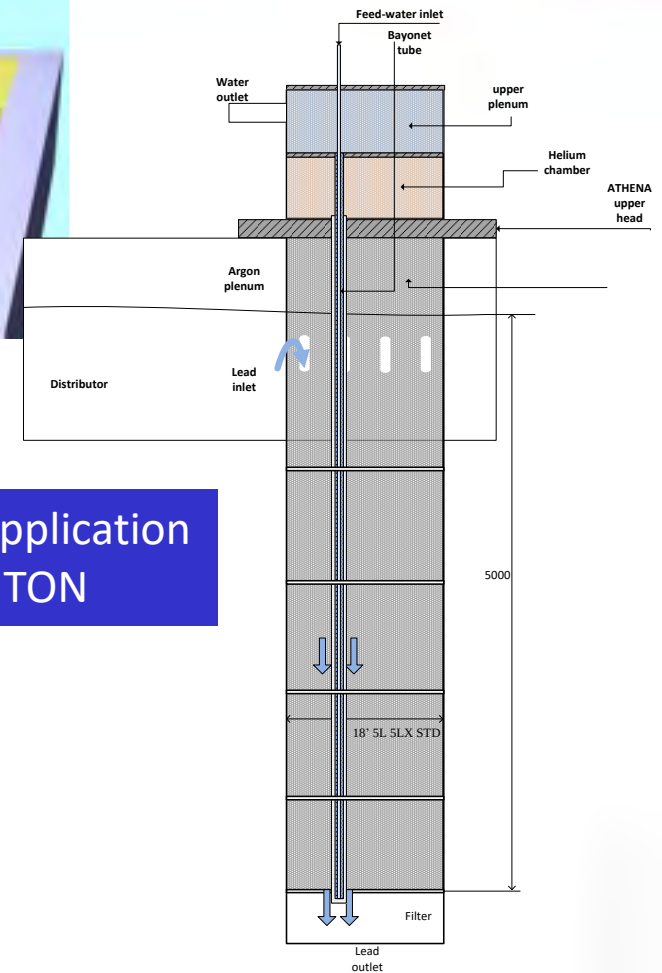
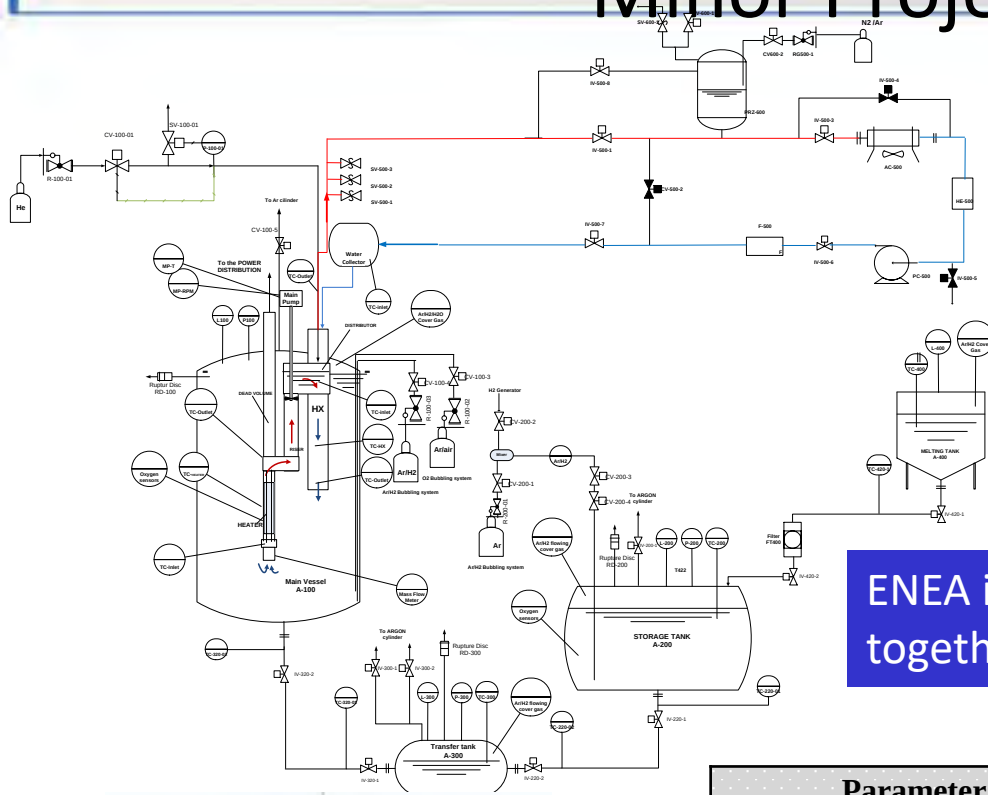
PHASE
2

- Detailed agreement
- R&D needs management
- Engineering design
- Licensing, and
- Commit the construction

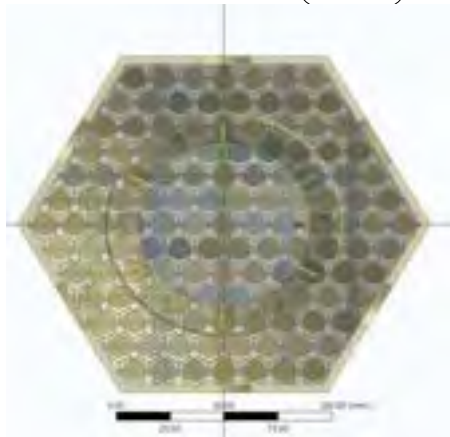


THE FALCON CONSORTIUM IS EXTENDED TO JUNE 2016

Applicazione al grant rumeno per Minor Projects (20 Meuro)



ENEA is carrying on the application together with ICN and CITON



Assembly of fuel pin simulators

Parameter	Quantity
Total power	2.21MW
Total mass flow rate	189 kg/s
FPS inlet temperature	400 °C
FPS outlet temperature	480 °C
Rod diameter (D)	10.5 mm
Pitch (P)	13.86 mm
P/D	1.32
Hexagonal key	166 mm
Wrapper width	4 mm
Active length	600 mm
Average linear power	29 kW/m
number of pins	127
Total power	2.21 MW
Mass flow rate	189 kg/s
Average velocity	1.7 m/s

Heat exchanger

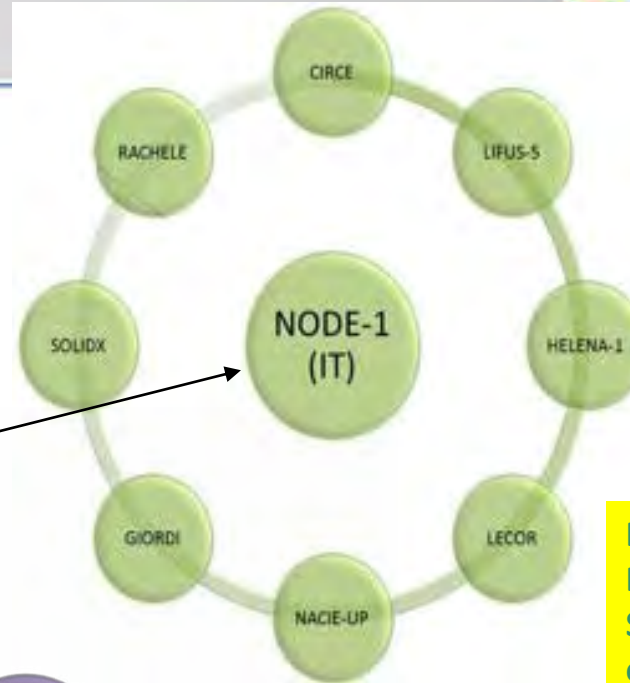
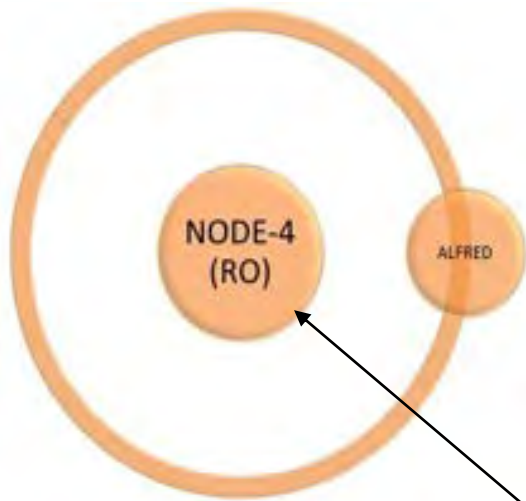
Richiesta che ALFRED venga classificato come Major Project (oltre 50Meuro)



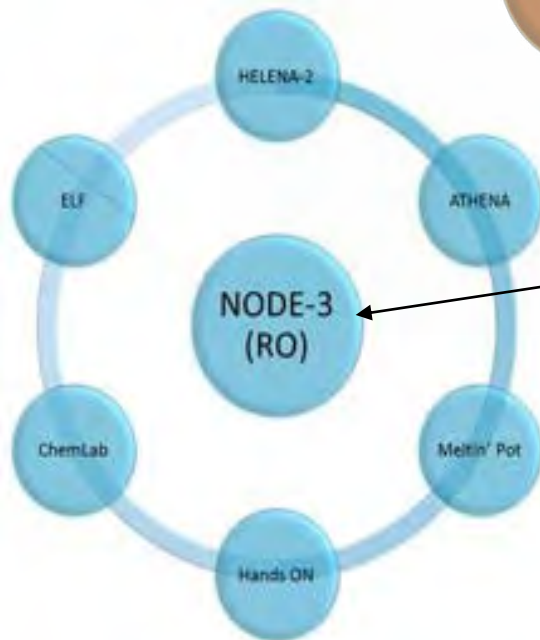
- Il 29 Ottobre, G.Villabruna di Ansaldo ha incontrato il ministro rumeno dell'Energia e la D.G. Elena Popescu
- Nella riunione G.V. ha sollecitato l'inserimento di ALFRED tra i "Major Projects" ricevendo un feedback positivo
- Il 4 Novembre, a causa delle dimissioni del primo ministro, il Memorandum, già firmato dal ministro dell'Energia e da quello dell'Educazione/Ricerca, si è arrestato presso il ministero dei fondi europei.
- Il 13 Novembre il Memorandum firmato dai tre Ministri e' stato portato alla riunione del Consiglio dei Ministri, ma, su indicazione del Ministero della Giustizia, non e' stato discusso in quanto essendoci un Governo ad interim non poteva essere approvato.
- Attendiamo la formazione del nuovo governo in Romania

iCRADLE in ESFRI

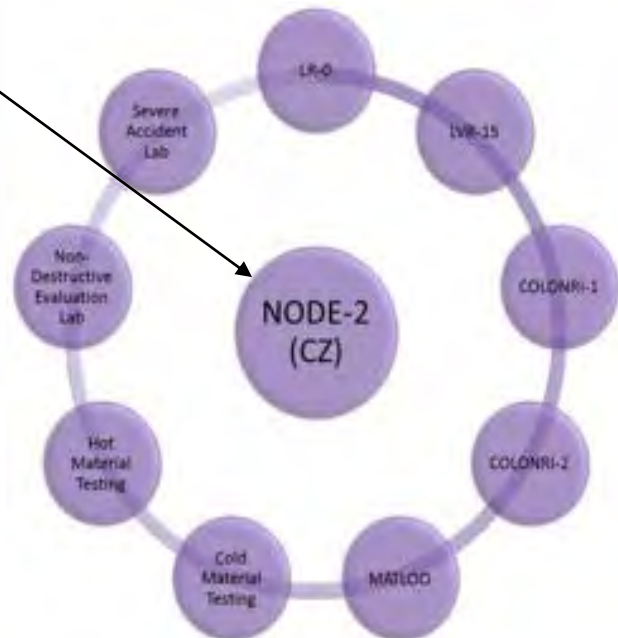
*"The iCRADLE proposal consists of a **Distributed Research Infrastructure (D-RI)** for research, development and qualification of the Heavy Liquid Metal (HLM) technology aimed to LFR reactor development"*



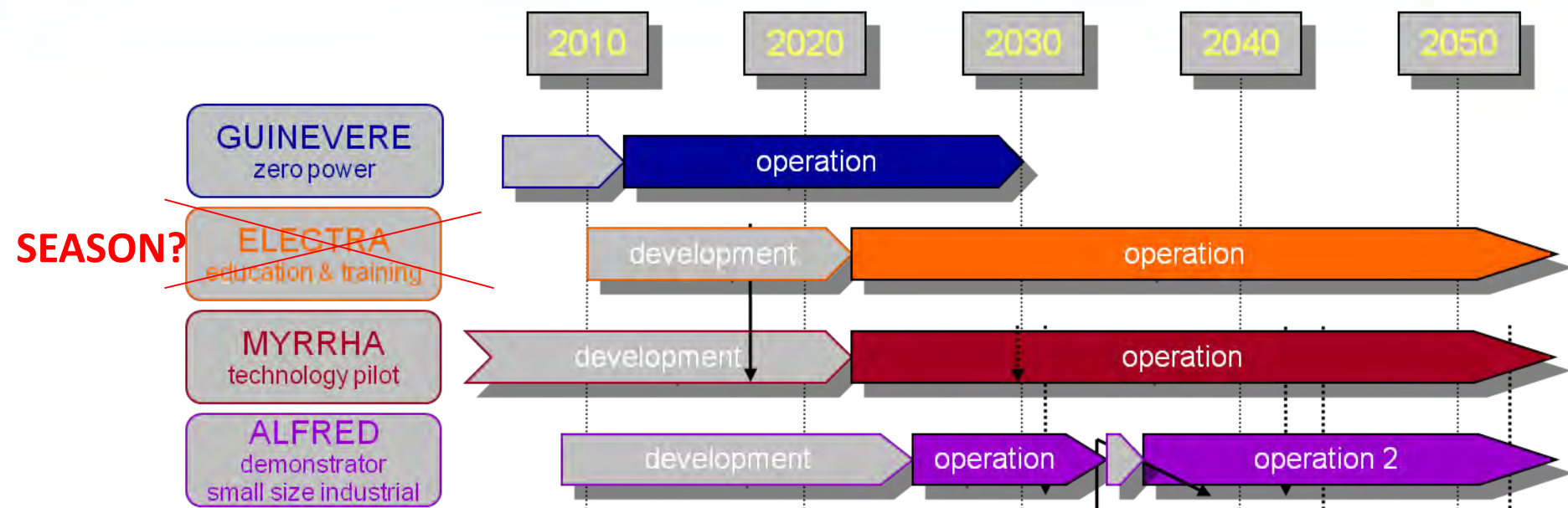
ESFRI is the European Strategy Forum on Research Infrastructures



Inclusion in ESFRI facilitates the access to European structural funds



Inserimento di un piccolo reattore nella strategia complessiva



- Il piccolo reattore svedese (ELECTRA) era già presente nella roadmap LFR.
- Nel 2013 il finanziamento fu cancellato dal governo svedese
- Il 20 Ottobre ENEA è stato contattato da Janne Wallenius, CEO della Lead Cool inc. per collaborare allo sviluppo del progetto **SEASON**: Small, Efficient And Safe Options for Nuclear
- Viene proposto di applicare ad NFRP 4 della recente call EURATOM

Prossime azioni nel Consorzio FALCON



- Sussistono ancora incertezze sulle modalità di accesso ai fondi strutturali europei ed incertezza sull'entità richiedibile. **Saranno intensificati i contatti con le autorità Rumene**
- Sono stati accumulati ritardi sull'avviamento delle attività tecniche incluse negli agreement of collaboration. **E' urgente definire e pianificare le attività in kind da affidare ai sottoscrittori**
- Sono in preparazione le proposte per i progetti di R&D della call EURATOM Fissione. **E' necessario armonizzare in essa i contenuti degli agreement of collaboration**
- Si prevede partecipazione significativa a progetti su:
 - **sicurezza, gen IV**
 - **materiali,**
 - **SMR.**

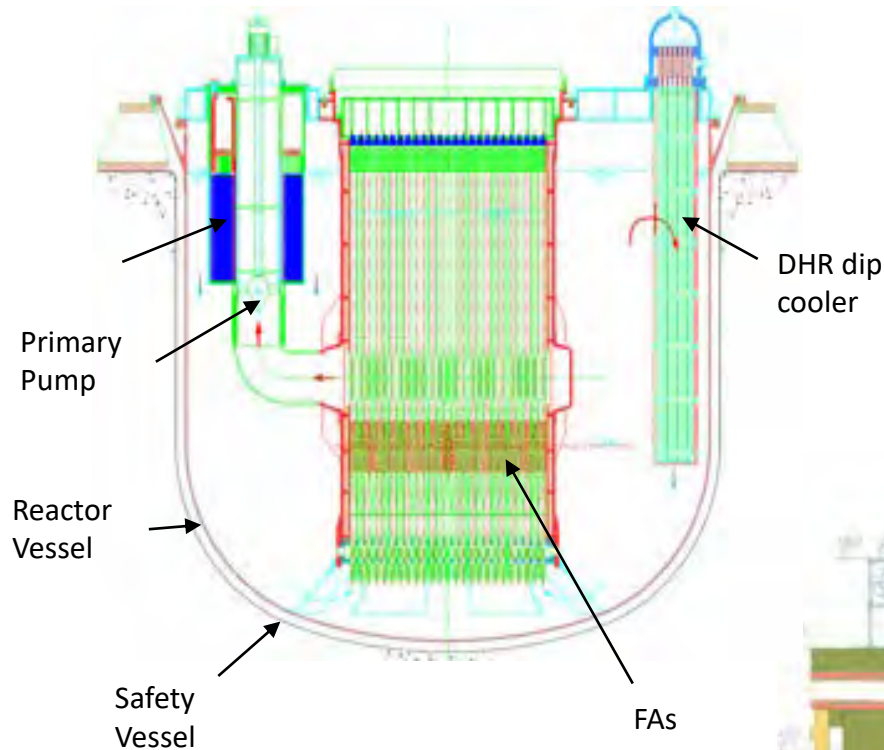


Stato delle collaborazioni in corso

Partecipazione a GIF -GEN IV Forum-

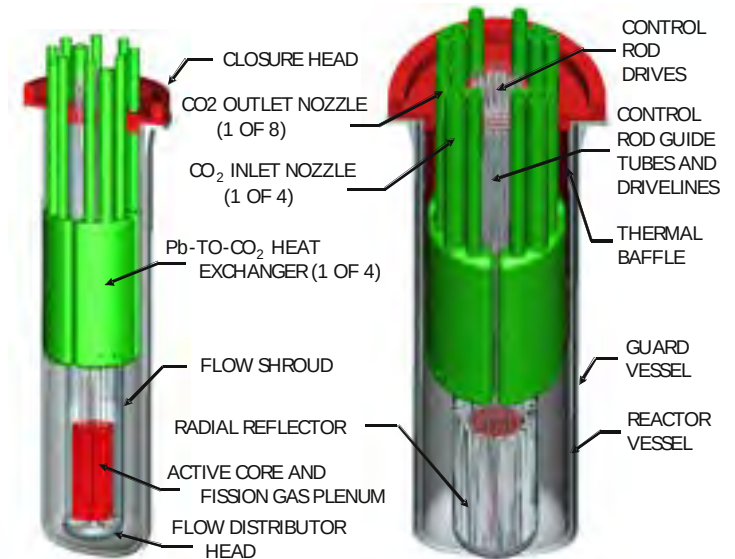
I paesi con interesse LFR in GIF sono: Europa, Russia, USA, Giappone, Corea

ELFR (600 MWe), BREST (300 MWe), and SSTAR (small size)

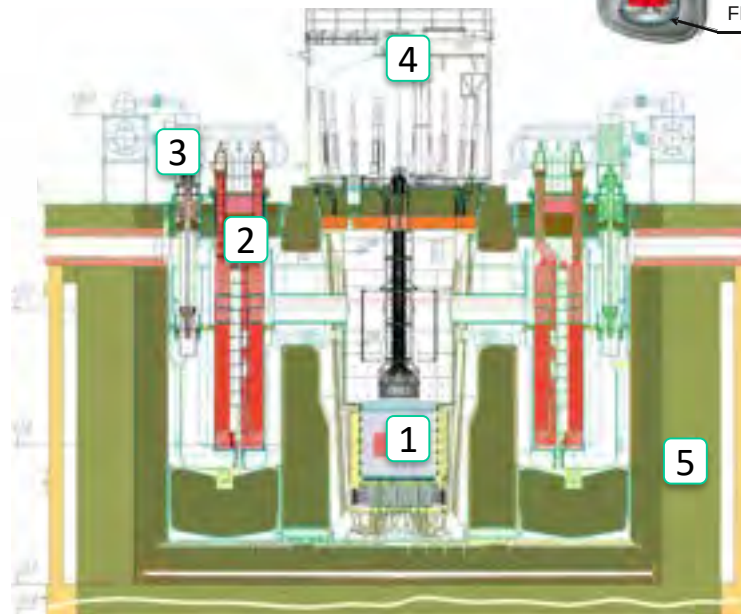


ELFR
system for central station
power generation

BREST
system of
intermediate size



SSTAR
system of small size with
long core life



- 1 - Core
- 2 - Steam Generator
- 3 - Pump
- 4 - Refueling Machine
- 5 - Reactor Vault

Collaborazione con USA

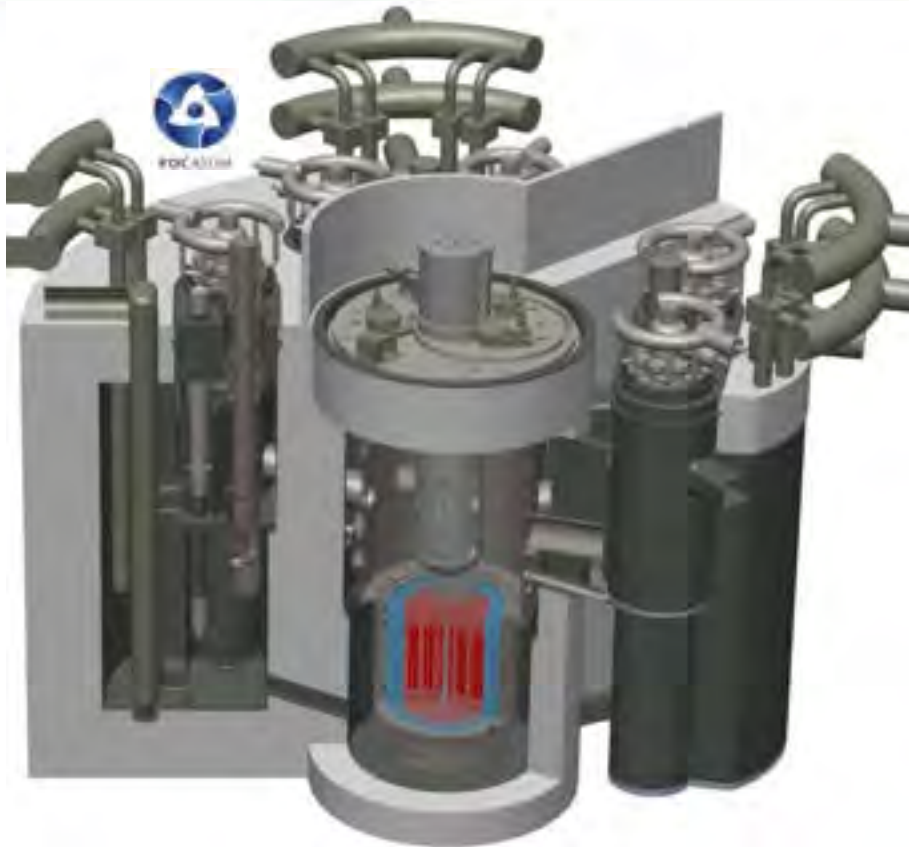


Fiscal Year 2016 Request: \$908M

- **Reactor Concepts** (\$108M)—Expands light water reactor sustainability efforts to maintain carbon free generation of the current fleet and supports development of non-water cooled reactor systems.
- **Small Modular Reactors** (\$63M)—Continues technical support for licensing SMRs.
- **STEP R&D** (\$5M) —Initiates multi-program effort to accelerate commercialization of sCO₂ Brayton cycle energy conversion technologies with a 10MW demonstration project.
- **Fuel Cycle R&D** (\$218M)—Expands effort to develop commercial used nuclear fuel disposal solutions; maintain schedule for 2016 selection of accident tolerant fuel candidates for further development and testing.
- **Nuclear Energy Enabling Technologies** (\$86M)—Continues Energy Innovation Hub for Modeling and Simulation for second 5-year period; advanced modeling and simulation for NE R&D programs.
- **Idaho National Laboratory** (\$338M) —Modernization of facilities and security capabilities.

- Nell'ambito dei bandi DOE 2016, WESTINGHOUSE ha applicato per una proposta LFR.
- L'unico partner non USA invitato a collaborare è stato ENEA
- ENEA partecipa alla proposta con una quota dell'8.5%
- Gli ambiti di partecipazione ENEA sono la progettazione del nocciolo e la tecnologia dei materiali
- Il consortium agreement tra ENEA e Westinghouse è attualmente in revisione presso ENEA

Collaborazione con la Russia



BREST-OD-300 SCHEDULE:

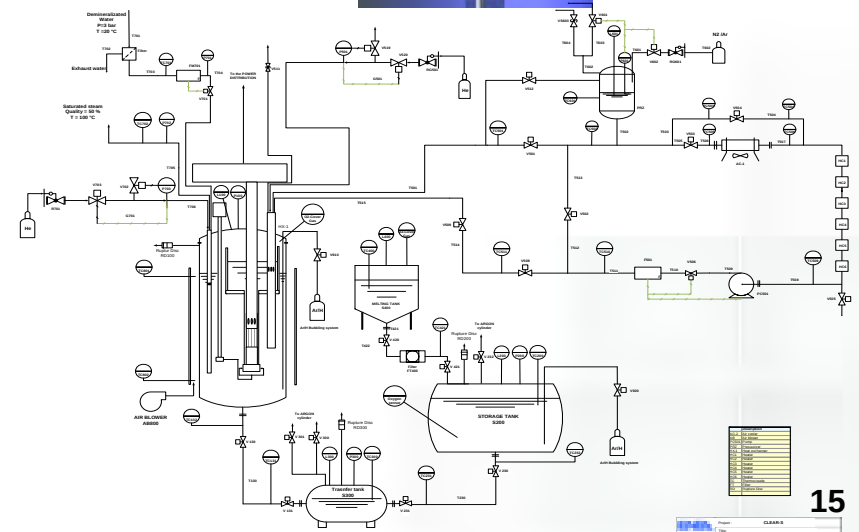
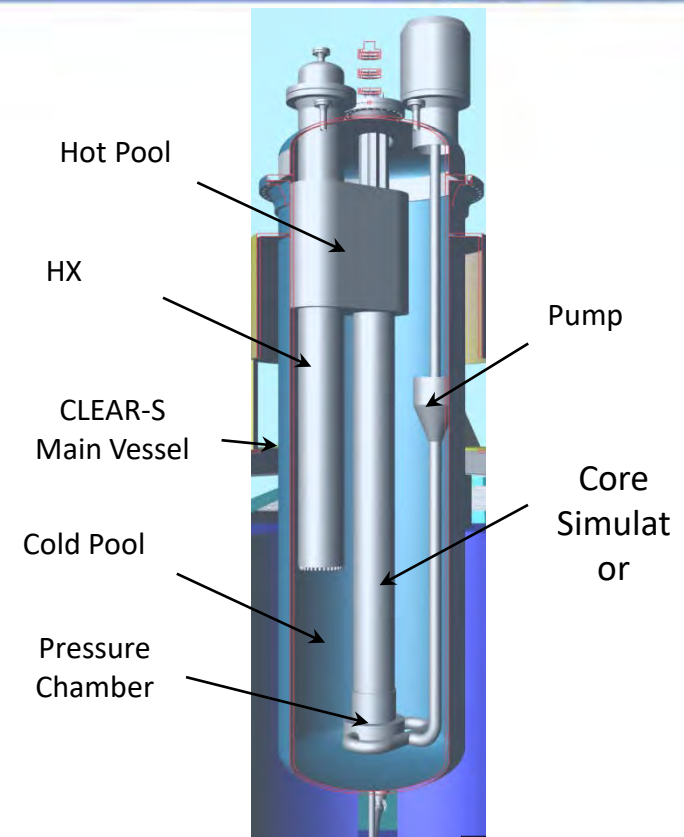
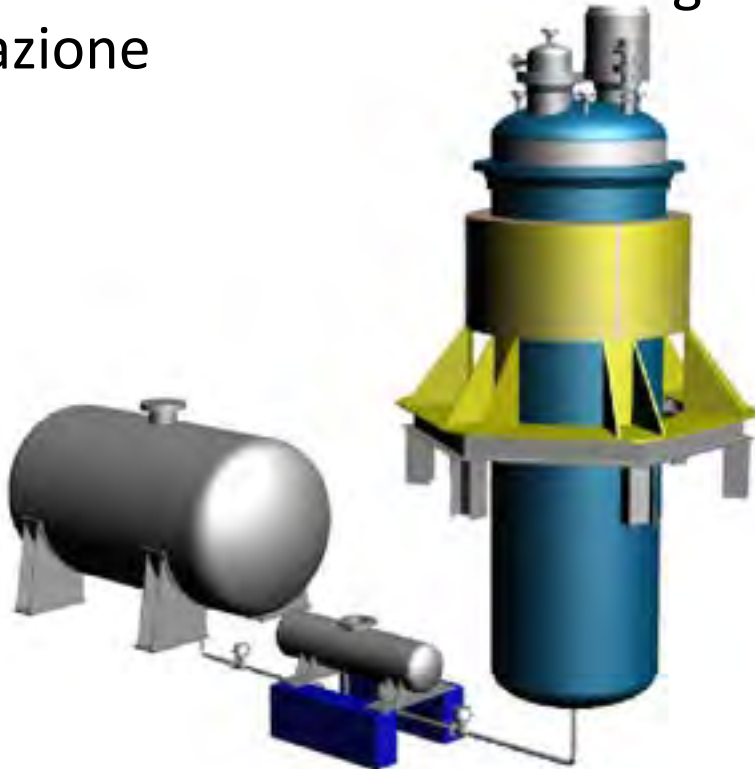
Design completed	2014
License approval	2015
Start of construction	2016
Commissioning	2020-2022

**Seminar on thermal-hydraulics of lead-cooled reactors
Ansaldo Nucleare HQs – December 2-3, 2015**

- Safety Approach for LFR.
- CFD modeling of mixing of heavy metal model flows
- 3D simulation of turbulent heat transfer in a swirling flow
- Study of partial blocking the flow cross section at the coolant inlet

Collaborazione con la Cina

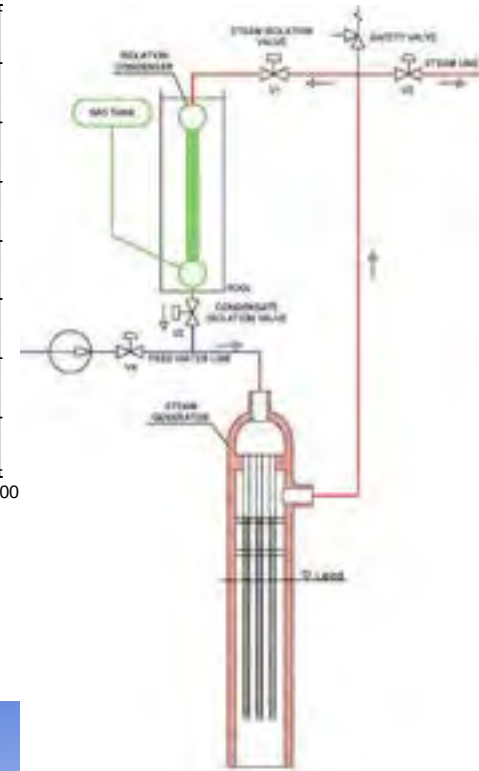
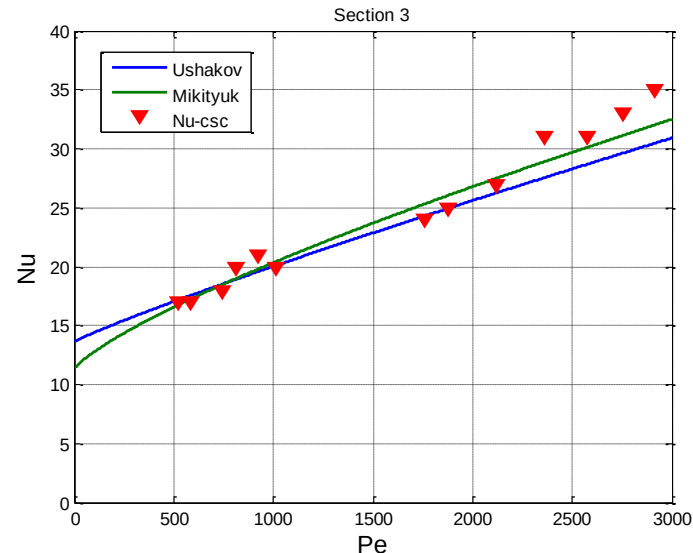
- ENEA Brasimone fornirà all' Accademia Cinese delle Scienze nel 2016 l'impianto CLEAR-S per la qualificazione sperimentale del prototipo di trasmutatore CLEAR I.
- La fornitura ha un valore di circa 6 Meuro
- L'accordo comprende anche assistenza nella fase di commissioning e sperimentazione nonché nella definizione della strategia di sperimentazione



Prospettive tecnologiche

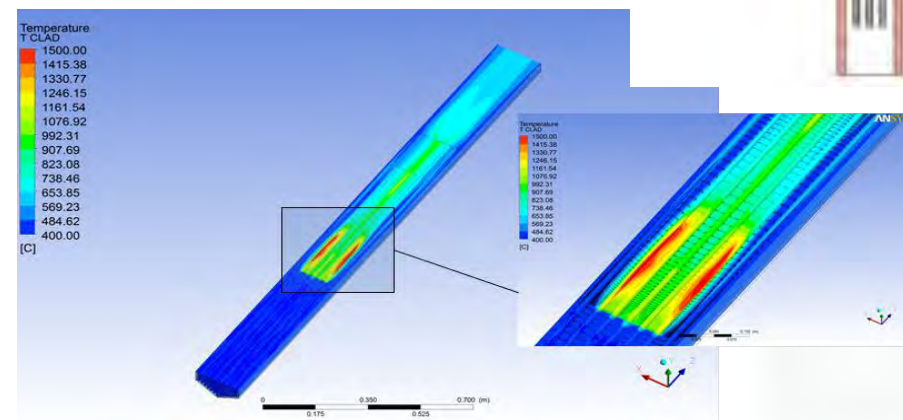
Termoidraulica

- Dal 2008 ad oggi sono state risolte molte incertezze grazie agli impianti del Brasimone.
- In particolare sono state fatte misure del numero di Nusselt ed è stata dimostrata l'efficacia di raffreddamento della convezione naturale in condizioni di emergenza.
- Sono stati validati i codici di calcolo termofluidodinamico rendendo credibile l'impiego di tali strumenti



Le prospettive future riguardano argomenti mirati a dimostrare la sicurezza del LFR :

- La dimostrazione dei dispositivi di emergenza (isolation condenser e DHX)
- L'approfondimento delle conseguenze del freezing e misure correttive
- L'approfondimento del flow blockage



Materiali

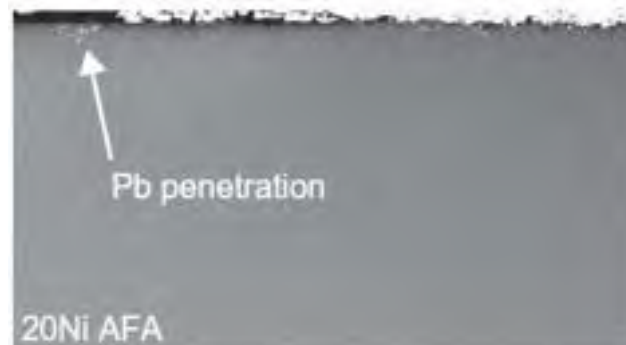
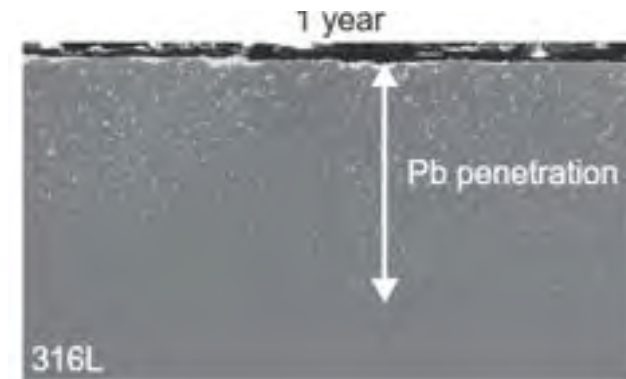
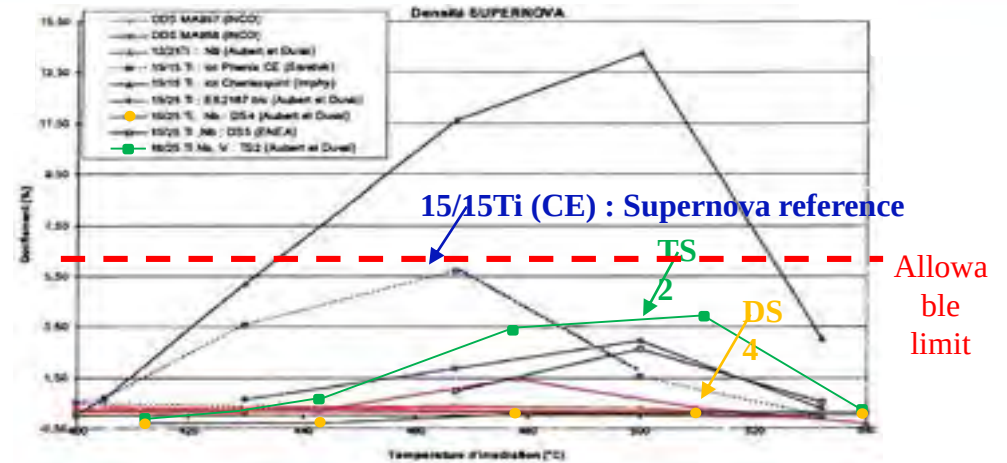
- Sono state condotte numerose ricerche, soprattutto nel progetto **MATTER** ed in **AdP**.
- Le ricerche hanno evidenziato **quali acciai escludere dal LFR** anziché identificare i materiali atti a fornire tutte le garanzie necessarie.
- La **scelta dei materiali** costituisce tuttora la maggiore incertezza di un reattore LFR.
- **L'assenza di efficaci facility di irraggiamento** rende arduo questo compito.
- La protezione delle camicie dalla corrosione è effettuata tramite un **rivestimento superficiale**

PROSPETTIVE

L'acciaio dei fuel cladding è il 15-15 Ti, in quanto qualificato, ma si tende ad un **austenitico a basso swelling**.

L'acciaio dei componenti (GV) è il 316 ma si tende ad un **AFA**.

Ancora **R&D da condurre** e necessità di facility di irraggiamento.





DEMO-LFR ALFRED: Technical Overview

WORKSHOP LFR-GEN IV - STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO

Brasimone, 19-20 Novembre, 2015 - Centro Ricerche ENEA Brasimone

Michele Iamele

Michele.iamele@ann.ansaldo.it



CONTENTS

- Introduction and Design Guidelines
- Overview of Main Primary System Components
 - Reactor Assembly Configuration
 - Reactor Vessel
 - Inner Vessel and Upper/Lower Core Support Plates
 - Steam Generator
 - Primary Pump
 - Decay Heat Removal Systems
 - Reactor Building
- Conclusions & Open issues



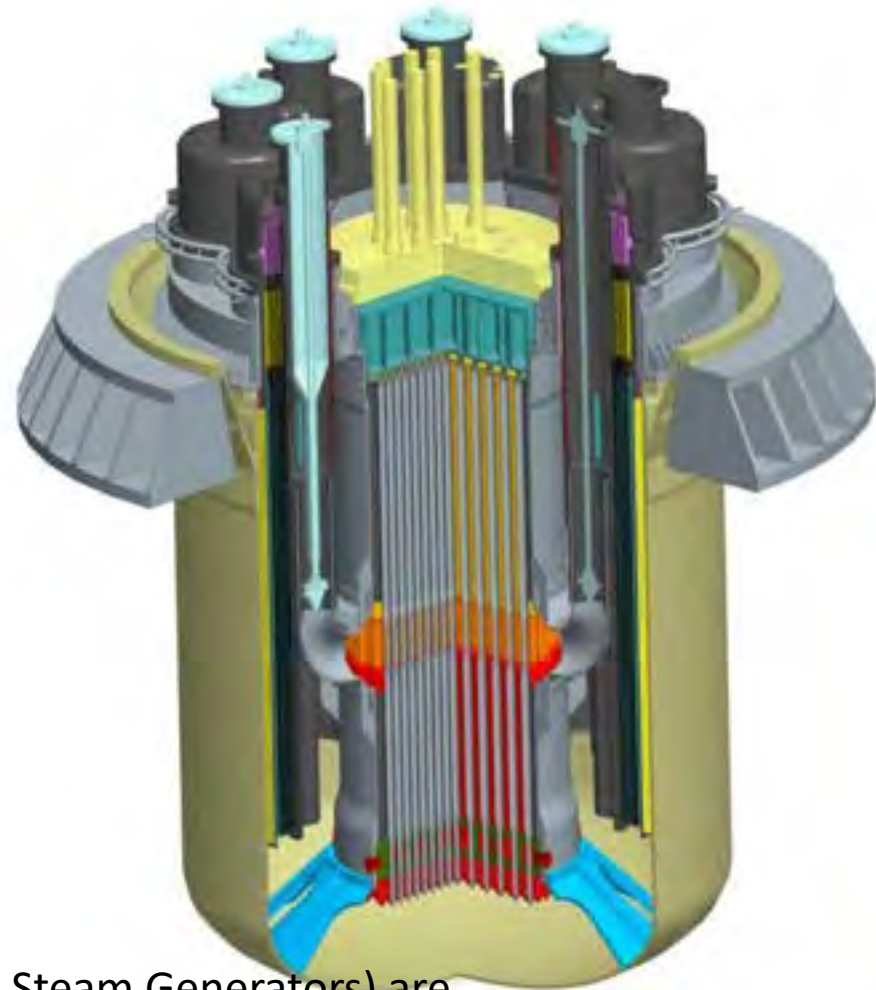
Main Design Guidelines

Top-level Technical Requirements

- ALFRED will be connected to the electrical grid (Reactor Power ~130 MWe)
- ALFRED design should be based on available technology as much as possible, in order to speed up the construction time
- ALFRED shall use structural materials compatible with the corrosive Lead used as coolant (Selected material AISI 316LN, T91, 15-15/Ti)
- ALFRED design shall limit coolant flow velocity to values compatible with the erosive Lead used as coolant
- ALFRED design solutions shall allow components to be removed from the Reactor Vessel to facilitate inspection, maintenance, replacement
- ALFRED design solutions (especially for Safety and Decay Heat Removal function) should be characterized by very robust and reliable choices to smooth the licensing process
- ALFRED Decay Heat Removal Systems shall be based on passive technology to reach the expected high Safety level



- Pool type primary system
- Relatively Low Power: 300 MWth (130 Mwe)
- Compact Design based on:
 - simple and removable components
 - proven technologies and materials
- The primary coolant is molten lead, which is characterized by good Nuclear and chemical properties
- The hot pool is enclosed by the Inner Vessel that feeds the suction pipes of the Primary Pumps and Steam Generators integrated into a single vertical unit.
- The Reactor assembly presents a simple flow path of the primary coolant, the position of the heat source (the Core) and the heat sink (the Steam Generators) are studied to allow an efficient natural circulation of the coolant.

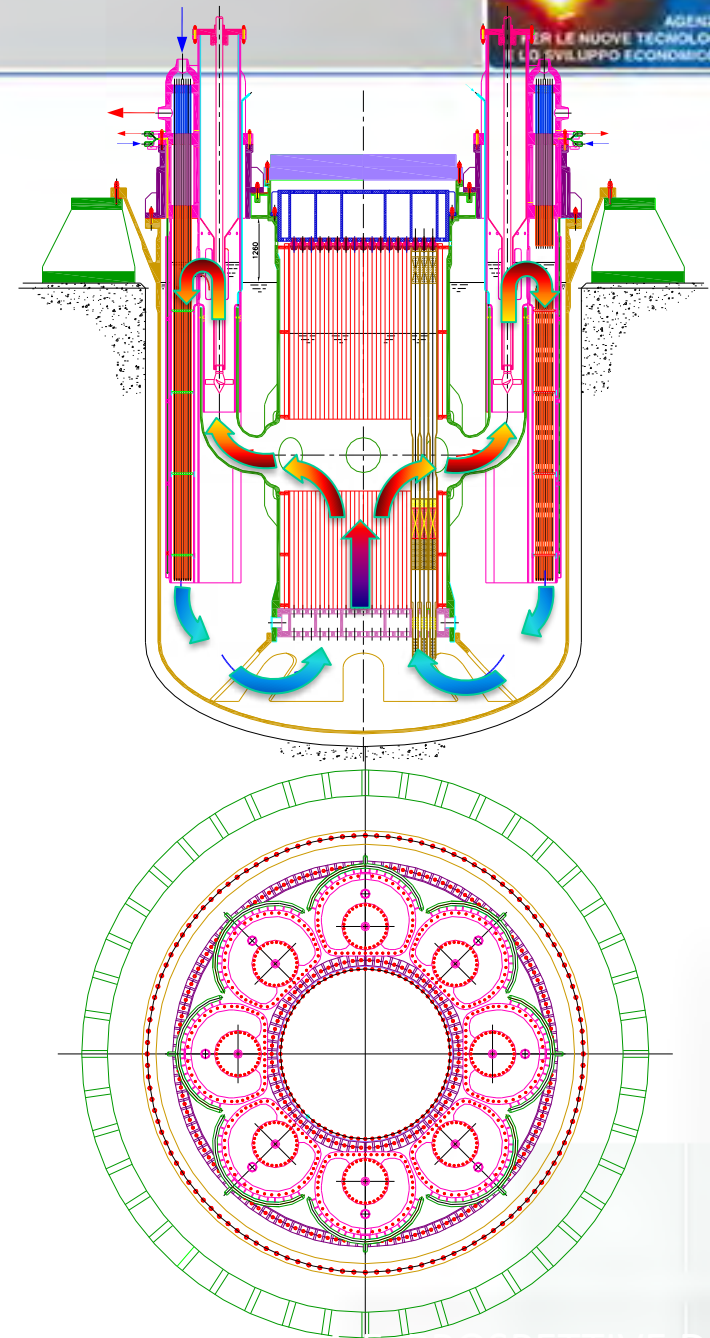


ALFRED - Reactor Configuration from LEADER



Main Design Data

Core power / Electrical Power	300 MW _t / 130 Mwe
Primary Coolant	Pure Lead
Reactor vessel	Austenitic SS Height = 10,7 m Inner diameter = 8 m
Safety Vessel	Anchored to reactor pit
Inner Vessel	Cylindrical, Height = 9.7 m Inner diameter = 3.3 m
Core Inlet/Outlet Temperatures	400° C / 480° C
Steam generators	8 units, bayonet tubes type, integrated in the reactor vessel, removable
Fuel Assembly	Closed (with wrapper), Hexagonal,
Refuelling System	No refuelling machine stored inside the Reactor Vessel
DHR System	2 separate and redundant systems of 4 Isolation Condensers connected to the Steam Generator (actively actuated, passively operated)

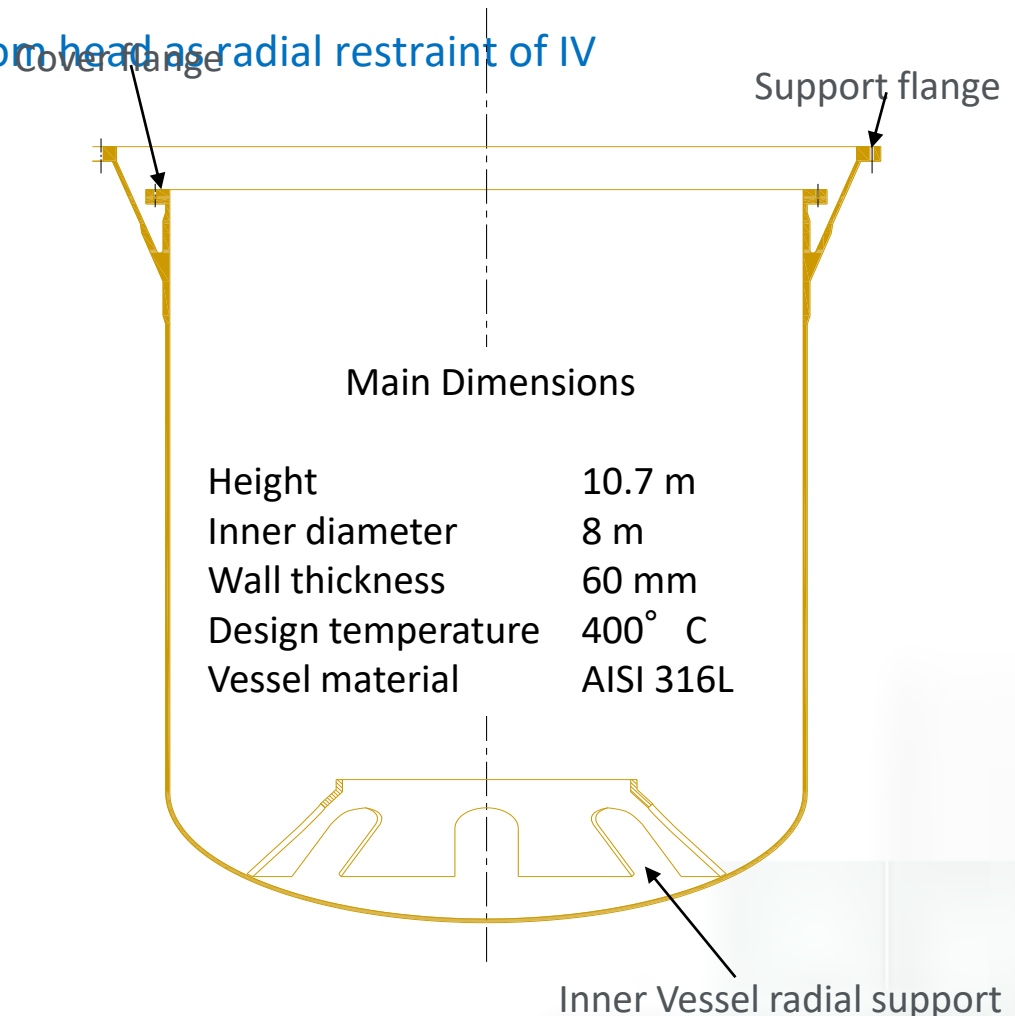


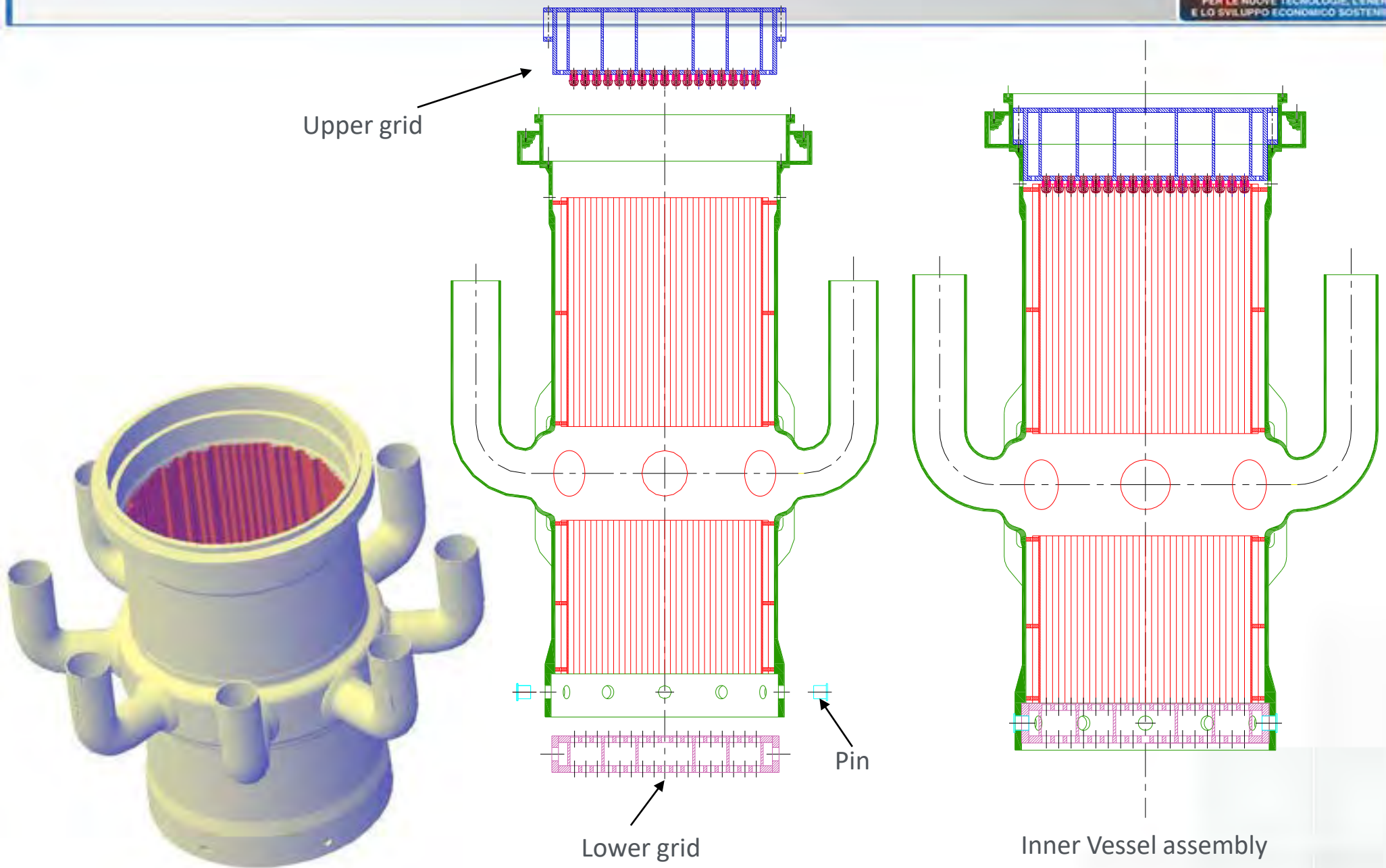
Cylindrical with a torospherical bottom head anchored to reactor pit from top

RV closed by a roof supporting core and all primary components

RV upper part divided in two branches by a "Y" junction: the conical skirt (cold) supporting weight and the cylindrical (hot) supporting the Reactor Cover

Cone frustum welded to the bottom head as radial restraint of IV





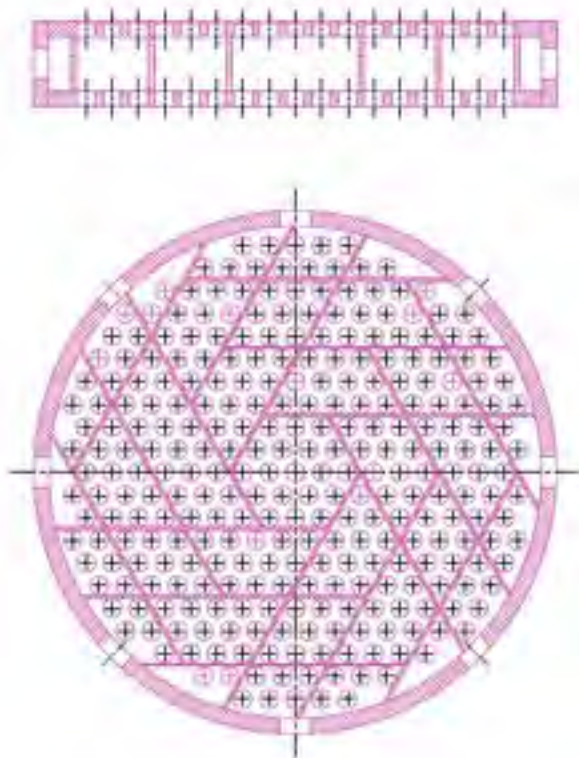
UPPER AND LOWER CORE SUPPORT PLATES

Lower core support plate

Box structure with two horizontal perforated plates connected by vertical plates.

Plates holes are the housing of FAs foots.

The plates distance assures the verticality of FAs

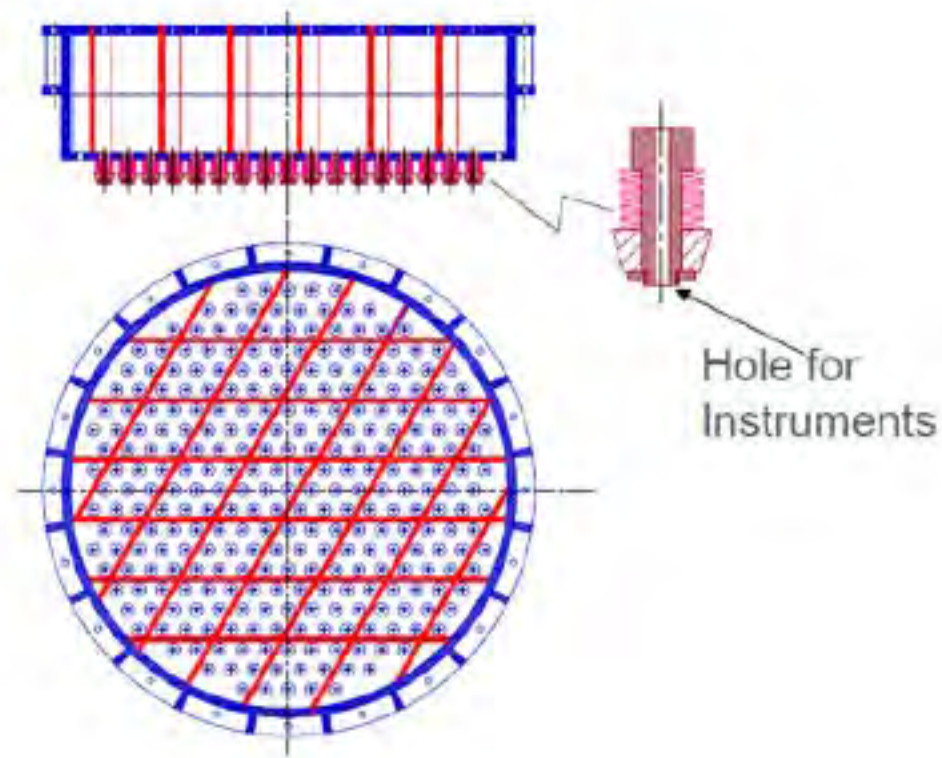


Upper core support plate

Box structure as lower grid but more stiff

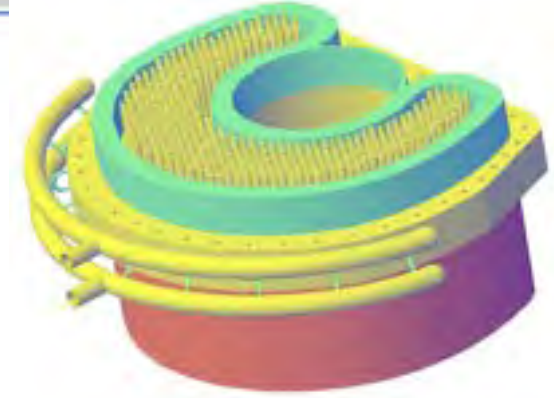
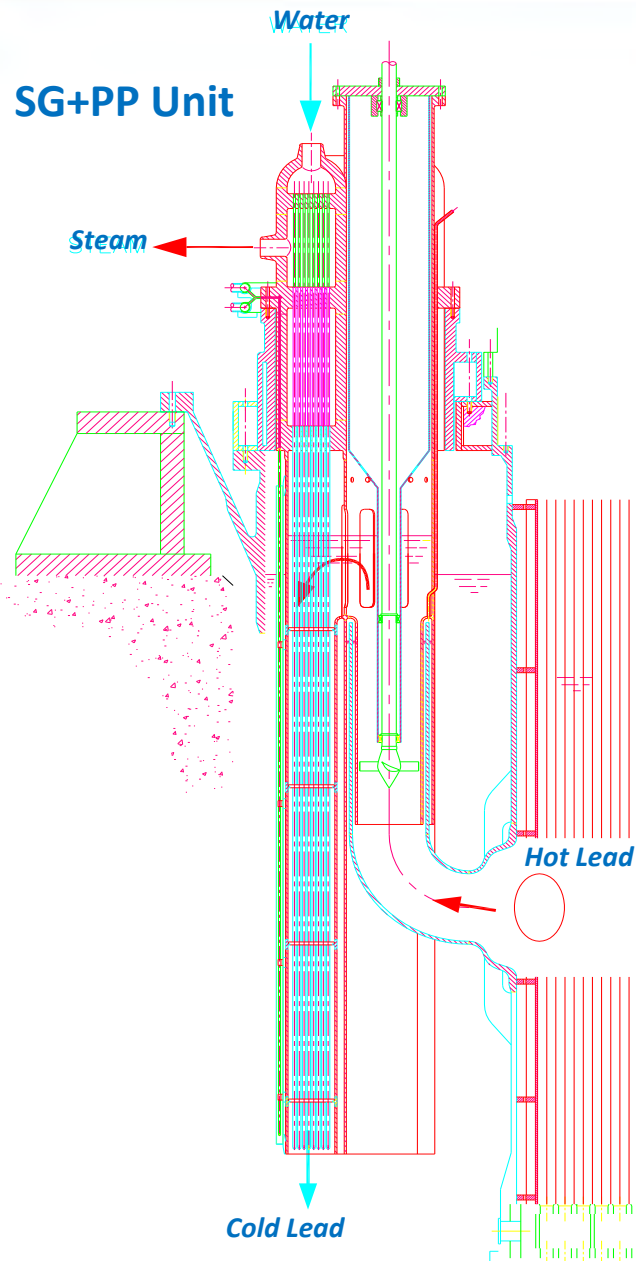
It has the function to push down the FAs during the reactor operation

A series of preloaded disk springs presses each FA on its lower housing

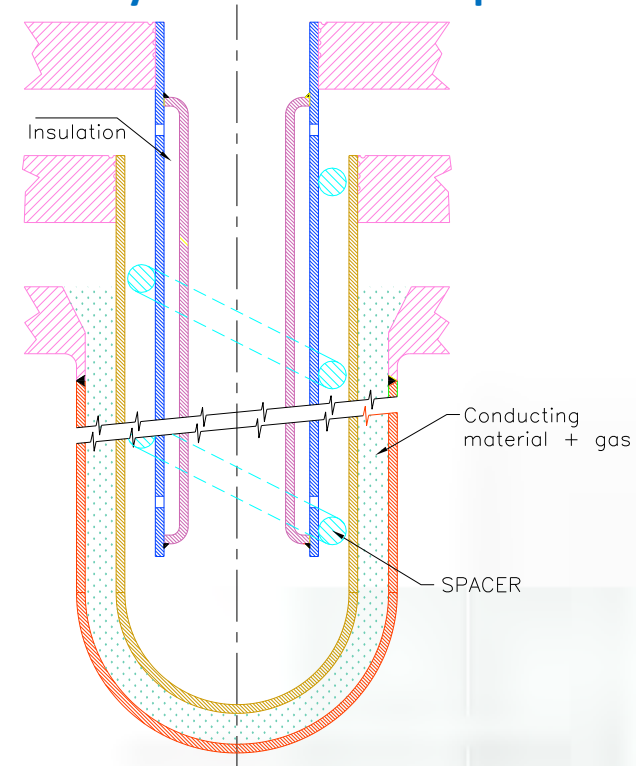


STEAM GENERATOR

Auxiliary cooling collector



Bayonet Tube Concept





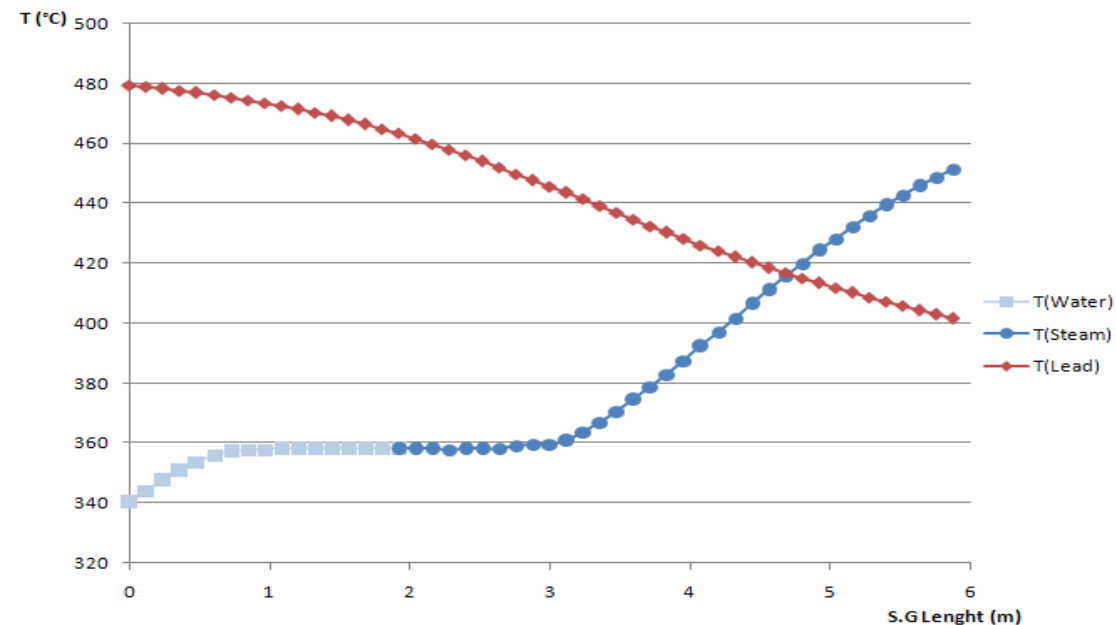
Steam Generator Geometry

Number of coaxial tubes	4
Slave tube O.D	9.52 mm
Slave tube thickness	1.07 mm
Inner tube O.D	19.05 mm
Inner tube thickness	1.88 mm
Outer tube O.D	25.4 mm
Outer tube thickness	1.88 mm
Outermost tube O.D	31.73 mm
Outermost tube thickness	2.11 mm
Length of exchange	6 m
Number of tubes	510

Steam Generator Performance

Removed Power [MW]	37.5
Core outlet Lead Temperature [°C]	480.0
Core inlet Lead Temperature [°C]	401.5
Feedwater Temperature [°C]	335.0
Immersed bayonet steam outlet T [°C]	451.5
Steam Plenum Temperature [°C]	450.1
SG steam/water side global Δp [bar]	3.3

Steam Generator Thermal Cycle



Primary pump is an axial mechanical pump, always running at constant speed, with blade profile designed to achieve the best efficiency



Parameters	Value
Flow rate	3247.5 kg/s
Head	1.5 m
Outside impeller diameter	0.59 m
Hub diameter	0.39 m
Impeller speed	315 rpm
Number of vanes	5
Vane profile	NACA 23012
Suction pipe velocity	1.12 m/s
Vanes tip velocity	9.8 m/s
Meridian (at impeller entrance and exit) velocity	2.0 m/s

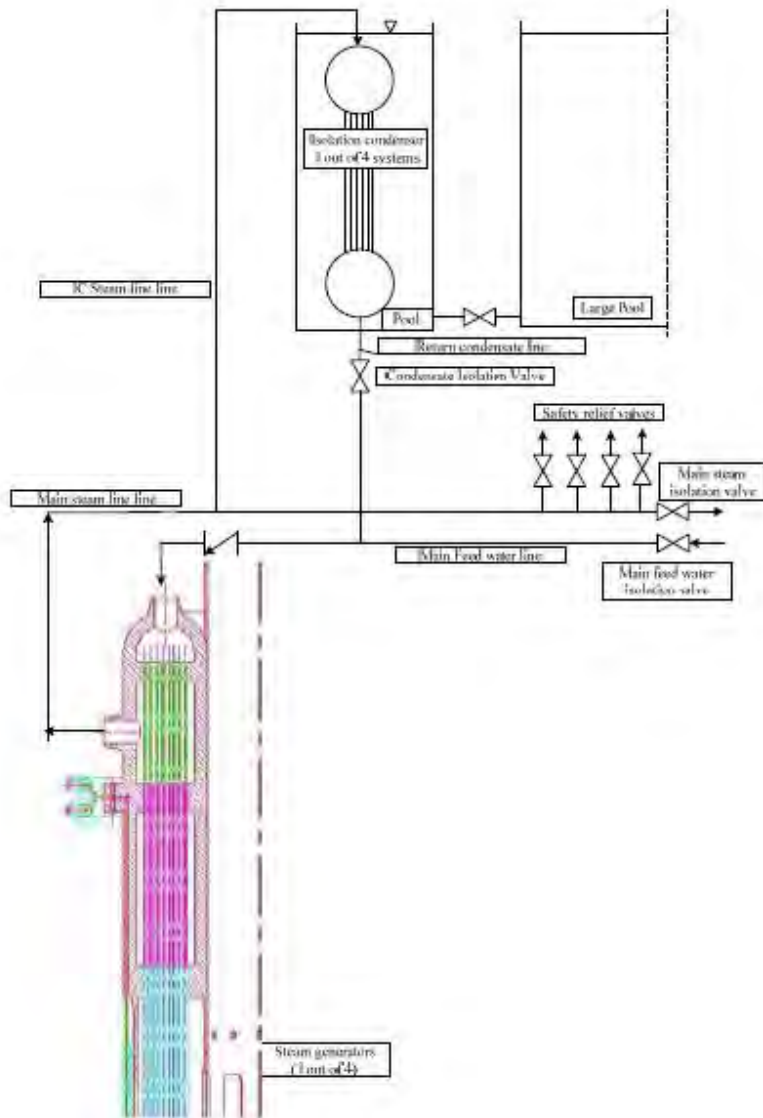
DHR Systems

One non safety-grade system, the secondary system, used for normal decay heat removal

Two independent, high reliable passive and redundant safety-related DHR systems:

in case of unavailability of the secondary system, the DHR1 is called to operate and

in the unlikely event of unavailability of the first two systems, the DHR2 is called to operate



DHR-1:

Isolation Condenser system connected to 4 out of 8 SGs

DHR-2:

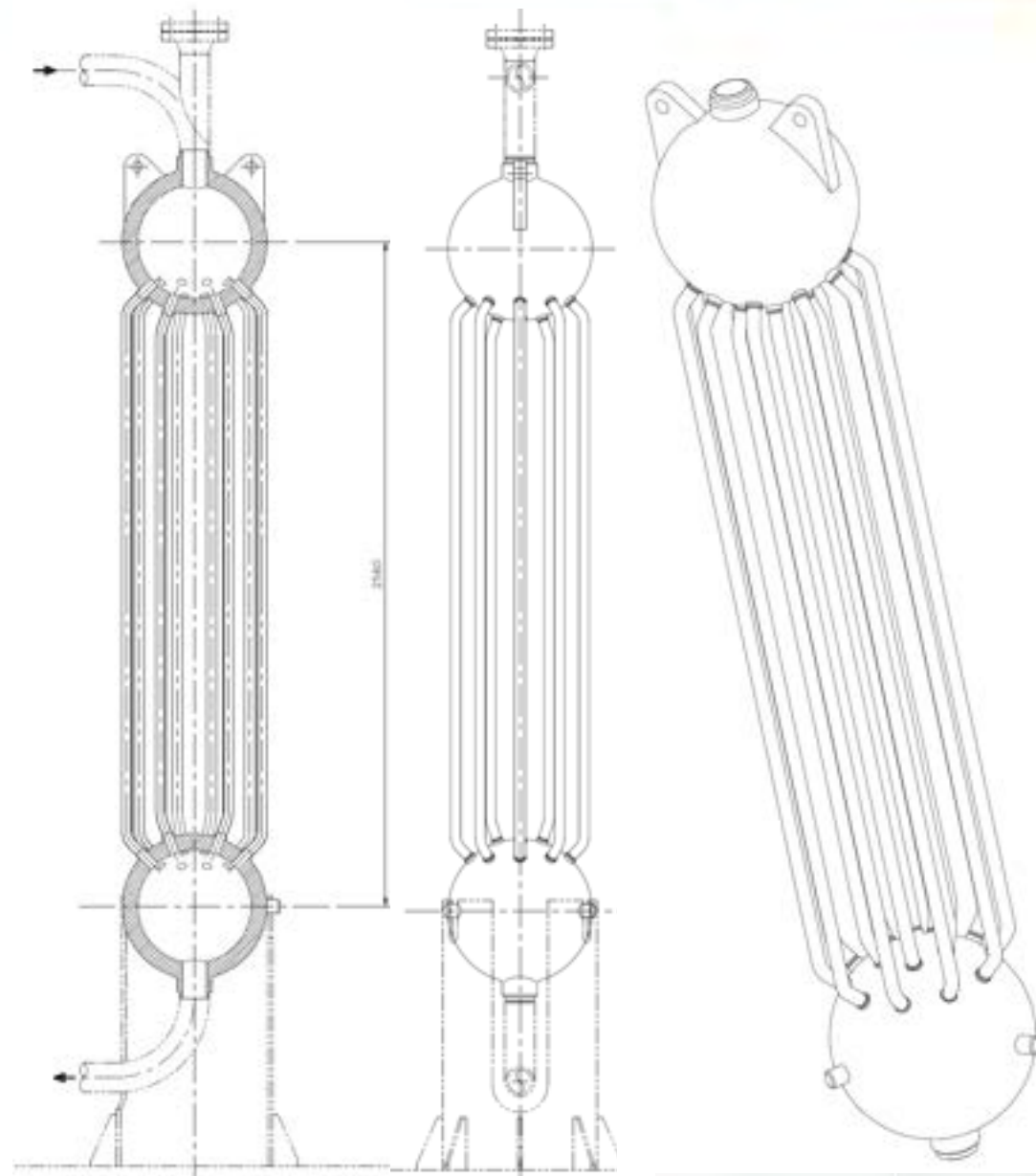
Isolation Condenser system connected to the other 4 SGs

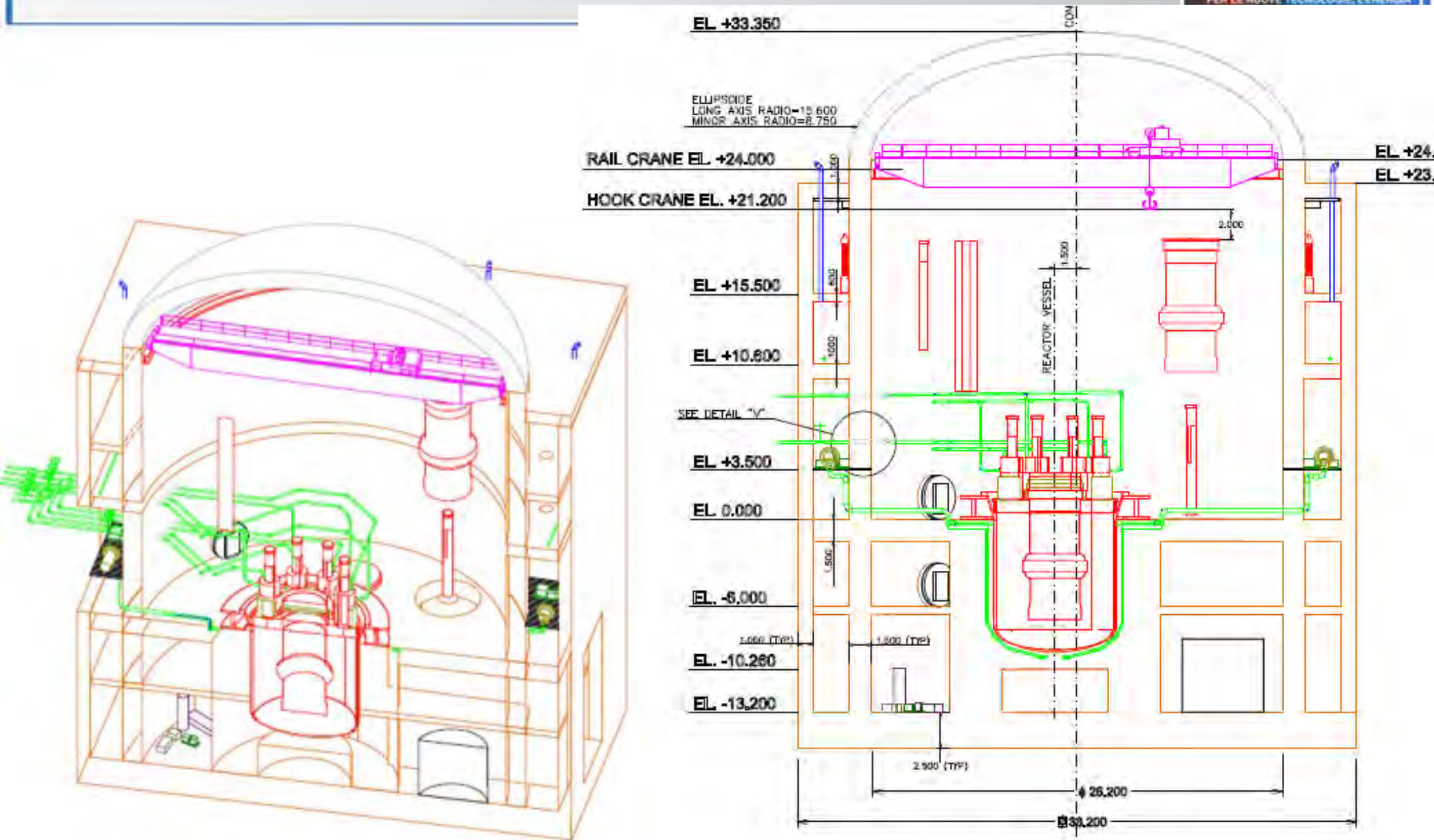
Considering that, each SG is continuously **monitored**, ALFRED is a **demonstrator** and a redundancy of **266%** is maintained, the Diversity concept could be relaxed

DHR Systems features:

- **Independence:** two different systems with nothing in common
- **Redundancy:** three out of four loops (of each system) sufficient to fulfil the DHR safety function even if a single failure occurs
- **Passivity:** using gravity to operate the system (no need of AC power)

Parameter	Value
Upper and lower spherical header diameter	560 mm
Tube diameter	38.1 mm
Number of tubes	16
Average tube length	2 m
Material Inconel	600





ALFRED Technical Review...

Open issues that need to be carefully addressed before defining the reference conceptual design:

- Upper part of the “cold plenum” could result stagnant

 - Stratification

 - Smaller fluid volume participating to the natural circulation phase

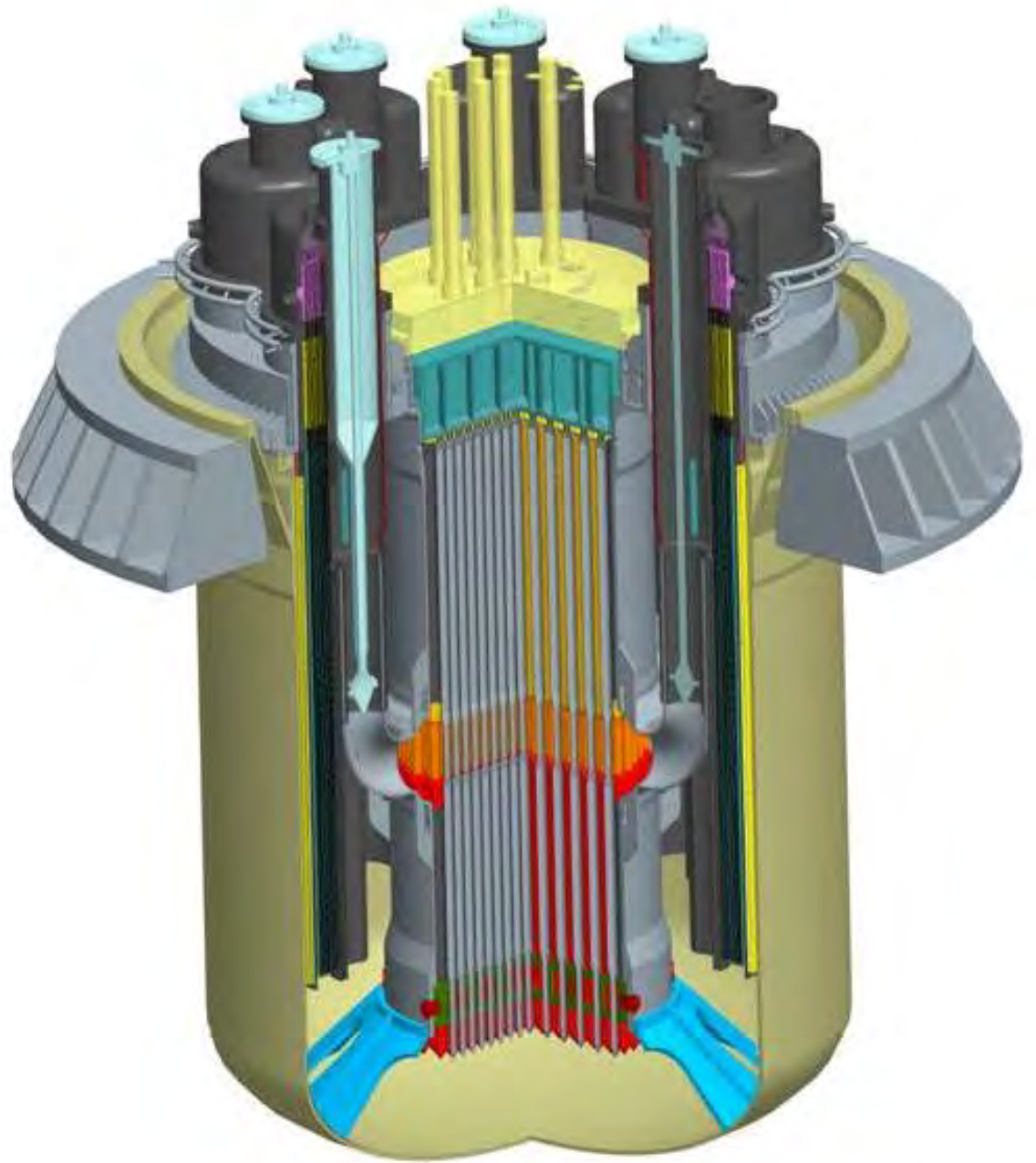
 - Oxygen/Chemical Control Issue

- SG design: by pass flow & mechanical issues.

- Need of two diverse DHR systems

The LEADER Project was able to give a reference configuration but much work has yet to be done before a final configuration is available.

*Thank you
for your attention*





TAPIRO Fast Reactor.

Feasibility study of minor actinides irradiation campaign

M. Carta*, P. Console Camprini, V. Fabrizio, A. Grossi, V. Peluso (ENEA)

P. Blaise, B. Geslot, A. Gruel (CEA)

F. Boccia (Università di Roma "La Sapienza")

C. Bethaz (Politecnico di Torino)

[*mario.carta@enea.it](mailto:mario.carta@enea.it)





Background



- The reduction of the nuclear waste is one of the most important nuclear issues.
- The high radiotoxicity of the spent fuel is due to plutonium and some minor actinides (MAs) such as neptunium, americium and curium, above all.
- To allow the MAs destruction an important effort have been done on the nuclear data due to the poor knowledge in this field.
- To improve MAs nuclear data, in the framework of the second *NEA Expert Group on Integral Experiments for Minor Actinide Management* an analysis of the feasibility of MAs irradiation campaign in the TAPIRO fast research reactor is in progress. The work is performed in close collaboration with *CEA*.
- Some preliminary results have been obtained by calculations modelling the irradiation, in different TAPIRO irradiation channels, of some CEA samples coming from the French experimental campaign *OSMOSE*.
- On the basis of neutron transport calculation results, obtained by both deterministic *ERANOS* and Monte Carlo *Serpent* calculation tools, an estimate of the irradiated samples counting levels has been obtained.
- The experimental campaign is named *AOSTA* (*Activation of OSMOSE Samples in TAPIRO*).



Background



Time integrated flux

$$\bar{\phi} T \sim \left[\frac{N_{Nd8}(T)}{N_{U5}(T)} \right]_m \frac{1}{\gamma_{Nd8} \bar{\sigma}_{U5}^f}$$

At TAPIRO core center this value is $1.265 \pm 3.5\%$ (barns).

MA capture x-section

$$\left[\frac{N_{A+1}(T)}{N_A(T)} \right]_m \equiv [R_{A+1}(T)]_m$$

$$\bar{\sigma}_A^c \sim \frac{[R_{A+1}(T)]_m - [R_{A+1}(0)]_m}{[\bar{\phi} T]_m}$$

Reasonable irradiation times?

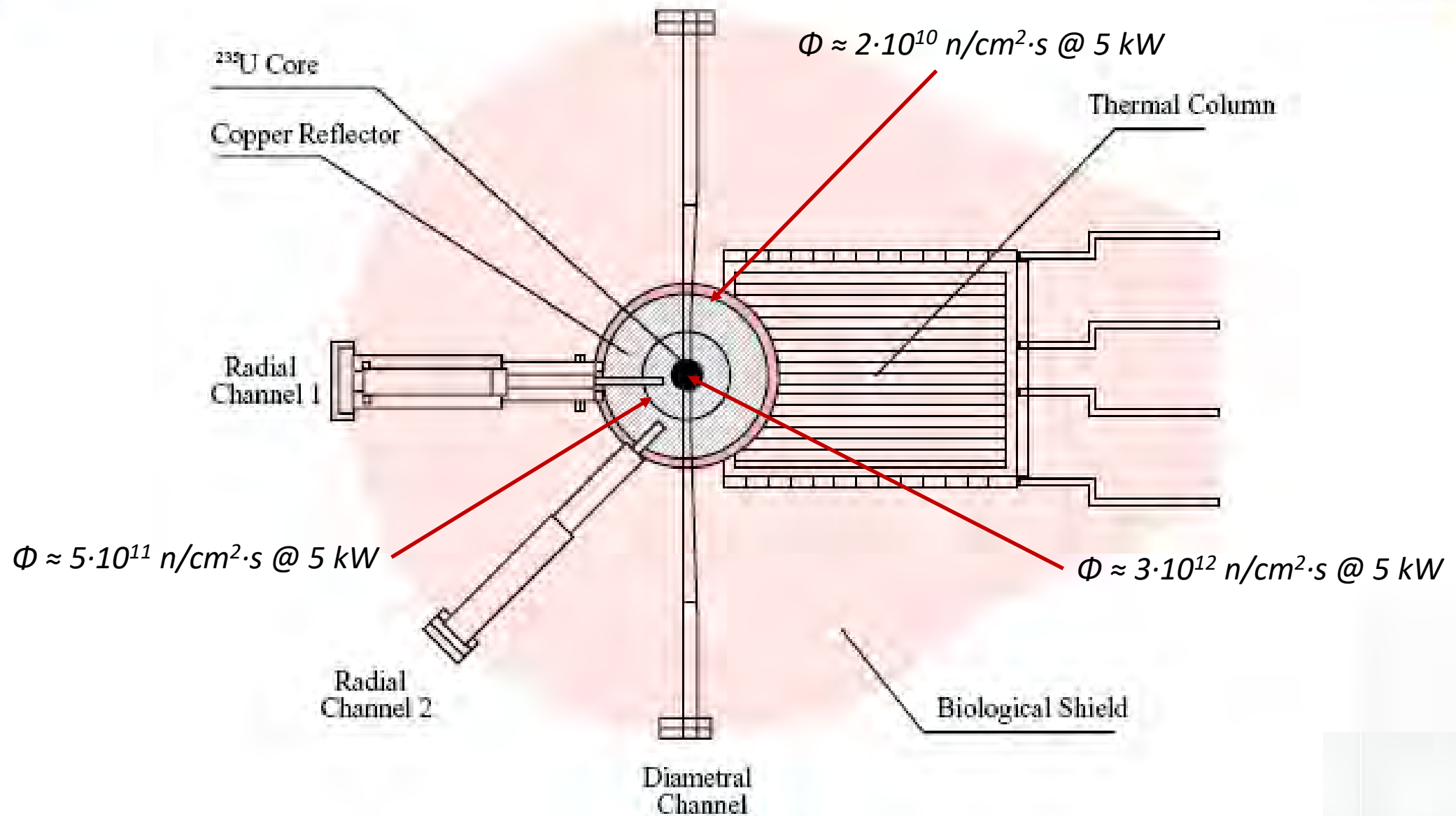
$$\bar{\sigma}_{A+1}^c \sim 2 \frac{[R_{A+2}(T)]_m}{[R_{A+1}(T)]_m [\bar{\phi} T]_m}$$

$$\bar{\sigma}_{A+2}^c \sim 3 \frac{[R_{A+3}(T)]_m}{[R_{A+2}(T)]_m [\bar{\phi} T]_m}$$



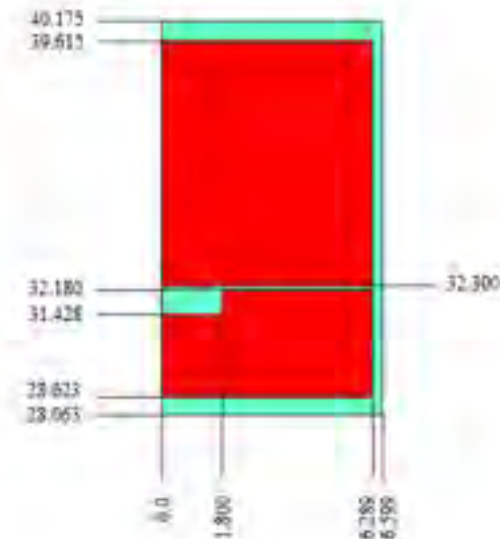
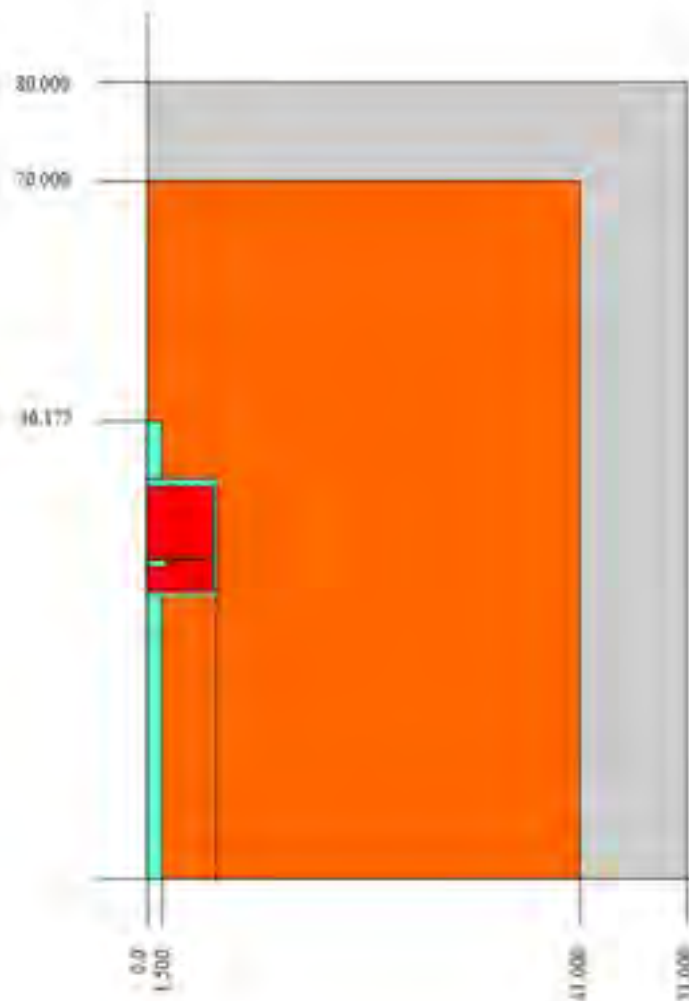
The TAPIRO reactor

Main characteristics





The TAPIRO reactor ERANOS RZ model



***TAPIRO is a simple system to model in view of benchmarking
among calculation tools and data libraries (IRPhE)***



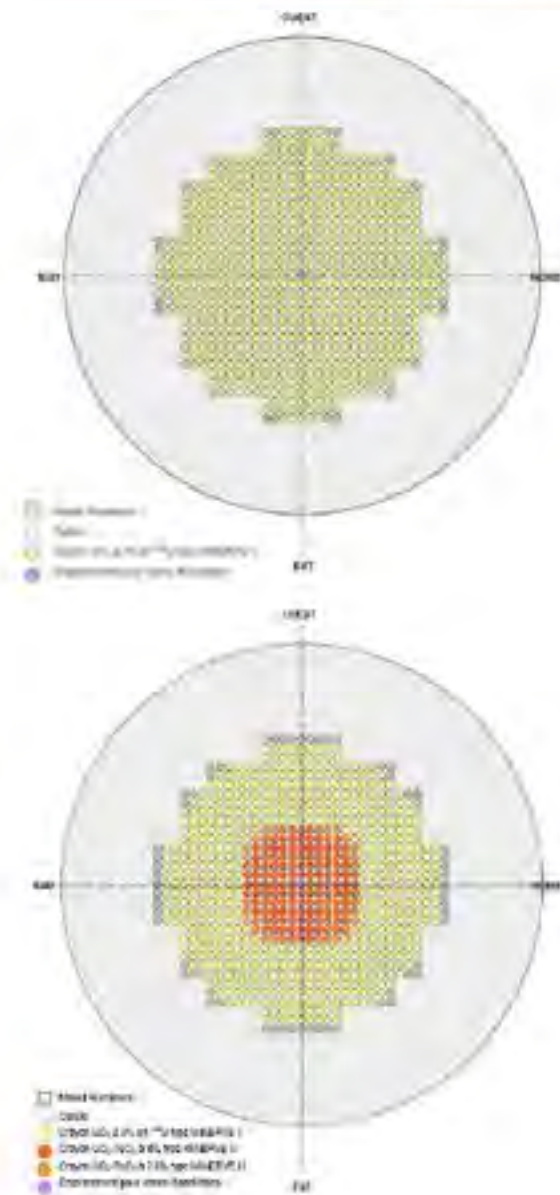
TAPIRO channels and OSMOSE samples

The OSMOSE programme



The OSMOSE programme in MINERVE

- Sample oscillation programme in MINERVE (2005 – 2010)
- In collaboration with DOE (INERI collaboration)
- Objectives :
 - Pu recycling in LWR
 - MA transmutation
 - Waste disposal and storage
- Two MINERVE configurations:
 - R1-UO₂ (REP-UO₂ spectrum)
 - R1-MOX (REP-MOX spectrum)
 - An over-moderated spectrum was foreseen but abandoned
- Main benefit: uncertainty reduction on nuclear cross sections of ²³⁷Np, ²³⁸Pu, ²⁴²Pu, ²⁴¹Am, ²⁴³Am et ²⁴⁵Cm
- Sample Manufacturing (CEA Marcoule):
 - UO₂ or U₃O₈ pills (sintered or compacted)
 - Reprocessed uranium
 - Pure ThO₂





TAPIRO channels and OSMOSE samples

OSMOSE samples



Dimensions

- Internal sheath (Zy4): 9,56 mm
- External sheath (Zy4): 10,6 mm
- Length : 103.5 mm



Precise Material certificate are available

Actinide	Sample n°1 (g)	Sample n°2 (g)	Matrix
Unat	48	/	/
Np237	0.1	0.6	UO2 nat
Pu242	0.5	/	UO2 nat
U236	0.6	2	UO2 nat
Am241	0.06	0.2	UO2 nat
Am243	0.1	0.5	UO2 nat
U234	0.3	/	UO2 nat
Pu238	0.4	/	UO2 nat
Pu240	0.15	/	UO2 nat
Pu239	0.6	/	UO2 nat
U233	0.5	/	UO2 nat
Th232	2	/	UO2 nat
Th232	48	/	/
Pu241	0.1	0.5	UO2 nat



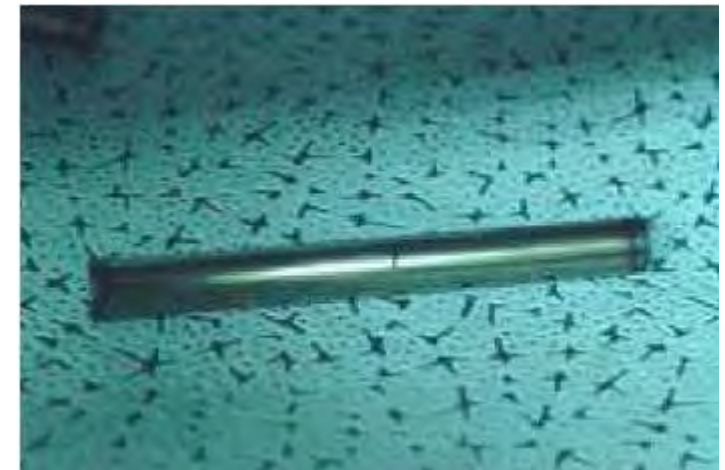
TAPIRO channels and OSMOSE samples Compatibility



Name	Position	Penetration	Useful diameter
Diametral channel (D.C.)	Piercing. Horizontal. Diametral in the core.	Inner and outer fixed reflector. Core.	10 mm in core
Tangential channel	Piercing. Horizontal. 50 mm above core mid-plane. Parallel to D.C. 106 mm from core axis.	Inner and outer fixed reflector.	30 mm in reflector
Radial channel 1 (R.C.1)	Radial. Horizontal on core mid-plane, at 90° with respect to D.C.	Inner and outer fixed reflector, up to 93 mm from core axis.	56 mm in reflector
Radial channel 2	Radial. Horizontal on core mid-plane, at 50° with respect to R.C.1.	Outer fixed reflector, up to 228 mm from core axis.	80 mm in reflector
Grand Horizontal Channel (G.H.C.)	Radial. Concentric with R.C.1.	Up to reflector outer surface	400 mm near reflector
Grand Vertical Channel (G.V.C.)	Above core, on the same axis.	Outer fixed reflector, up to 100 mm from upper core base.	800 ÷ 900 mm in reflector
Thermal column	Horizontal.	Shield, up to outer reflector	110x116x160 cm ³
Irradiation cavity	On safety plug upper base.	7.4 mm	33 mm

Dimensions

- Internal sheath (Zy4): 9,56 mm
- External sheath (Zy4): 10,6 mm
- Length : 103.5 mm



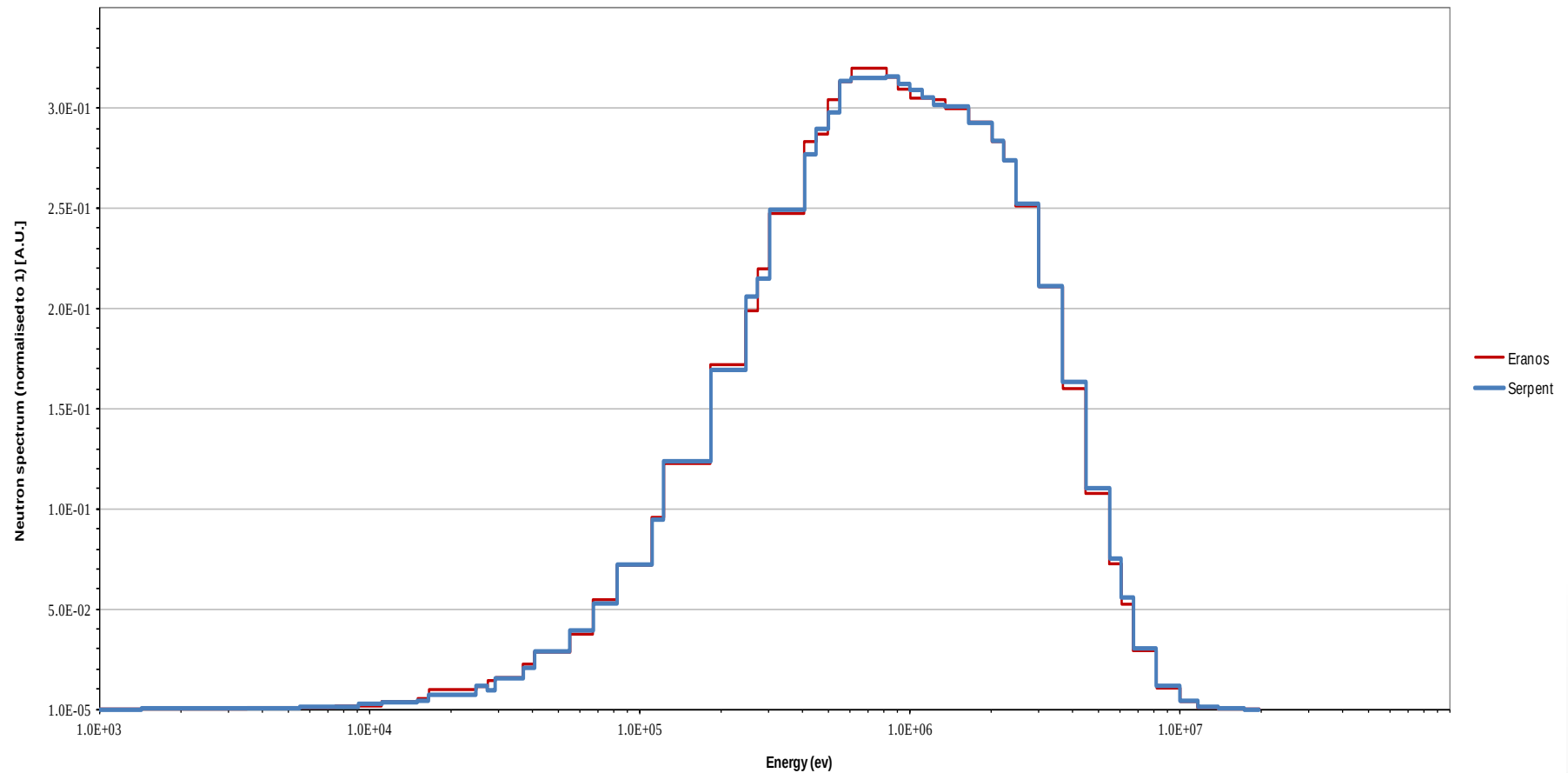


TAPIRO neutronic field analyses

ERANOS vs. Serpent



CORE CENTER ERANOS/SERPENT COMPARISON



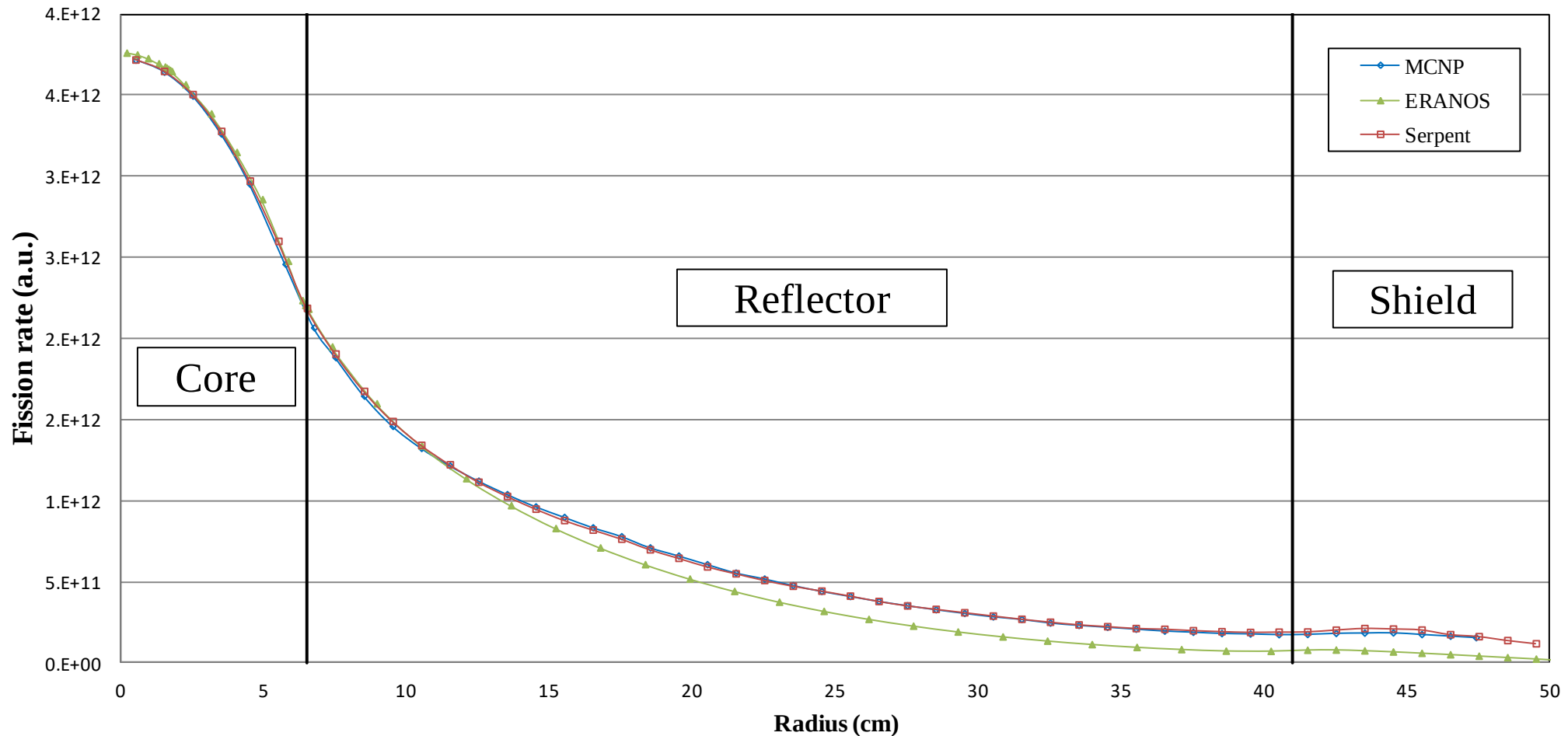


TAPIRO neutronic field analyses

ERANOS vs. Serpent/MCNP



Fission Rate U^{235} diametral channel



Per i risultati MCNP si ringrazia il CRESCO team, nelle persone dei colleghi Guido Guarnieri e Agostino Funel, che sono stati di grande supporto nella preparazione e ottimizzazione dell'ambiente di calcolo CRESCO per MCNP.



TAPIRO neutronic field analyses

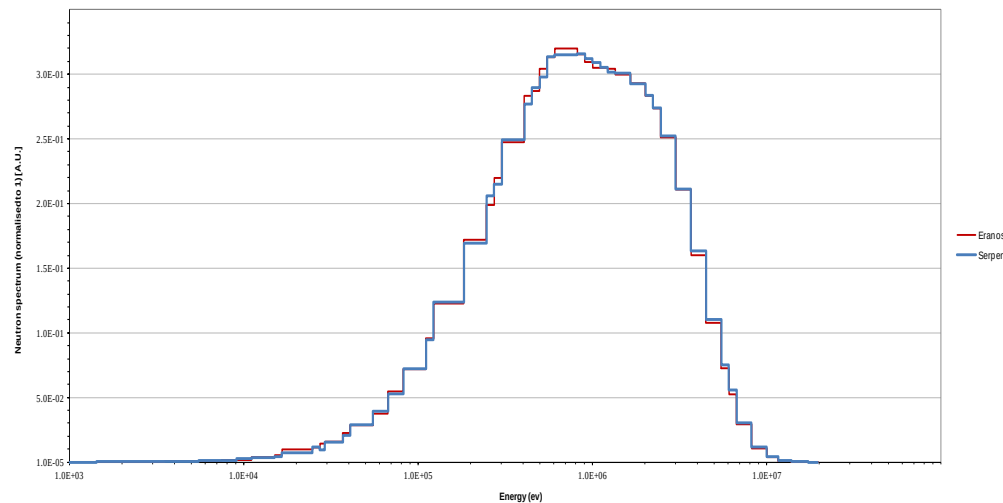
Average capture cross sections (JEFF 3.1)



$$\overline{\sigma_c(\mathbf{r})} = \frac{\langle \sigma_c(\mathbf{r}, E) \phi(\mathbf{r}, E) \rangle_E}{\langle \phi(\mathbf{r}, E) \rangle_E}$$



CORE CENTER ERANOS/SERPENT COMPARISON

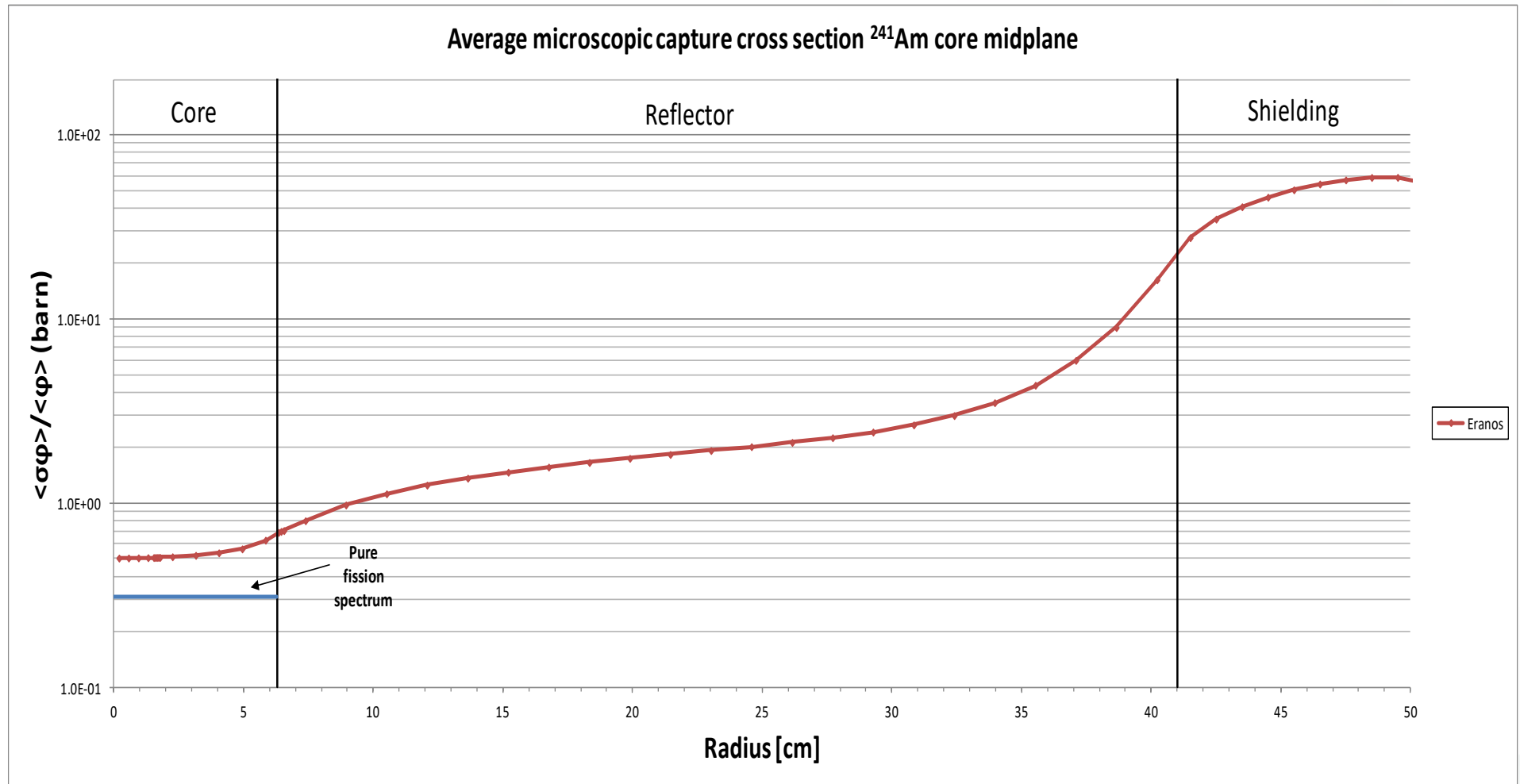


Isotopes considered: Np^{237} , Pu^{242} , Am^{241} , Am^{243}



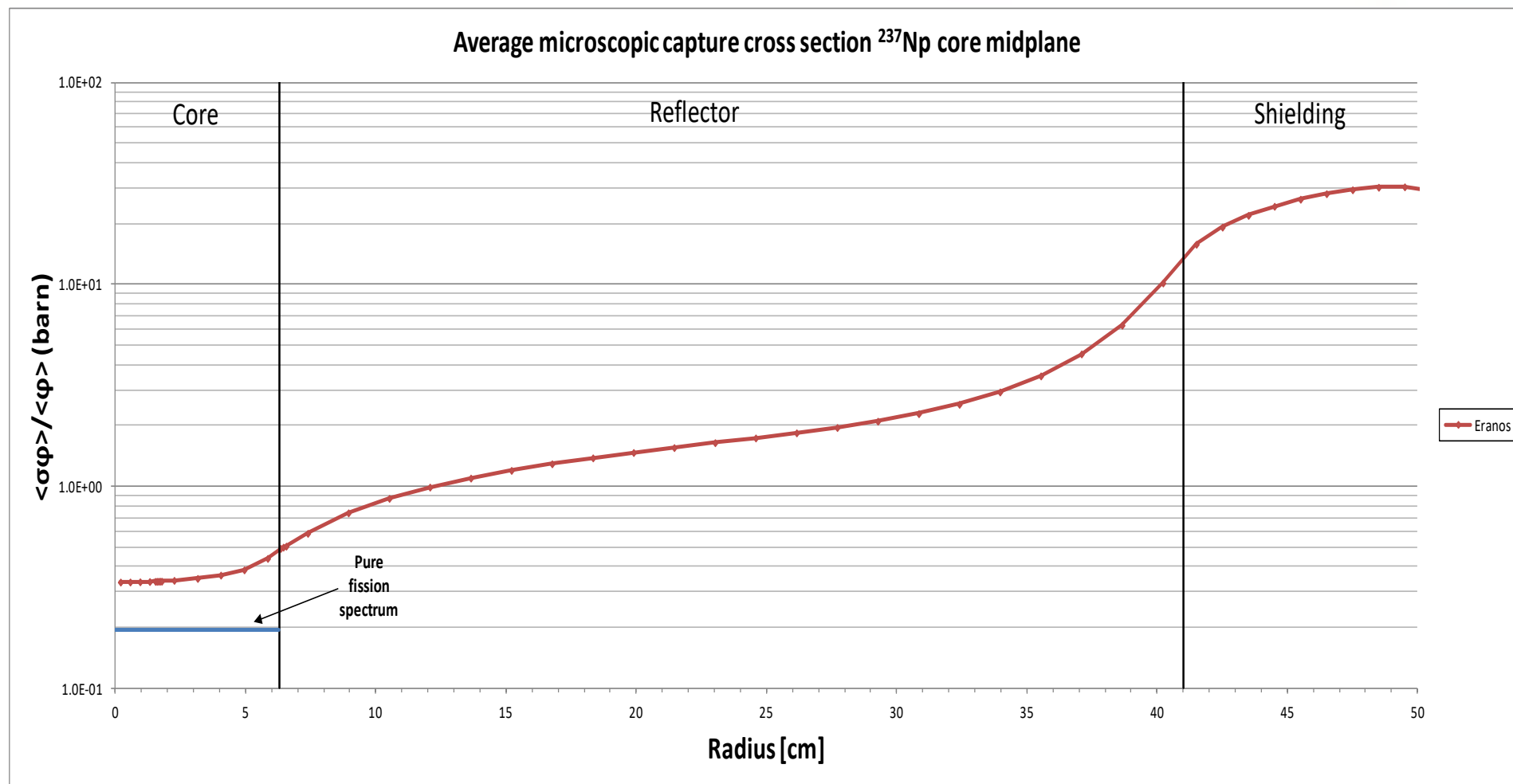
TAPIRO neutronic field analyses

Average capture cross sections (JEFF 3.1)



TAPIRO neutronic field analyses

Average capture cross sections (JEFF 3.1)



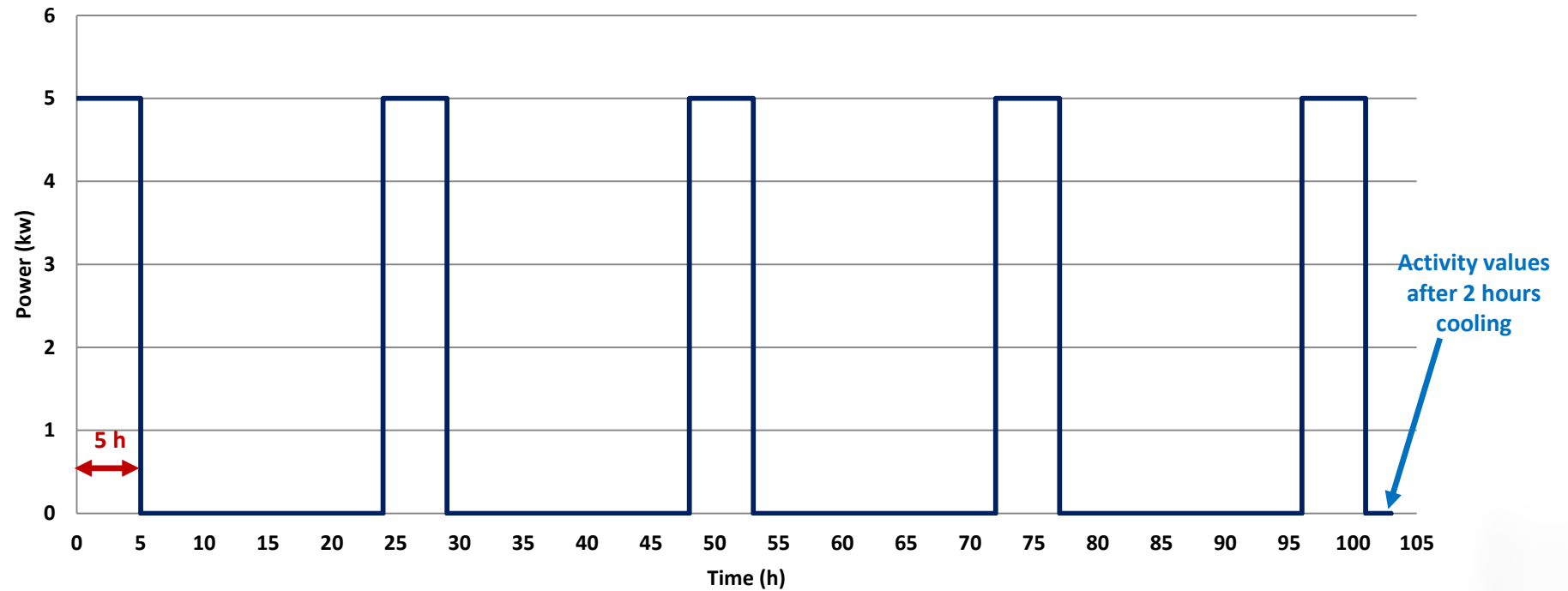


Results

Irradiation scheme for activities (@ 5kW)



1 week irradiation scheme





Results

FISPACT results (analytically checked...)

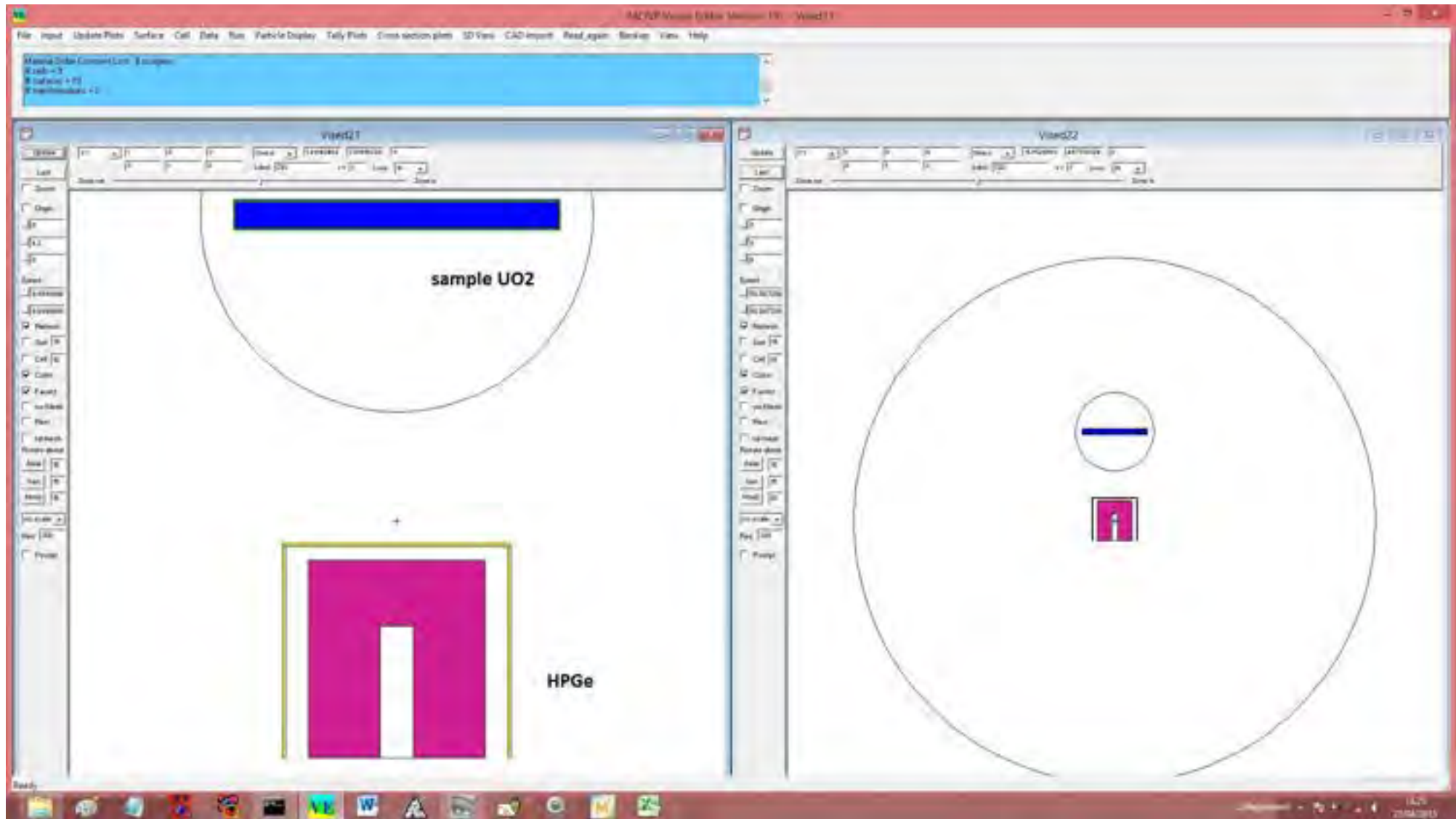


	Position	r = 12.07 cm	r = 24.58 cm	r = 45.5 cm
OSMOSE Samples	ϕ (n·cm ⁻² ·s ⁻¹)	6.94E+11	1.74E+11	8.79E+09
Np237	$\sigma_{c,Np237}$ (barn)	1.04	1.73	19.57
	A (Bq)	2.04E+08	8.49E+07	4.85E+07
Pu242	$\sigma_{c,Pu242}$ (barn)	0.34	0.62	22.48
	A (Bq)	1.15E+08	5.30E+07	9.68E+07
Am241	$\sigma_{c,Am241}$ (barn)	1.32	2.06	32.61
	A (Bq)	1.15E+08	4.50E+07	3.61E+07
Am243	$\sigma_{c,Am243}$ (barn)	1.13	1.83	33.40
	A (Bq)	2.10E+07	8.10E+06	7.14E+06



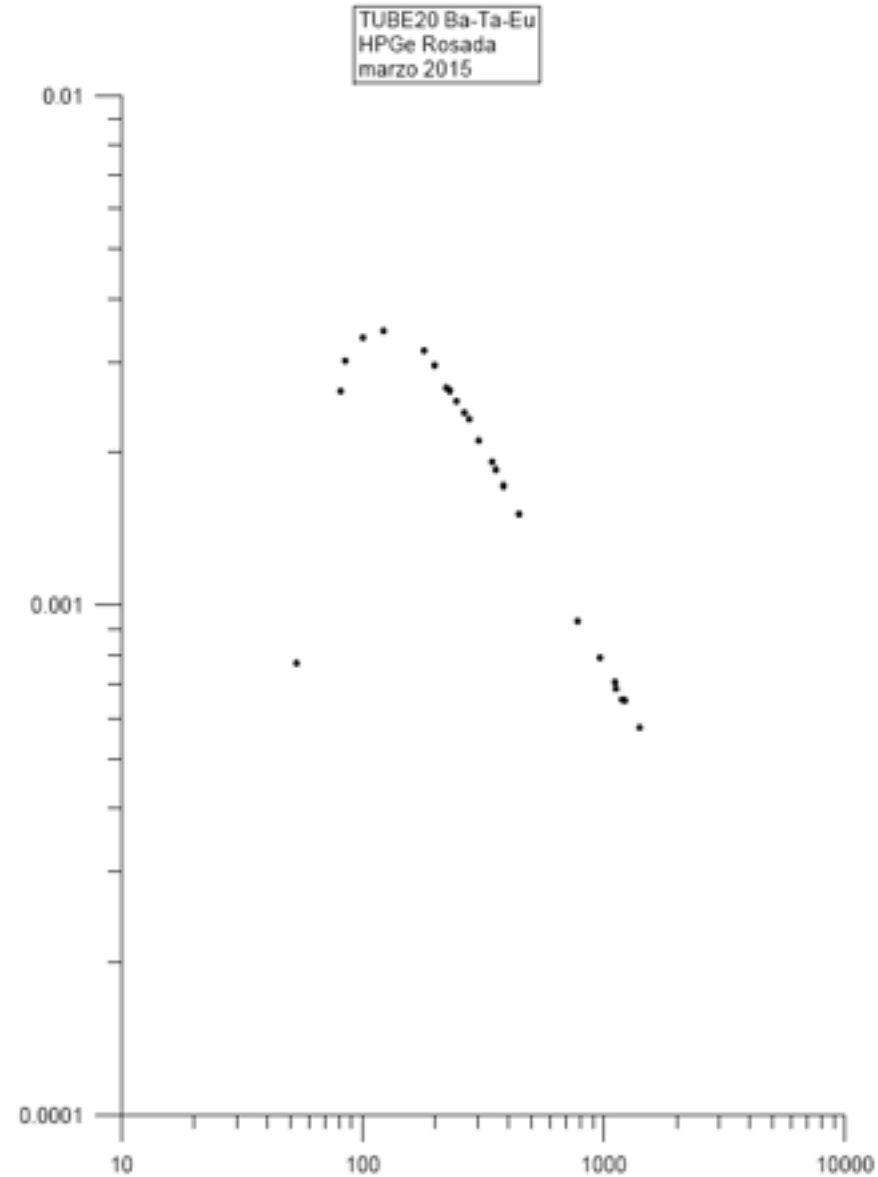
Results

Detection efficiency - MCNP evaluation





HPGe efficiency





Results

Counts estimate



$$\text{CPS (counts/s)} \approx \text{Activity (Bq)} \times$$
$$\gamma \div X \text{ Intensity (line appearance/ disintegration)} \times$$
$$\varepsilon (\gamma \div X \text{ detected/ } \gamma \div X \text{ emitted})$$



Results

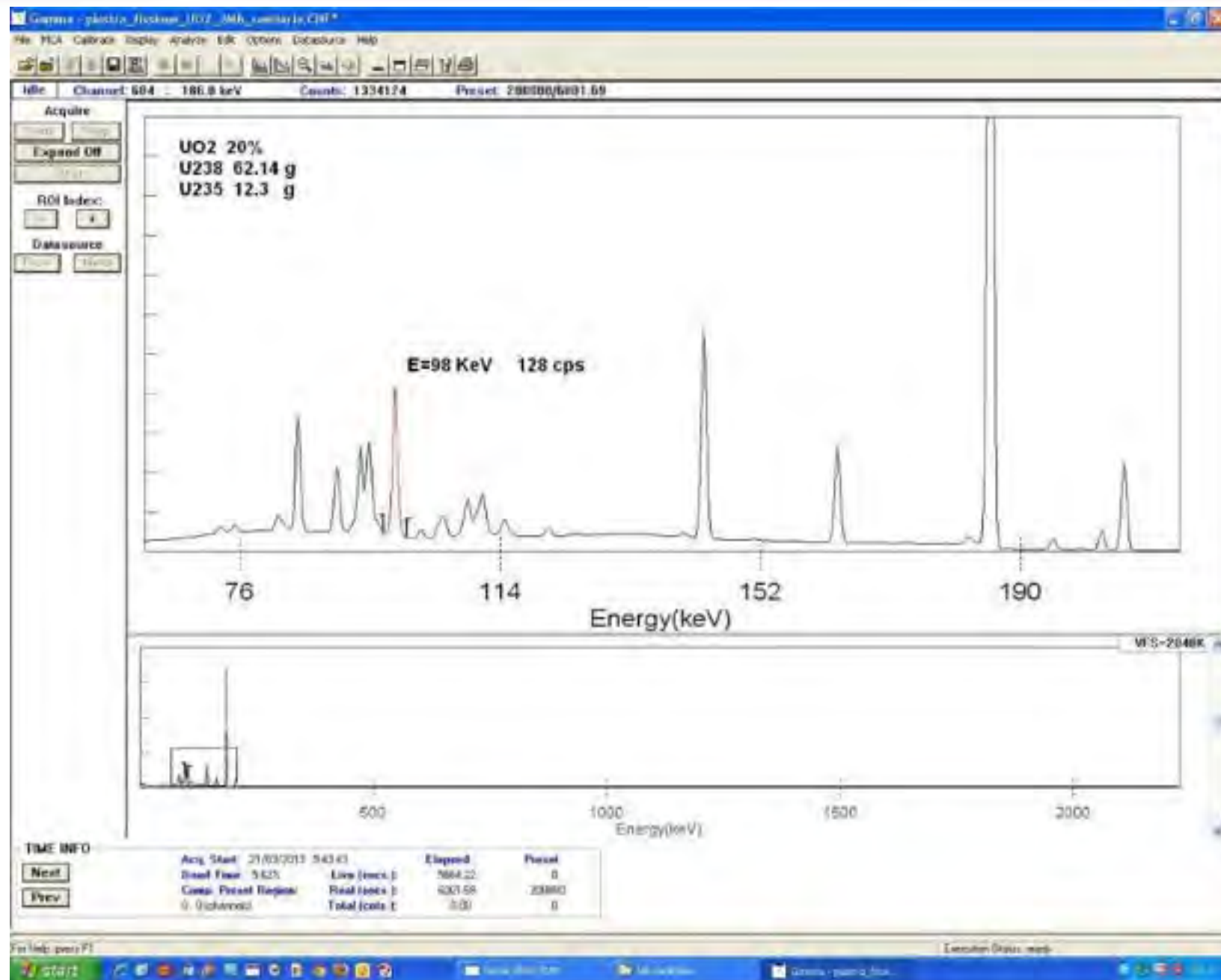
Counts estimate



	Position	r = 12.07 cm	r = 24.58 cm	r = 45.5 cm
OSMOSE Samples	ϕ (n·cm ⁻² ·s ⁻¹)	6.94E+11	1.74E+11	8.79E+09
Np237/2	Np238 E γ (keV)	984.45	984.45	984.45
	γ Intensity (%)	25.19	25.19	25.19
	ϵ Detection (%)	0.186	0.186	0.186
	C (cps)	95487	39779	22738
Pu242	Pu243 E γ (keV)	84	84	84
	γ Intensity (%)	23.10	23.10	23.10
	ϵ Detection (%)	0.530	0.530	0.530
	C (cps)	140305	64912	118561
Am241/1	Am 242 E X _{Kα1} (keV)	103.374	103.374	103.374
	X _{Kα1} Intensity (%)	5.70	5.70	5.70
	ϵ Detection (%)	0.107	0.107	0.107
	C (cps)	2104	823	661
Am241/2	Am 242 E X _{Kα1} (keV)	103.374	103.374	103.374
	X _{Kα1} Intensity (%)	5.70	5.70	5.70
	ϵ Detection (%)	0.107	0.107	0.107
	C (cps)	7014	2745	2204
Am243	Am244 E γ (keV)	743.971	743.971	743.971
	γ Intensity (%)	66.00	66.00	66.00
	ϵ Detection (%)	0.213	0.213	0.213
	C (cps)	29466	11391	10032



Not overlapping lines with UO₂ lines





NEA framework actions chronology since April 2015



- **EGIEMAM-II-02 (29-30 Apr. 2015). List of Actions connected to AOSTA program:**
 - ✓ All to provide information of the FCs to NEA Secretariat [as soon as possible].
 - ✓ NEA Secretariat to send the list of FCs to M. Carta [by the end of May 2015].
 - ✓ M. Carta, P. Blaise, B. Geslot, and G. Imel to consider detailed experimental programs at TAPIRO using the FCs and OSMOSE samples
- **What has happened since then:**
 - ✓ **22 June.** NEA sends list of **SCK•CEN** FCs available for the measurements in TAPIRO (contribution by **Anatoly Kochetkov**).
 - ✓ **6 July.** NEA sends material concerning **CEA** FCs available for the measurements in TAPIRO + papers about FCs manufacturing, spectral indexes measurements and calibration issues (contribution by **Benoit Geslot**) .
 - ✓ **6 July.** NEA sends material concerning **JAEA** FCs available for the measurements in TAPIRO (contribution by **Kazufumi Tsujimoto**).
 - ✓ **May ÷ September.** ENEA checks some aspects regarding FCs and measurement chains available in house. Checks are made also with the Italian National Institute for Environmental Protection and Research (ISPRA) about eventual constraints under the safety point of view. ENEA prepares a first scheduling of a preparatory program to the AOSTA campaign. Collaboration with CEA continues (Serpent TAPIRO input sent from ENEA to CEA).



From ENEA side



- **First of all thanks to all the contributors!**
- **ENEA checks some aspects regarding FCs and measurement chains available at home.**
 - ✓ Available FCs: #3 U235 (different characteristics) ; #5 U238 (different characteristics); #1 Np237; #1 Pu239. All chambers (except one) have to be checked. Calibration??? 😞
 - ✓ Measurement chains exist and are complete. 😊
- **Checks are made also with the Italian National Institute for Environmental Protection and Research (ISPRA) about eventual constraints under the safety point of view:**
 - ✓ Only reactivity margins, regardless the kind of material, have to be taken into account. 😊
- **ENEA prepares a first scheduling of a preparatory program to the AOSTA campaign:**
 - ✓ TAPIRO will come back to its original configuration within this year.
 - ✓ A measurement campaign with some detectors in different positions (in collaboration with CEA, but of course all the volunteers are very welcomed!) has to be performed before AOSTA. Detectors calibration issues must be solved to obtain spectral indexes of interest.
 - ✓ A calculation benchmark has to go along with this experimental phase (→ IRPhE).
 - ✓ During this preliminary phase, but also in parallel to AOSTA, other experiments can be performed (George Imel proposals).



THANK YOU GEORGIOS!

Characterization of the new **ALFRED** core configuration

Francesco Lodi², Giacomo Grasso¹, Antonio Cammi³, Stefano Lorenzi³, Davide Mattioli¹, Marco Sumini²

1 ENEA – SICNUC - PSSN

2 Università di Bologna - DIN

3 Politecnico di Milano



- Introduzione
- Review configurazione precedente
- Nuovi modelli di nocciolo
- Caratterizzazione della nuova configurazione
 - Analisi della stabilità e dinamica di ALFRED
- Verifica termoidraulica
- Conclusioni



Dopo la **revisione critica** della configurazione di nocciolo, così come emersa dal progetto LEADER, lo scorso anno si era arrivati ad un possibile assetto nel quale le criticità rivelate sono state corrette.

L'obiettivo della presente attività è perciò la **caratterizzazione neutronica** della nuova configurazione di riferimento così da ricavare gli arricchimenti e la zonizzazione che garantiscano l'operabilità del reattore per il tempo atteso, rispettando i limiti di progetto.

I dati ottenuti nella fase di caratterizzazione sono stati utilizzati per verificare le performance termoidrauliche di elemento in modo da fare un cross-check dell'effettivo raggiungimento degli obiettivi.

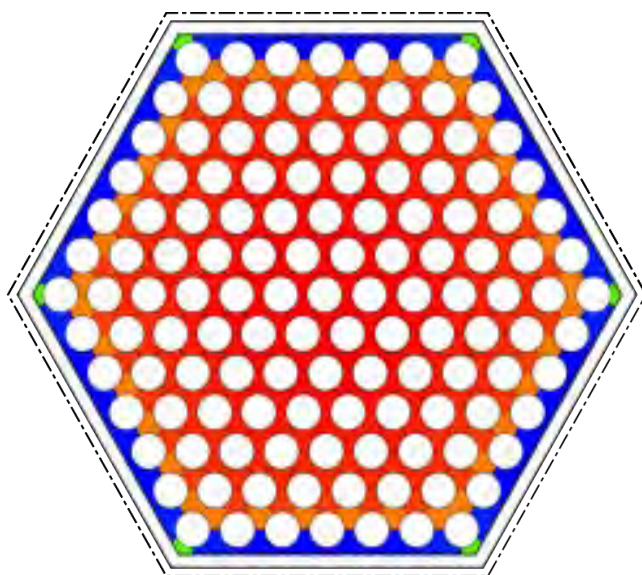
Poiché alcune modifiche hanno un impatto sui coefficienti di reattività un modello per l'analisi dinamica di ALFRED è stato sviluppato e applicato allo **studio di stabilità** del sistema.



Revisione critica:1

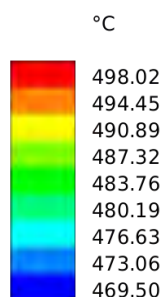


Evitare sovrariscaldamento canali angolari:
allargamento della scatola esagonale.



Elemento centrale

$$T_{\text{guaina}} = 522^{\circ}\text{C}$$



Parametro	Valore nominale [°C]	Fattore di macchia calda	Valore atteso [°C]
Temperatura d'ingresso	400	--	400
Salto termico nel sottocanale	98	1,203	117
Temperatura di bulk	498	--	517
Salto termico alla parete	24	1,382	33
Temperatura di parete	522	--	550

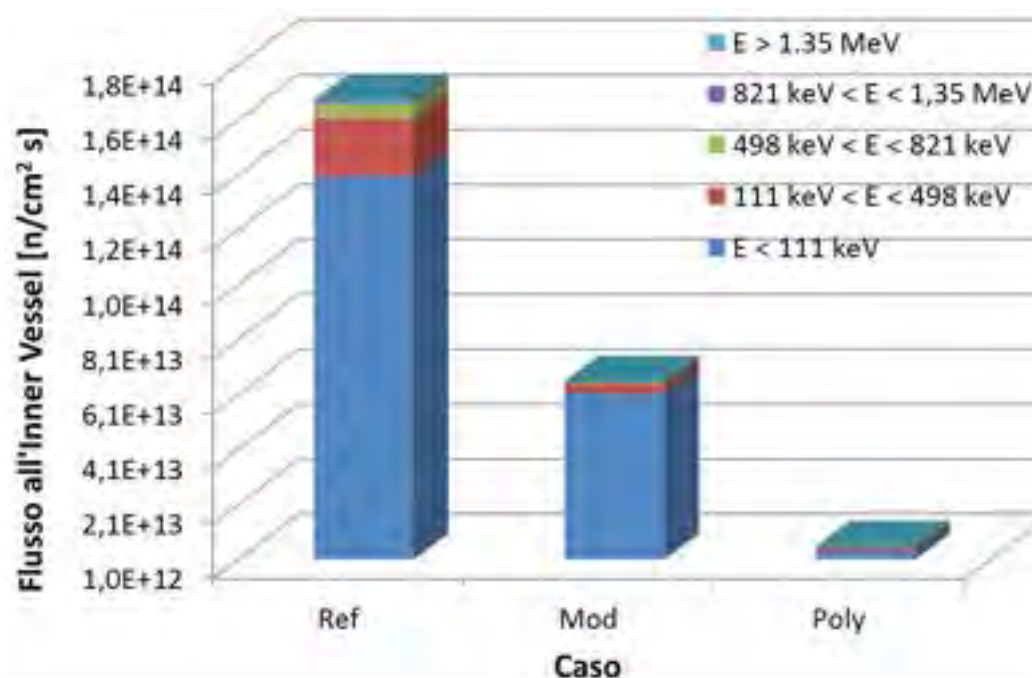


Revisione critica:2&3



Sovra-danneggiamento dell'Inner Vessel e mancanza di margini di aggiustamento della massa critica:

- estensione della vita dell'Inner Vessel a
 - 45 (schermo semplicemente modificato) o
 - 500 (**schermo polifunzionale**) anni.



($\approx -200 \text{ pcm}$)



Revisione critica: 4&5



Valutazione dell'impatto sulla criticità di:

1. impurità nel piombo

	Pb puro	C00	C0	C1	C2C
Grado purezza	100%	99,9985%	99,992%	99,985%	99,97%
Concentrazione Bi	0%	0,0005%	0,004%	0,006%	0,02%
Δk_{eff}	--	-74 pcm	-77 pcm	-83 pcm	-99 pcm

2. materiale della scatola

	Materiale	Spessore	Δk_{eff}
Riferimento	T91	4,0 mm	--
Rimpiazzo	15-15Ti	4,0 mm	-391 pcm
Candidato	15-15Ti	3,5 mm	+193 pcm

Aggiunta posizione instrumentate



Nuovi modelli nocciolo



Data la necessità di caratterizzare la nuova configurazione e dati i cambiamenti geometrici e materiali da aggiungere ai modelli, sembra appropriato **aggiornare gli input di ERANOS2.2 e MCNP6.1**; inoltre, considerando che i precedenti input erano stati preparati da organizzazioni differenti (CEA per ERANOS e ENEA per MCNP), qualche incongruenza era presente nelle proprietà materiali, temperature e dilatazioni utilizzati.

Codice	ERANOS 2.2	MCNP 6.1	
Libreria	JEFF3.1.1	JEFF3.1.2	ENDF/B-7.1b
k_{eff}	1.08307	$1.08373 \pm 21\text{pcm}$	$1.07756 \pm 22\text{pcm}$
Err _{max} su potenza FA a BoL relativo a MCNP-ENDF/B- 7.1b	1.32%	1.35%	--

Le principali differenze possono ora essere imputate ai differenti approcci numerici dei codici e alle librerie di sezioni d'urto utilizzate.



OBIETTIVO: determinare i nuovi arricchimenti e la zonizzazione per garantire l'operabilità del reattore per il tempo stabilito (5 anni), rispettando tutti i vincoli progettuali:

- $T_{\text{guaina}} < 550^{\circ}\text{C}$
- $q' < 340\text{W/cm}$
- $\text{BU} < 100\text{MWd/kg}$
- $\text{DPA}_{\text{guaina}} < 100$
- $\text{DPA}_{\text{inn_vessel}} < 2$ in 60 anni
- ...

La strategia neutronica utilizzata è stata appiattare il più possibile la temperatura di guaina, a livello di pin, incluso le incertezze fin dalle prime fasi; l'appiattimento è perseguito sia a EoC che a BoC.



Caratterizzazione: CR



Con l'obiettivo di massimizzare lo sfruttamento del combustibile:

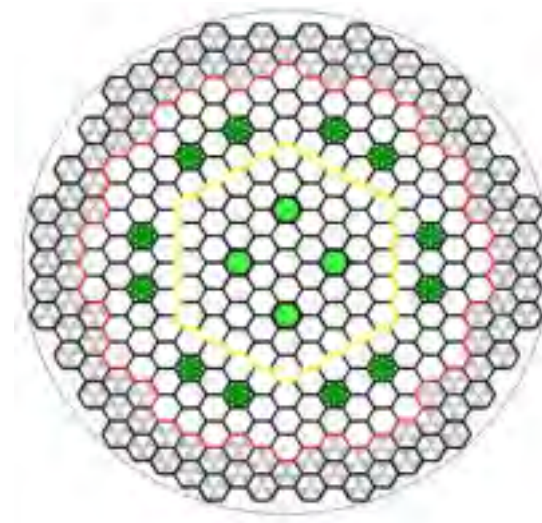
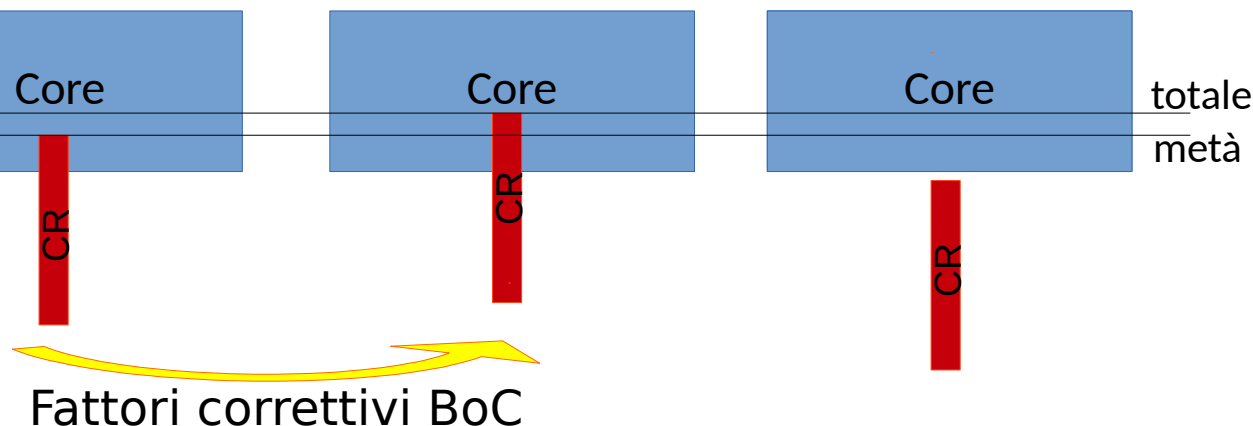
- BoC → CR inserite così da compensare la reattività in eccesso dovuta allo swing di BU
- EoC → CR considerate completamente estratte

In media quindi sono inserite in modo da dare un'anti-reattività pari a metà BU swing. Poiché le CR sono inserite dal basso, incrementano la potenza nella zona di maggior temperatura di guaina.

Come simulare in modo semplice il loro movimento?

Calcoli
a BoL

Fattori correttivi EoC





Caratterizzazione: CR



Con l'obiettivo di massimizzare lo sfruttamento del combustibile:

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- EoC → CR considerate completamente estratte

In media quindi sono inserite in modo da dare un'anti-reattività pari a metà BU swing. Poichè le CR sono inserite dal basso, incrementano la potenza nella zona di maggior temperatura di guaina.

Come simulare in modo semplice il loro movimento?

Stato	BoC		EoC	
Zona	INN	OUT	INN	OUT
FADF	1.093	0.994	0.932	1.006
ADF media	1.003	1.020	0.992	0.974
ADF fine	0.996	1.047	1.004	0.922
FPDF	1.011	1.024	1.009	0.979



Caratterizzazione: Risultati



La zonizzazione è rimasta invariata

Altezza attiva: **60 → 65 cm**

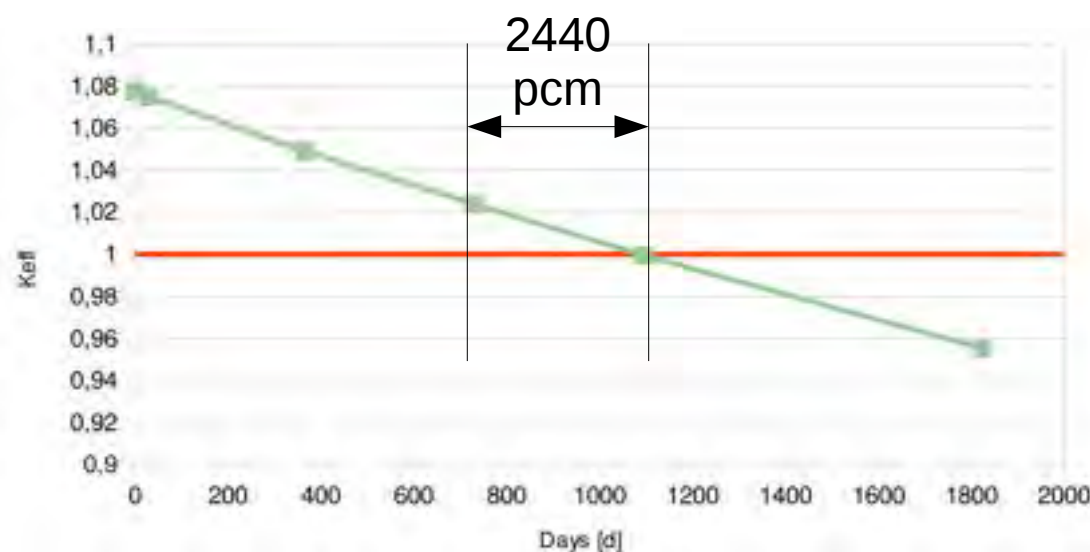


Consente di rispettare i vincoli sulla potenza lineare e BU.

$$q_{\max}' = 332 \text{ W/cm}$$

Arricchimento Pu
in peso

INN	OUT
22.2%	27.4%



DPA _{guaina}	95
DPA _{vessel}	2

5 anni

60 anni

L'incremento di altezza peggiora l'effetto di densità del piombo nella zona attiva e aumenta le perdite di carico di conseguenza si riduce la circolazione naturale. Grazie ai margini di sicurezza dimostrati in LEADER questo non dovrebbe porre problemi. Per valutare preliminarmente il **marginale di stabilità** un'analisi dinamica è stata effettuata in **funzione del coefficiente di densità**.



Analisi di stabilità



L'analisi di stabilità è stata effettuata sia per il nocciolo stand-alone sia per il caso di accoppiamento con il circuito primario. Per tenere in conto gli effetti del bruciamento, lo studio è stato ripetuto sia a BoC che EoC.

OBIETTIVO: dare al progettista un feedback quantitativo riguardo al coefficiente di densità da una prospettiva safety-related.

Il modello sviluppato è **analitico zero-dimensionale**:

Neutronica → Cinetica punto con 8 gruppi di precursori collassati ad 1

Termoidraulica → Scambio termico con singolo nodo e 3 regioni di temperatura (refrigerante, guaina e combustibile)

Reattività → Coefficienti funzione di T_{media} nelle varie regioni a differenti livelli di potenza

Primario → Generatore di vapore (SG) modellato così da dare in condizioni nominali un salto di 80°C tra ingresso ed uscita nocciolo

Dopo aver linearizzato il sistema si arriva a:

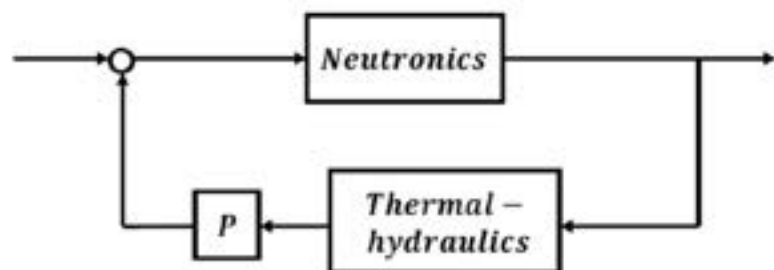
$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

x : vettore variabili di stato
 u : vettore di input
 y : vettore di output

Studio degli autovalori della matrice di stato



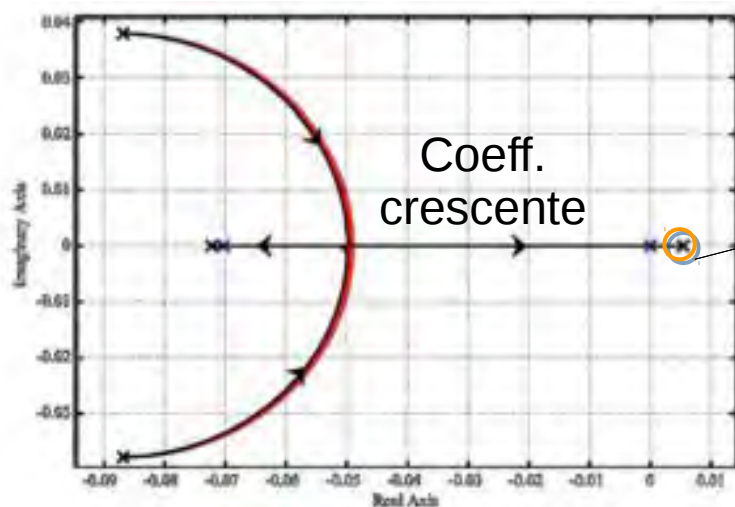
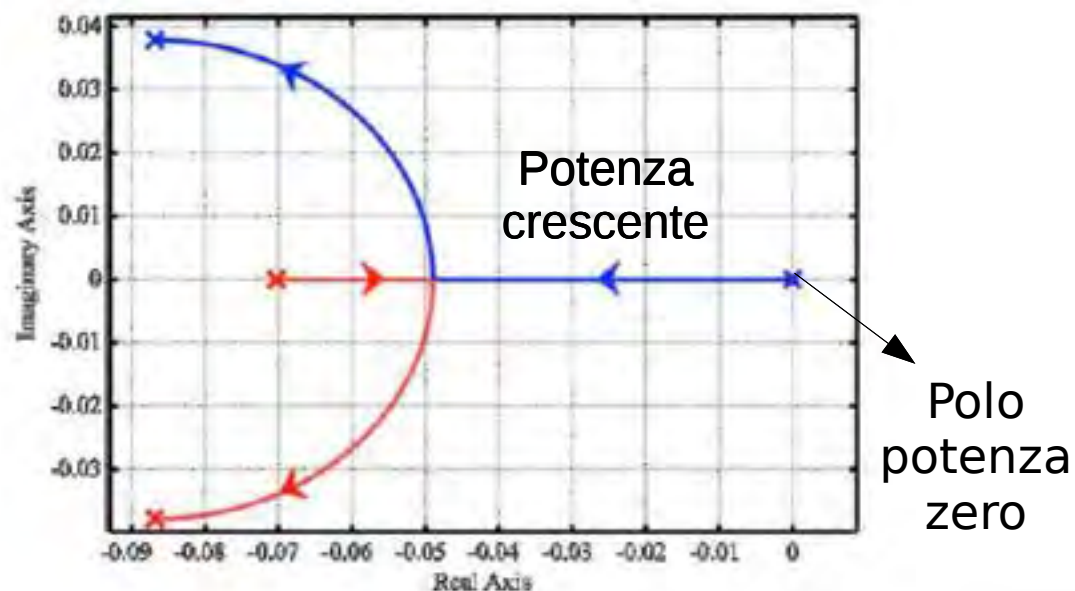
Analisi di stabilità: Nocciolo stand-alone



L'effetto del BU è trascurabile
BoC simile ad EoC

Dopo una certa potenza il sistema presenta oscillazioni smorzate con frequenza crescente

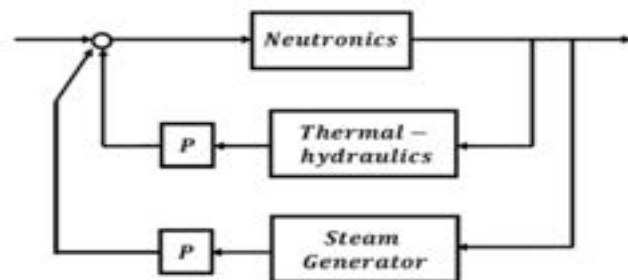
Neutronica come loop aperto e termoidraulica come feedback



A potenza nominale il sistema è instabile quando il coeff. di densità diventa **+12pcm/K**. Valore non realisticamente raggiungibile (in ALFRED 0.5pcm/K solo zona attiva).

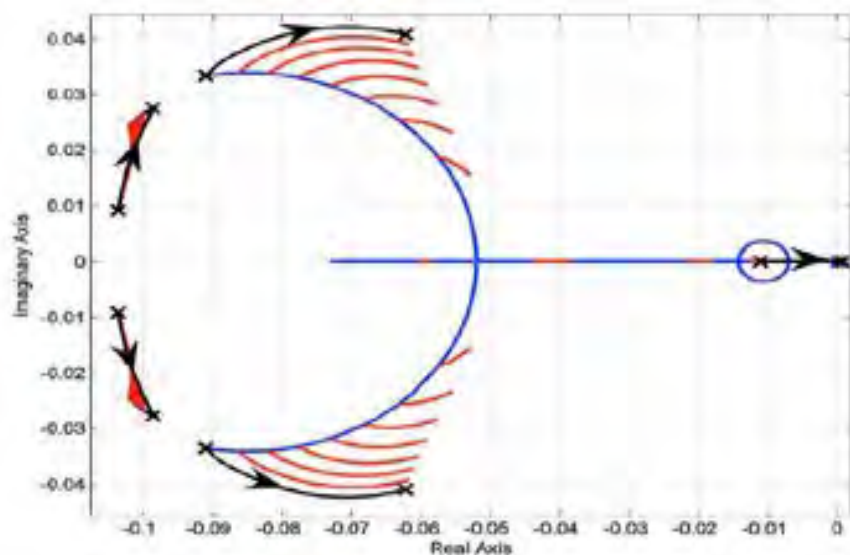
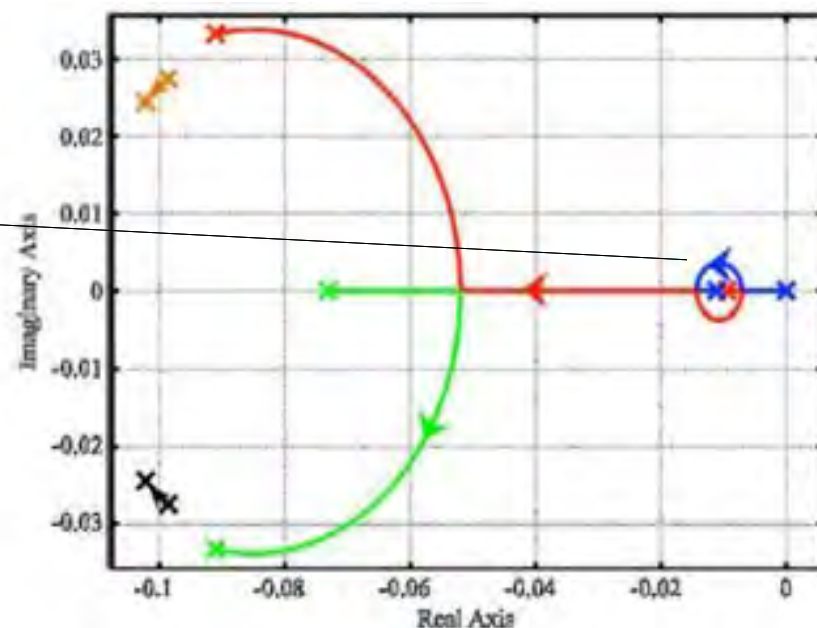


Analisi di stabilità: Nocciolo+SG



Aggiunta del feedback del SG

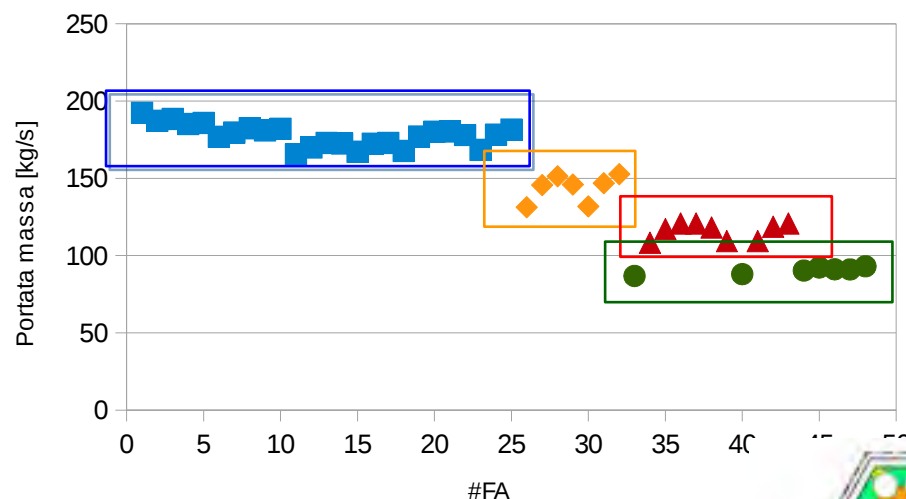
Comparsa di oscillazioni smorzate a più bassa frequenza, dovute alla modifica della $T_{ingresso}$ nocciolo



Andamento qualitativo simile al caso precedente, ma sistema instabile quando il coeff. di densità diventa **+6pcm/K**. Il cambio di altezza attiva non pregiudica stabilità.



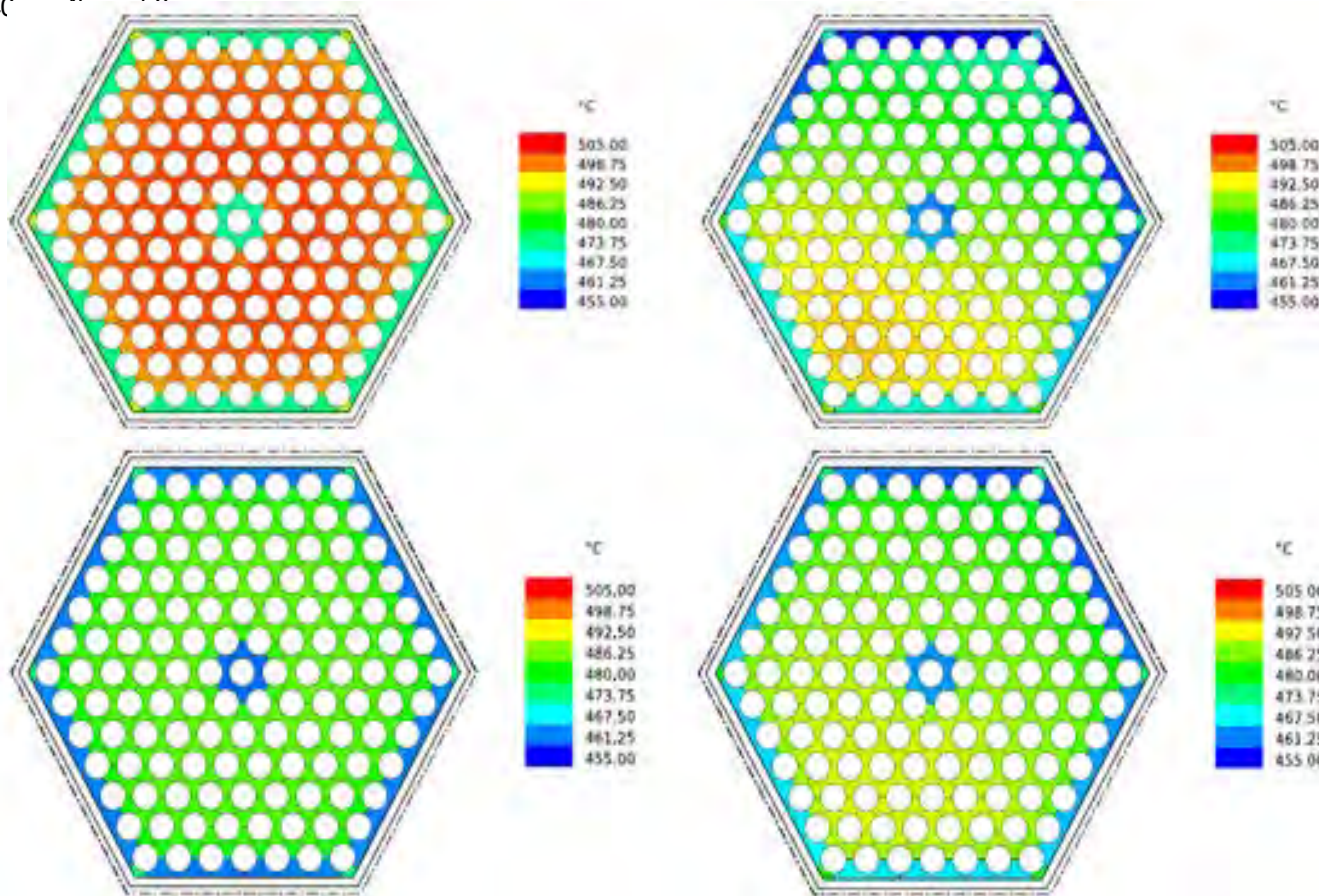
Verifica TH



Nuovo schema di orifiziatura con 4 gruppi di raffreddamento

Verifica
termoidraulica
preliminare con
ANTEO+

Potenza =
combustibile +
riscaldamento
gamma





Verifica TH



L'effetto delle incertezze è stato valutato in via preliminare, includendo incertezze dovute alle proprietà fisiche, tolleranze di fabbricazione, modelli usati nel design e sistemi di misura e controllo.

Il metodo utilizzato è noto come “Semi-statistical vertical approach”

$$F_y^D = \prod_x^{N_D} f_{y,x}^D$$

Contributo diretto

$$F_y^S = 1 + \sqrt{\sum_x^{N_S} (f_{y,x}^S - 1)^2}$$

Contributo statistico

$$F_y = F_y^D F_y^S$$

Fattore di punto caldo

Stato	BoC		EoC	
Zona	INN	OUT	INN	OUT
Pb _{media} uscita [°C]	494	481	479	481
Pb _{max} uscita [°C]	501	495	485	491
Guaina _{max} [°C]	523	522	502	513
Guaina _{max} + unc [°C]	550	551	525	540

Vincolo rispettato



Conclusioni



Chiudendo il percorso delineato negli ultimi due anni dell'AdP, il nocciolo di ALFRED, così come emerso dal progetto LEADER, è stato criticamente analizzato in un ampio spettro di aspetti in modo da arrivare ad una **configurazione di riferimento** più matura.

In questo lavoro la caratterizzazione neutronica è stata presentata tenendo in conto il movimento delle CR e le incertezze, rispettando gli imposti vincoli di progetto sulle potenze lineari, BU, DPA etc.

Una preliminare verifica termoidraulica a livello di FA è stata effettuata in modo da assicurare che i vincoli sulle temperature fossero realmente rispettati in condizioni stazionarie. La verifica ha rivelato la robustezza della configurazione in condizioni nominali.

Il modello dinamico sviluppato ha inoltre evidenziato i buoni margini di stabilità della configurazione proposta, con particolare enfasi per il coefficiente di densità del piombo.

Concludendo la configurazione di nocciolo di ALFRED qui presentata viene proposta come il nuovo riferimento per future analisi, che potrebbero includere il calcolo dei coefficienti di reattività.



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POLITECNICO DI MILANO

Workshop tematico “LFR-Gen IV: Stato attuale della tecnologia e prospettive di sviluppo”
Presentazione attività LP2.A.2_A C.R. ENEA Brasimone, 19 Novembre 2015

Supporto alla progettazione del combustibile nucleare per il reattore LFR – **Lead-cooled Fast Reactor**

Responsabile PoliMi: Lelio Luzzi
Collaboratori PoliMi: Davide Pizzocri, Stefano Lorenzi



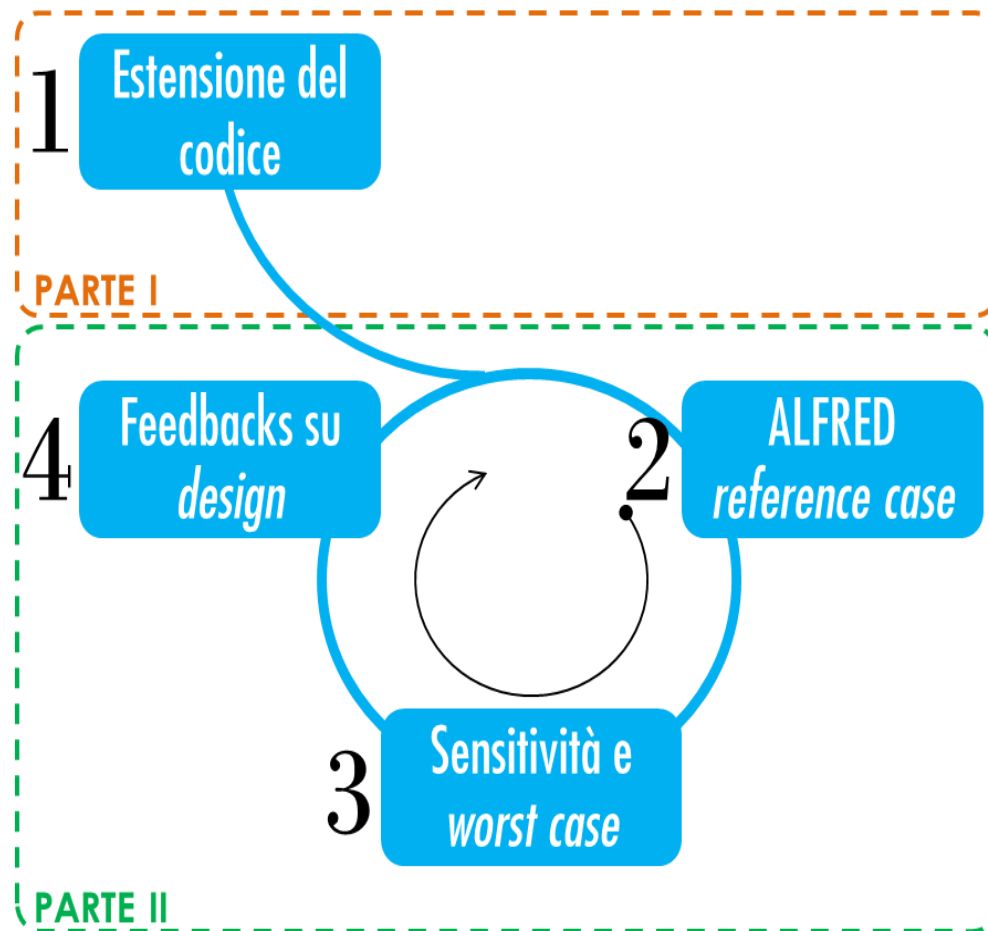
Nuclear
Ractors
Group

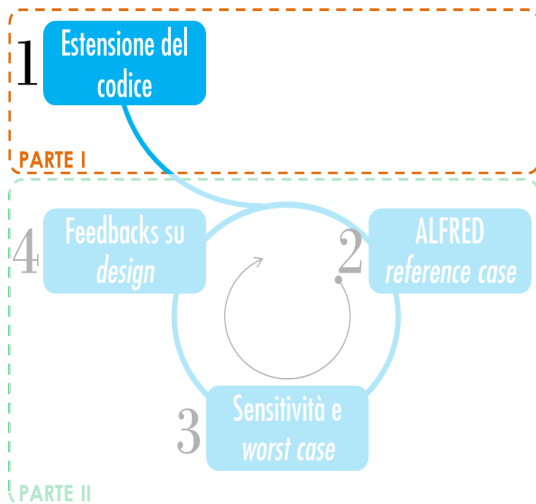
Modellazione e analisi del comportamento integrale di barretta di combustibile per il progetto di reattori a piombo innovativi

Supporto alla progettazione del combustibile nucleare per reattori veloci

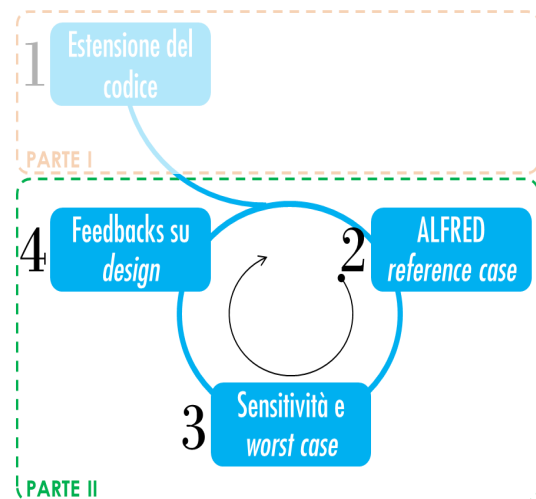


Attività POLIMI + ENEA:
Estensione del codice
TRANSURANUS per l'analisi
dei reattori veloci a piombo ed
applicazione alla *fuel pin*
performance di ALFRED



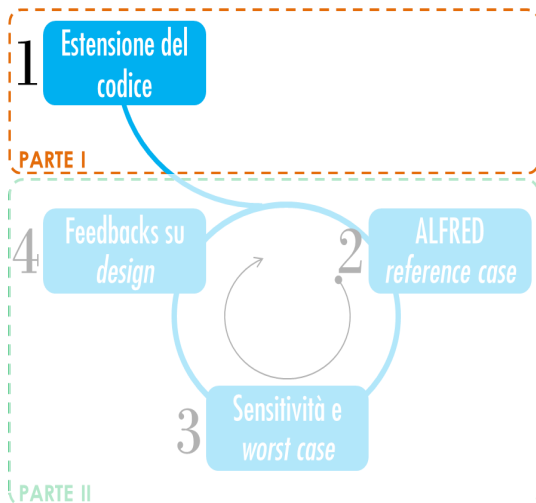


Aggiornamento del codice di *fuel pin performance* TRANSURANUS, **rispetto alla versione LFR-oriented** (PAR2013)

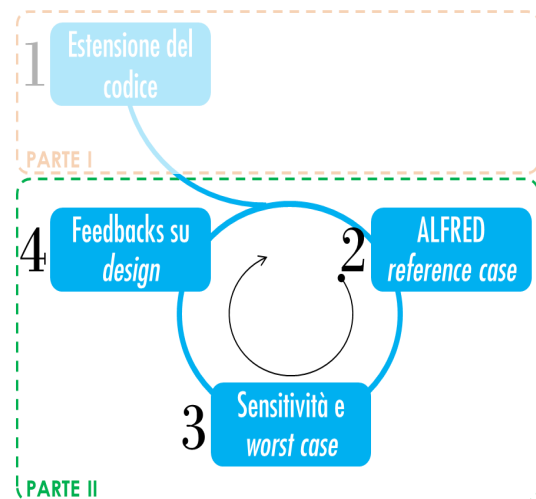


Modellazione e analisi termo-meccanica di barretta (**ALFRED**), per migliorarne il *design* concettuale e le caratteristiche di sicurezza

Attività svolte

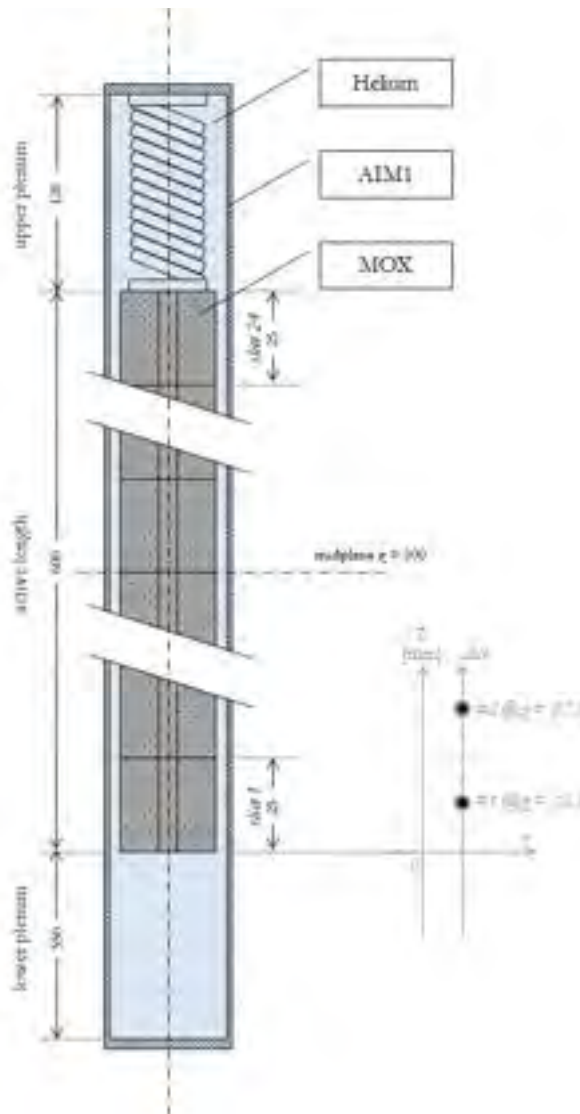
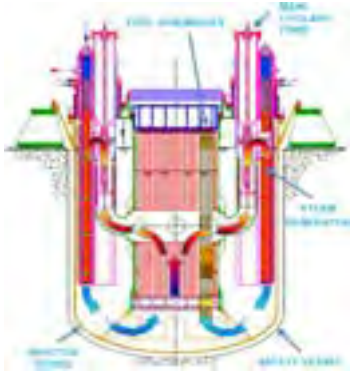


1. Modello di **ridistribuzione del plutonio**
2. Modello per il rilascio di gas di fissione in transitori di potenza (**burst release**)



1. Modellazione della barretta di combustibile di ALFRED
2. **Verifica** del rispetto dei limiti di *design* preliminari (reference scenario = modellazione best estimate)
3. **Analisi di sensitività** su alcuni aspetti significativi (worst case scenario)
4. **Ottimizzazione** di alcuni parametri di progetto della barretta di combustibile

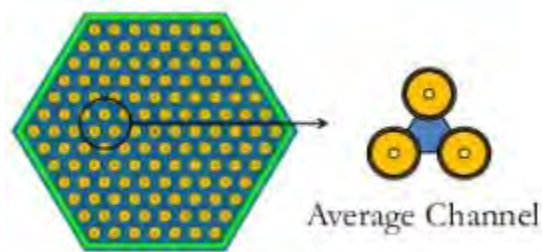
ALFRED – barretta di combustibile



Parametri di progetto

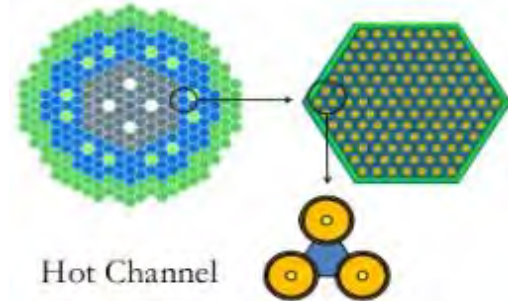
Combustibile	MOX
Guaina	AIM1
Termo-vettore	Lead
Arricchimento Pu/(Pu+U) (wt. %) (zona interna)	21.7
Arricchimento Pu/(Pu+U) (wt. %) (zona esterna)	27.80
Densità del combustibile (%TD)	95
O/M (/)	1.97
Gas di riempimento	He
Pressione iniziale di riempimento (MPa)	0.1
Volume plenum superiore (mm ³)	≈ 30000
Altezza plenum superiore (mm)	120
Altezza attiva (mm)	600
Altezza plenum inferiore (mm)	550
Diametro esterno guaina (mm)	10.5
Diametro interno guaina (mm)	9.3
Diametro esterno combustibile (mm)	9
Diametro interno combustibile (mm)	2
Intercapedine guaina-combustibile (μm)	150
Pin pitch (mm)	13.86

ALFRED – selezione dei canali di potenza



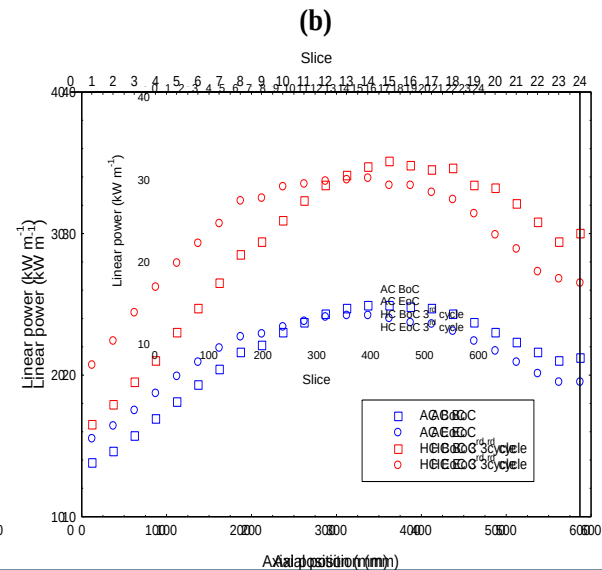
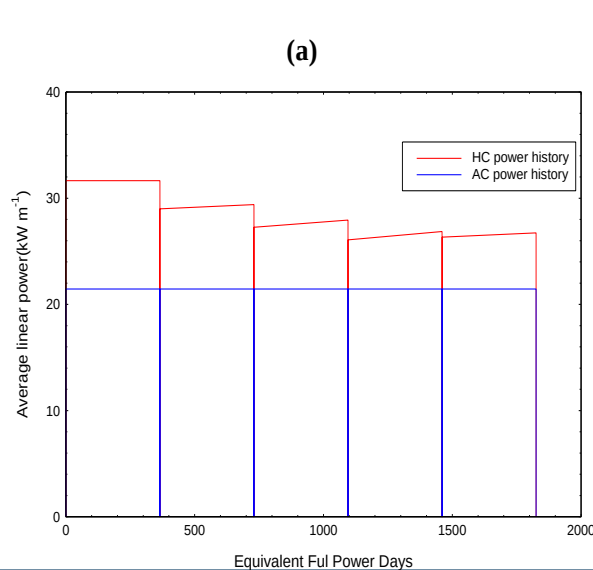
Average Channel (AC)

Condizioni di potenza medie del reattore
(12.9 kW/pin)



Hot Channel (HC)

Elemento di combustibile della regione esterna più prossimo al centro del core, pin prossima all'angolo (17.7 kW/m)



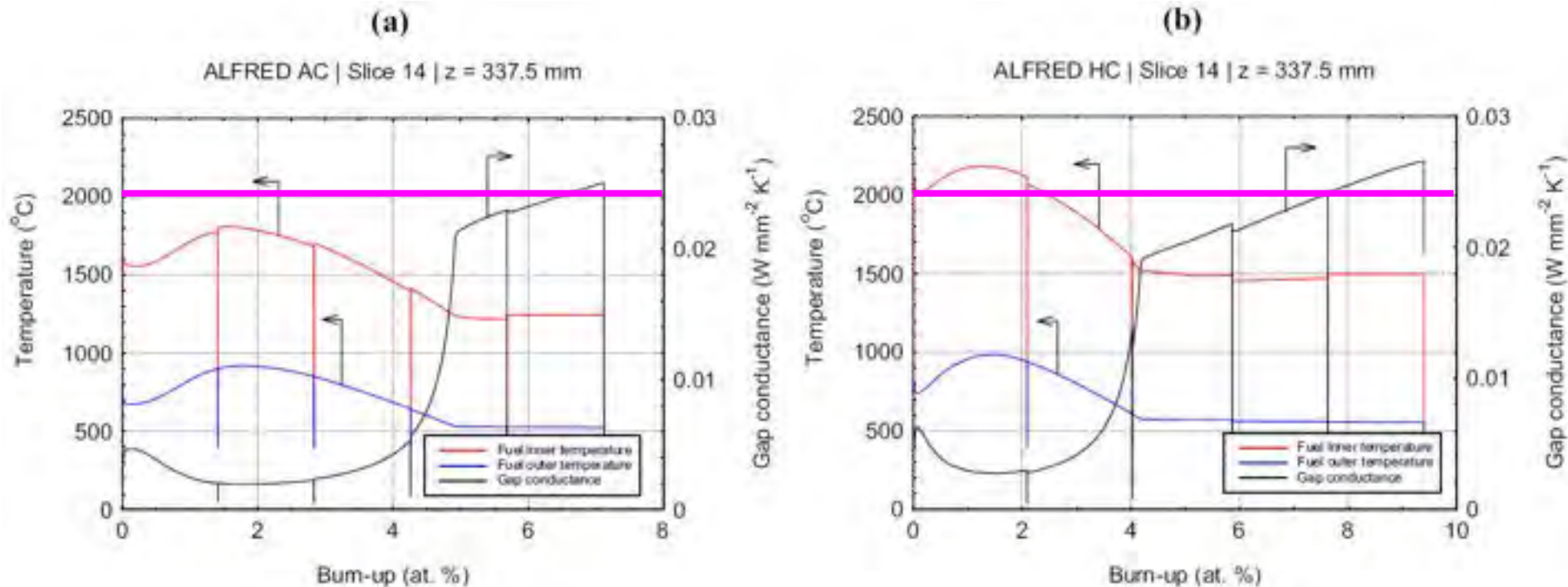
ALFRED – limiti di design preliminari

	Limite proposto	Reference
Massima temperatura del combustibile	$< 2000^{\circ}\text{C}$	Grasso et al., 2013
Temperatura esterna della guaina	$< 550^{\circ}\text{C}$	Grasso et al., 2013
Pressione nel plenum	$< 5 \text{ MPa}$	Grasso et al., 2013
Deformazione della guaina, $\Delta D/D$	$< 3\%$	IAEA, 2012
Deformazione da swelling della guaina	$< 5\%$	NEA, 2005
Deformazione da thermal creep della guaina (1)	$< 0.2\%$	IAEA, 2012
Deformazione da thermal creep della guaina (2)	$< 1\%$	NEA, 2005
Deformazione da creep della guaina	$< 3\%$	NEA, 2005
Cumulative damage function*	$< 0.2\text{-}0.3$	IAEA, 2012
Deformazione plastica della guaina	$< 0.5\%$	Vettraino and Luzzi, 2001

*The Cumulative Damage Function (CDF) is a pin lifetime parameter that considers the linear accumulation of the fraction damage calculated as ratio between the short time interval and the time-to-rupture. (Luzzi et al., 2014).

Risultati – ALFRED Reference case

Temperatura del combustibile

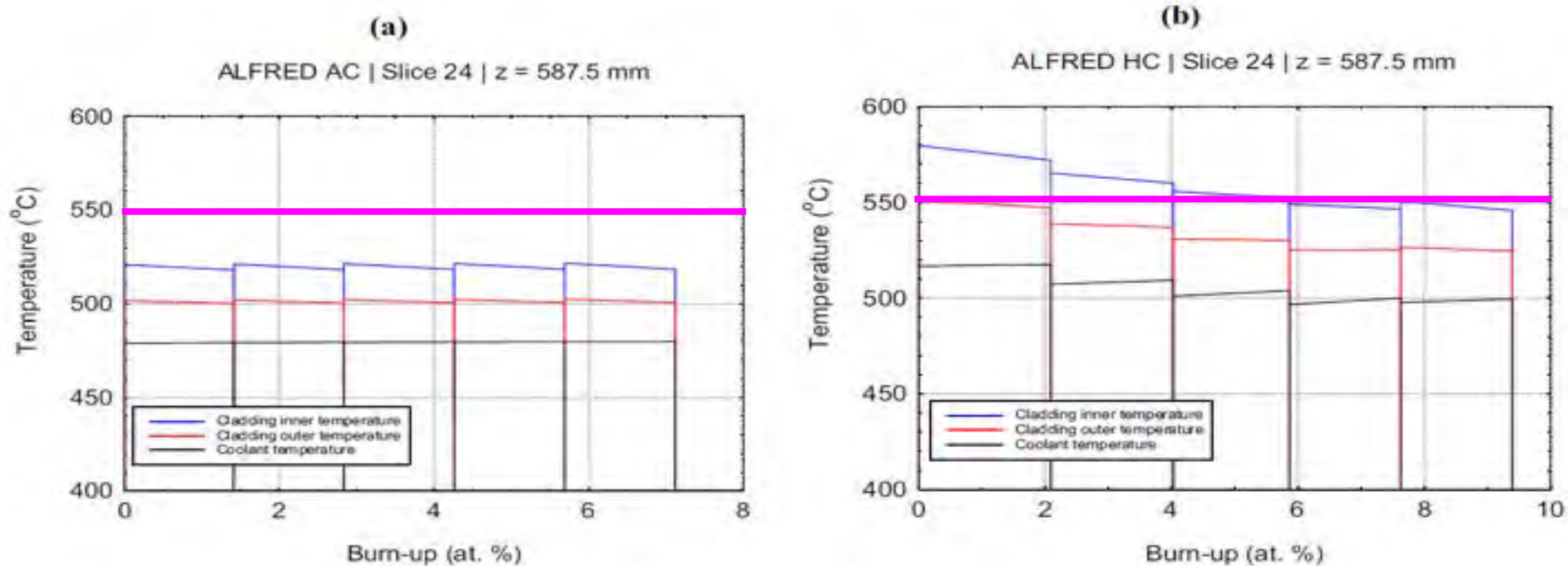


Temperatura dell'AC al di sotto del **limite (2000 °C)**, mentre HC sopra il limite di circa 200 °C

La conduttanza dell'intercapedine dipende dalla combinazione di FGR e chiusura dell'intercapedine

Risultati – ALFRED Reference case

Temperatura della guaina

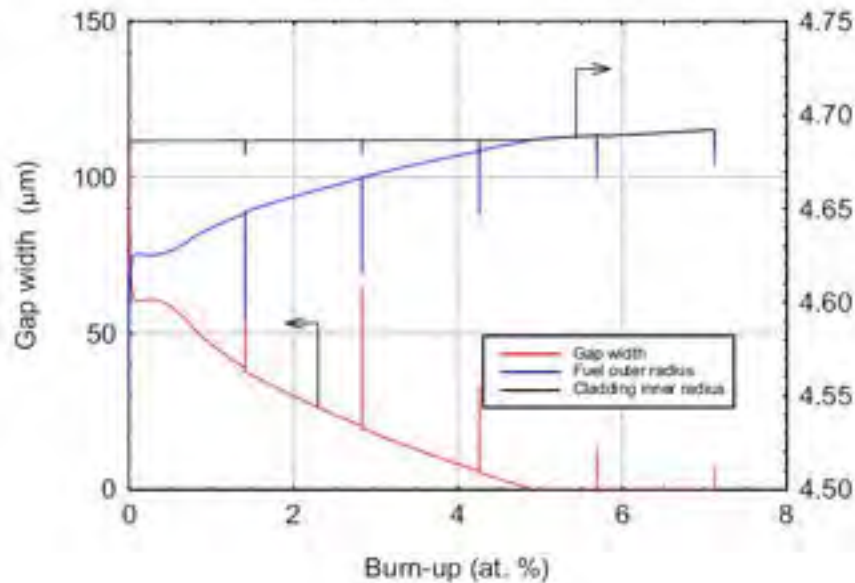


La temperatura esterna della guaina rimane sempre sotto il **limite** di **550 °C**

Dinamica dell'intercapedine

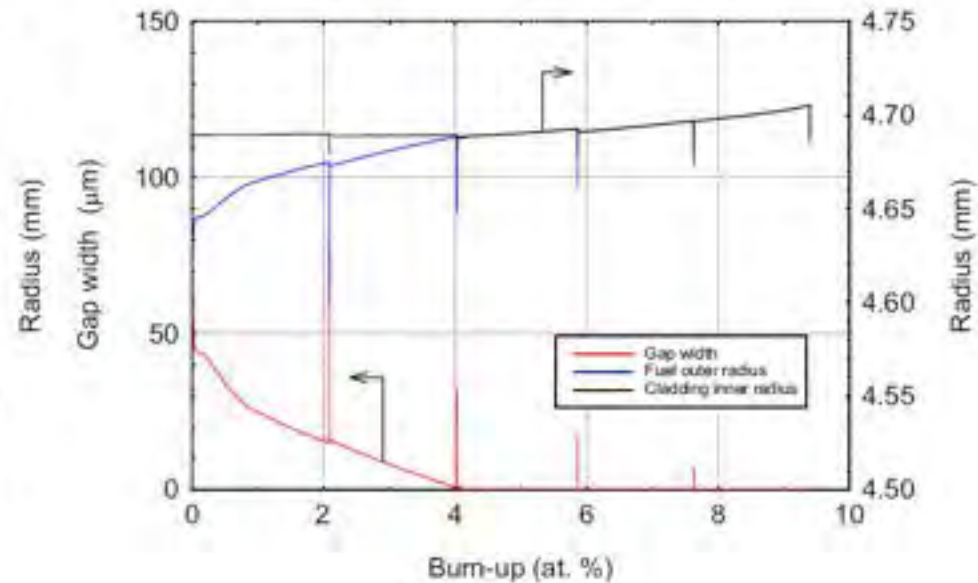
(a)

ALFRED AC | Slice 14 | $z = 337.5$ mm



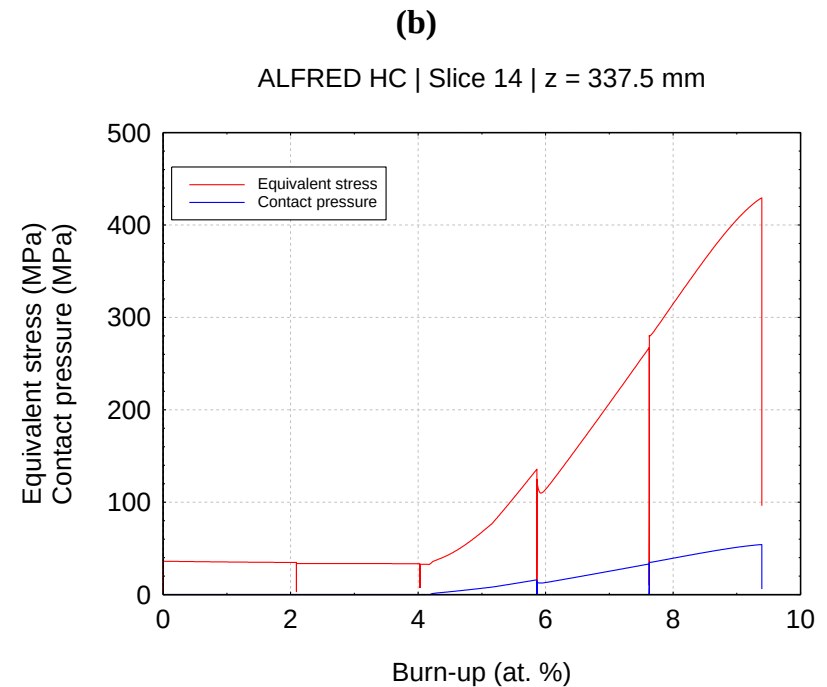
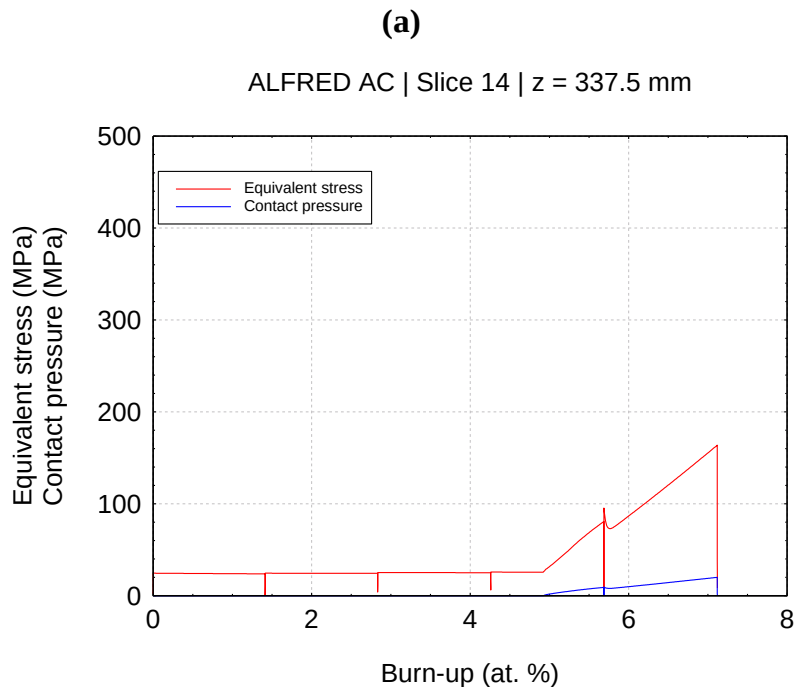
(b)

ALFRED HC | Slice 14 | $z = 337.5$ mm



La dinamica dell'intercapedine è governata dall'espansione del combustibile

Sforzi e deformazioni nella guaina



Lo sforzo subisce una forte crescita dovuto all'interazione guaina-combustibile
Per l'HC, a fine vita, il valore è vicino allo snervamento con una lieve deformazione plastica

Limiti di design

	AC	HC	Limite proposto
Massima temperatura del combustibile (°C)	1810	2184	< 2000°C
Temperatura esterna della guaina (°C)	497	551	< 550°C
Pressione nel plenum (MPa)	1.7	2.41	< 5 MPa
Deformazione da swelling della guaina (%)	0.020	0.024	< 5%
Deformazione da thermal creep della guaina (%)	$1.8 \cdot 10^{-5}$	0.086	< 0.2% (1)
Cumulative damage function (-)	0.000	0.0051	< 0.2-0.3
Deformazione plastica della guaina (%)	0	$1.07 \cdot 10^{-3}$	< 0.5%

Modelli considerati

1. Swelling del combustibile
2. Conducibilità termica del combustibile
3. Swelling della guaina / frazione di flusso veloce

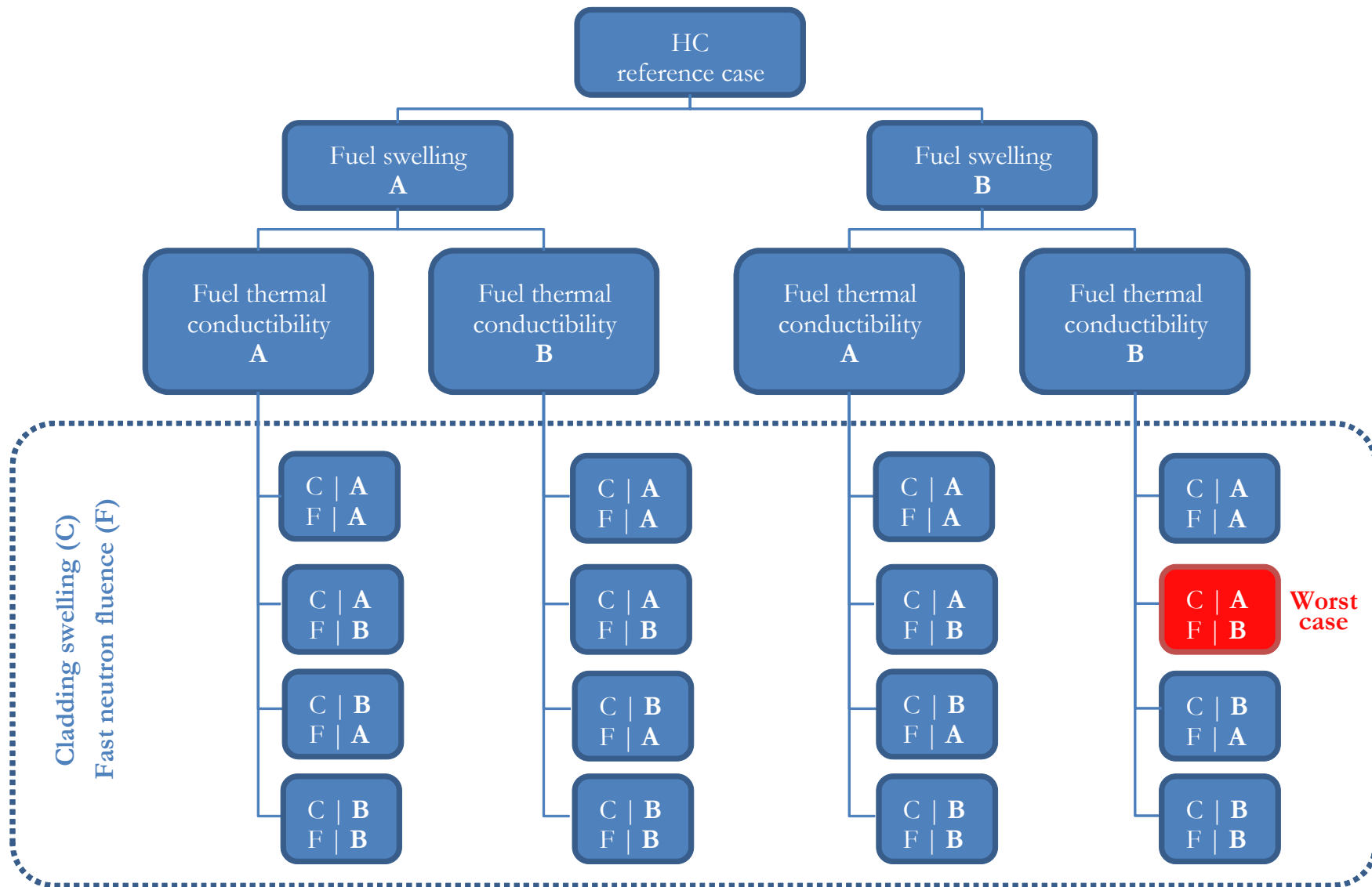
Motivazioni

1. Governano la dinamica dell'intercapedine
2. Influenzano la temperatura del combustibile

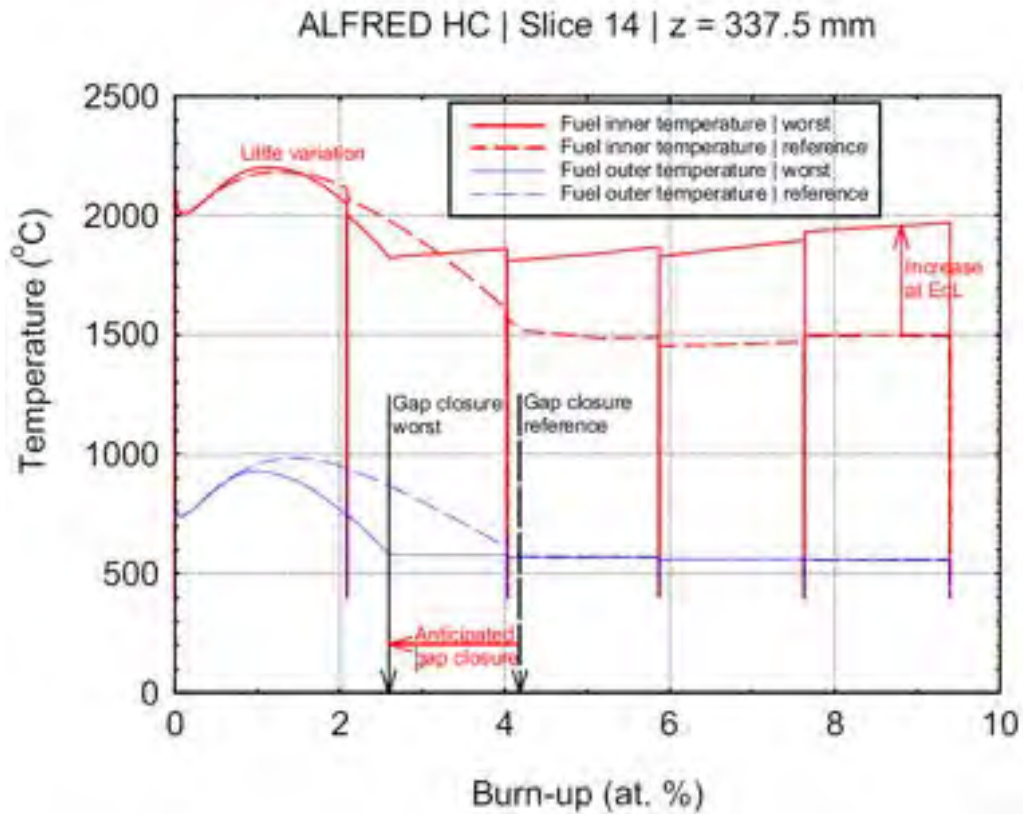
Modello	Reference (“Option A”)	Sensitivity (“Option B”)
Swelling del combustibile	1.2% / at.% con intercapedine aperta (Preusser, 1985)	2.0% / at.% con intercapedine aperta (Freund et al., 1987)
Conducibilità termica del combustibile	Philipponneau, 1992	Carbajo et al., 2001 (più marcata riduzione con il burnup)
Swelling della guaina	“Specific AIM1”	“Generalized 15-15Ti”
Frazione di flusso veloce	> 100 keV	> 10 keV

Figura di merito Cumulative Damage Function, CDF

Analisi di sensitività



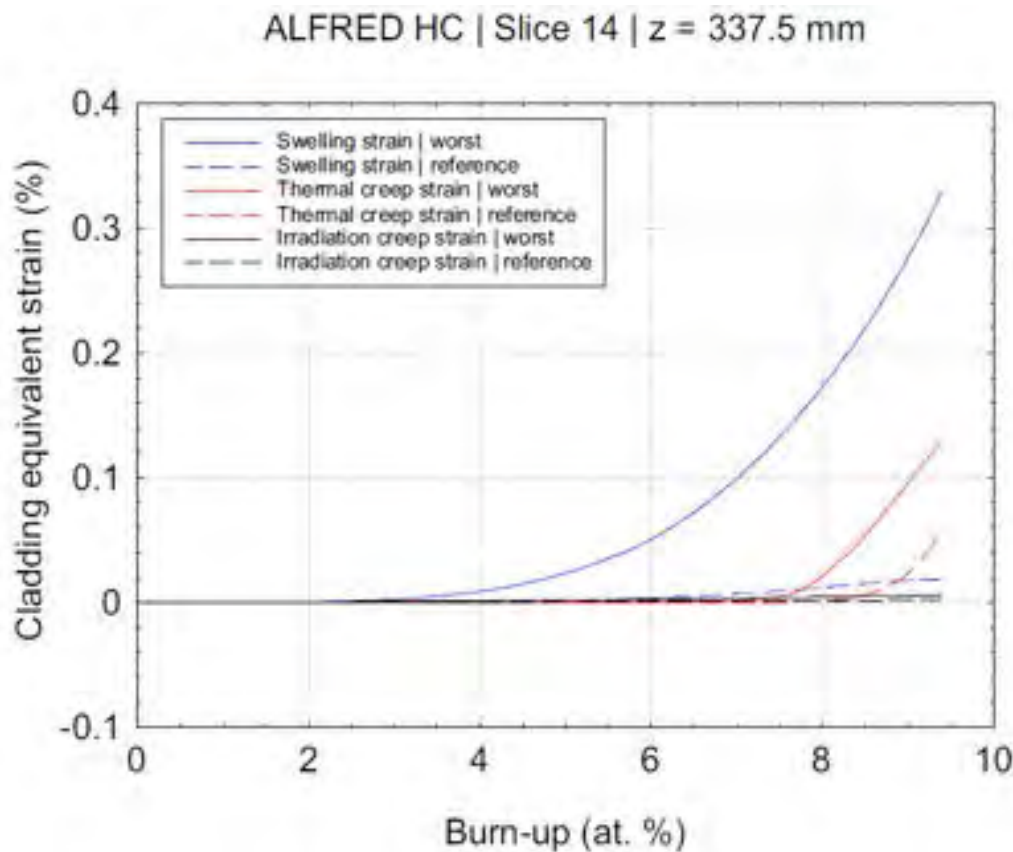
Temperatura del combustibile



Rispetto al reference case HC

1. Anticipata chiusura dell'intercapedine
2. Maggior temperatura a fine vita (conducibilità termica minore)
3. Massima temperatura comparabile

Deformazioni nella guaina



Rispetto al
reference case HC

1. Tutto le deformazioni sono al di sotto dei rispettivi limiti
2. Considerevole incremento dello swelling (modello peggiorativo)
3. CDF = 0.08 << 0.2

Limiti di design

	Worst case AC	Worst case HC	Limite proposto
Massima temperatura del combustibile (°C)	1816	2201	< 2000°C
Temperatura esterna della guaina (°C)	497	551	< 550°C
Pressione nel plenum (MPa)	1.86	2.97	< 5 MPa
Deformazione da swelling della guaina (%)	0.26	0.35	< 5%
Deformazione da thermal creep della guaina (%)	$1.85 \cdot 10^{-5}$	0.135	< 0.2% (1)
Cumulative damage function (-)	0.000	0.081	< 0.2-0.3
Deformazione plastica della guaina (%)	0	$2.62 \cdot 10^{-5}$	< 0.5%

Problematiche

1. Solo l'HC presenta problemi
2. Temperatura del combustibile al di sopra dei limiti preliminari
3. Deformazioni e CDF alte, ma ben al di sotto dei limiti



Tre parametri di progetto sono stati scelti come variabili

Tali da non modificare drasticamente il design del core

1. Dimensione dell'intercapedine
2. Altezza dell'upper plenum
3. Pressione di riempimento

Feedback per il design preliminare

Obiettivo

Riduzione della temperatura del combustibile sotto i **2000°C** nel worst case HC

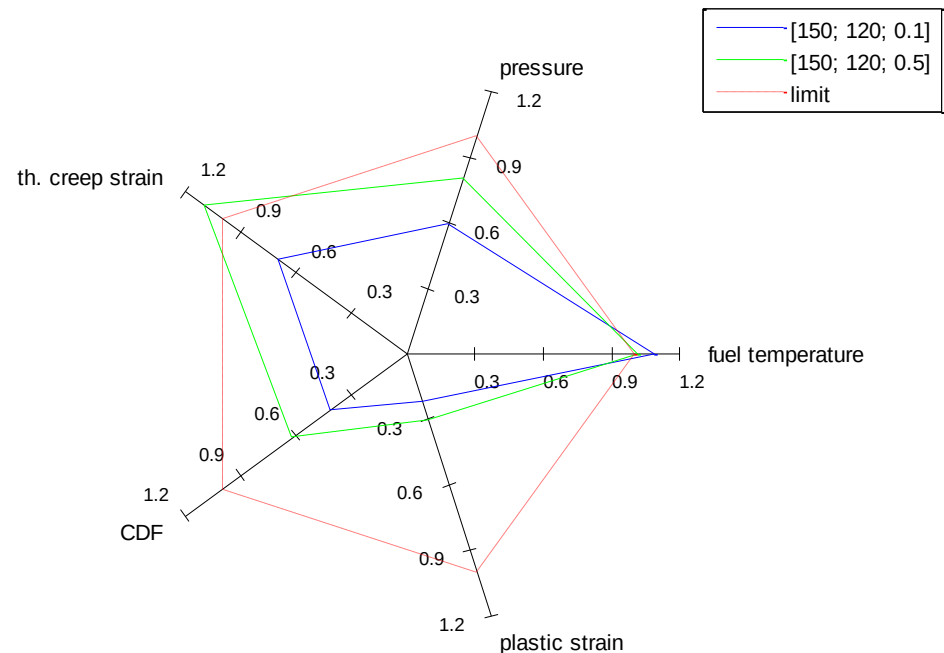
Conseguenze

Generale peggioramento della PCMI

Con i modelli del reference case, la barretta rispetta tutti i limiti preliminari

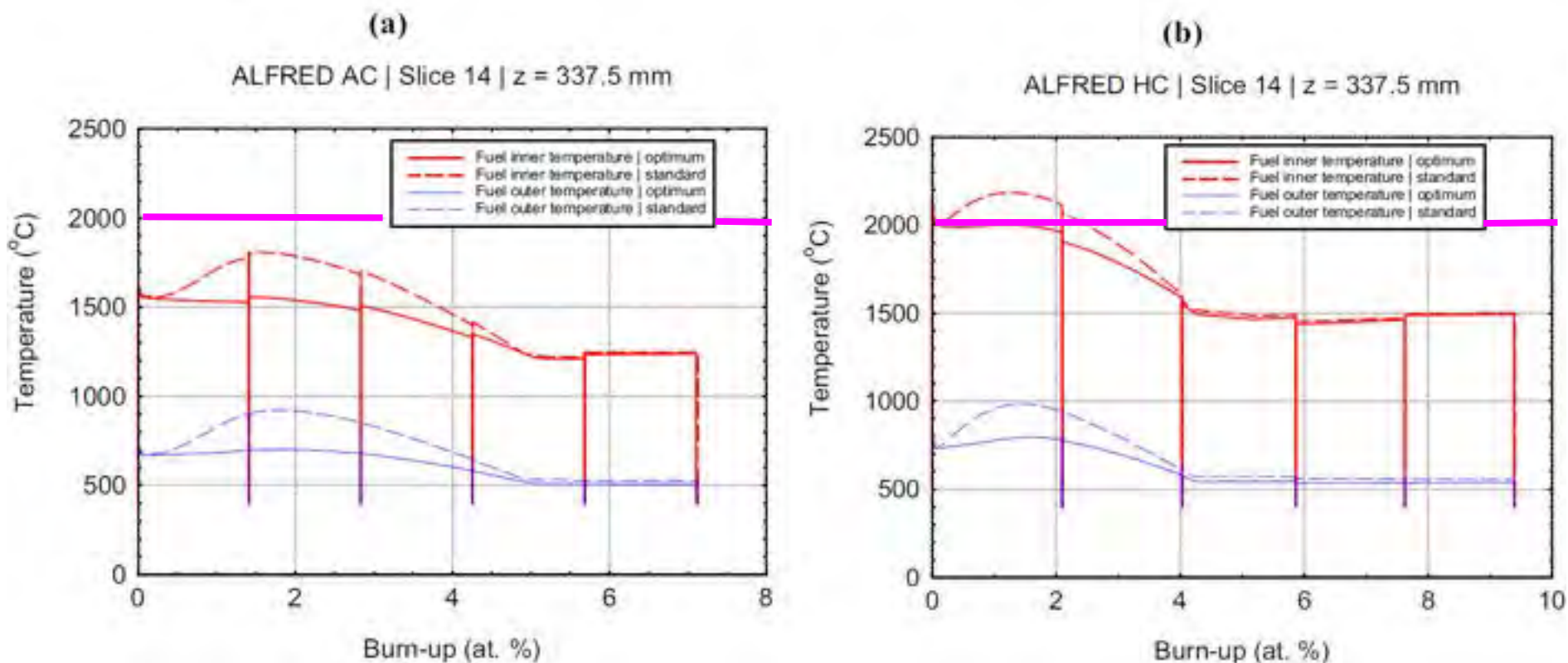
Pressione di riempimento

da 0.1 MPa a 0.5 MPa



Feedback per il design preliminare

Temperatura del combustibile



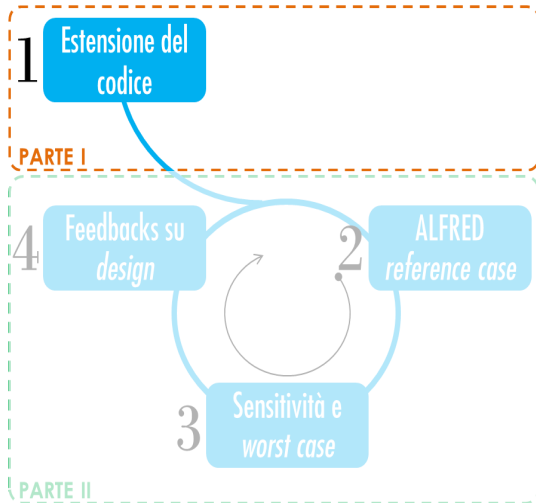
AC ed HC al di sotto del **limite (2000°C)**

Significativa riduzione della temperatura nei primi cicli

Feedback per il design preliminare

	Optimum AC	Optimum HC	Limite proposto
Massima temperatura del combustibile (°C)	1810 -> 1620	2184 -> 1994	< 2000°C
Temperatura esterna della guaina (°C)	497	551	< 550°C
Pressione nel plenum (MPa)	1.7 -> 2.32	2.41 -> 3.15	< 5 MPa
Deformazione da swelling della guaina (%)	0.020	0.024	< 5%
Deformazione da thermal creep della guaina (%)	$1.8 \cdot 10^{-5}$	0.086 -> 0.15	< 0.2% (1)
Cumulative damage function (-)	0.000	0.0051 -> 0.085	< 0.2-0.3
Deformazione plastica della guaina (%)	0	$1.07 \cdot 10^{-3}$ -> 0.0554	< 0.5%

Conclusioni attività

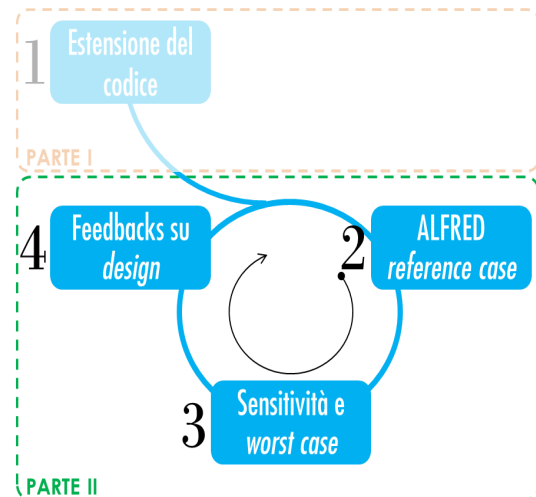


1. Disponibilità di una **versione di TRANSURANUS orientata ai reattori a piombo**

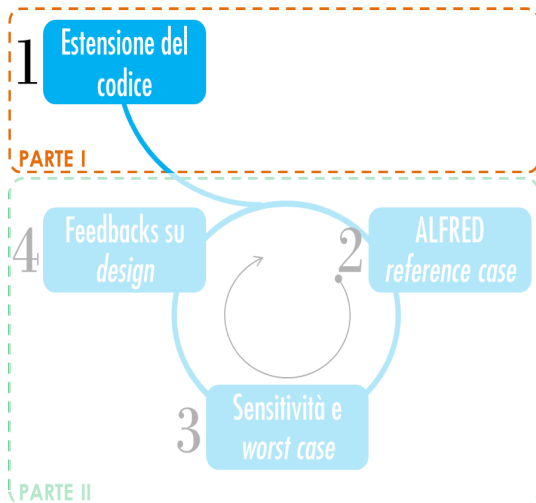
2. Valutazione dell'**evoluzione** del comportamento in reattore **del sistema "guaina-combustibile" di ALFRED**

3. **Analisi di sensitività** sui modelli più delicati, in particolare per quanto riguarda il combustibile.

4. Individuazione di soluzioni costruttive finalizzate al conseguimento di **margini di sicurezza più ampi, i.e., aumento della pressione di riempimento a 0.5 MPa**



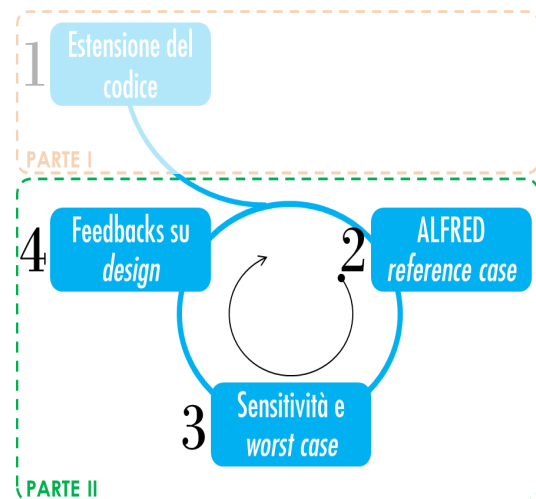
Sviluppi futuri

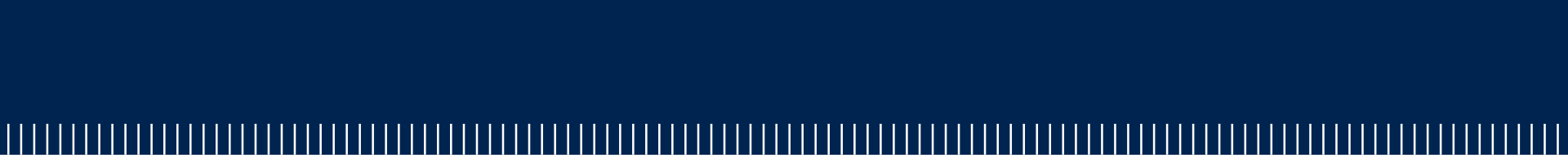


1. Estensione del codice con nuovi modelli per il MOX (**sviluppo fuel-oriented**). Il miglioramento del modello di Fission Gas Release in transitorio è prioritario (diffusione inter e intra grani, High Burnup Structure)

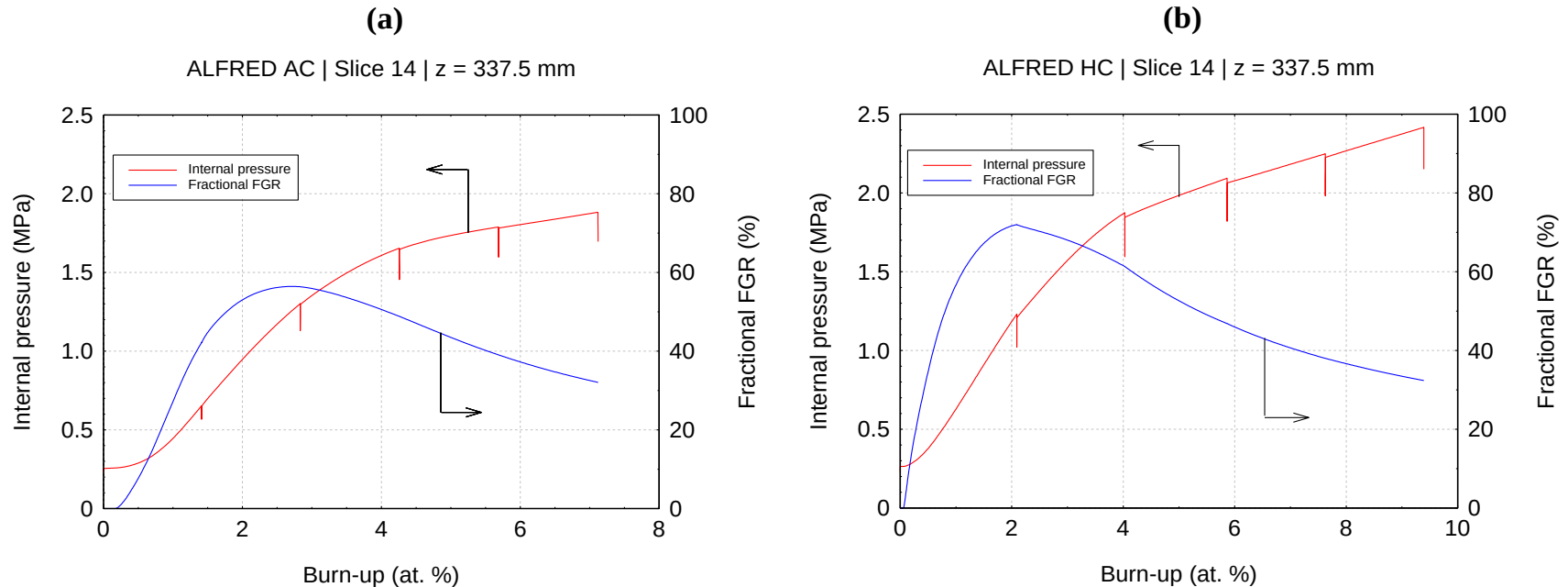
2. Miglioramento dei modelli di **interazione guaina-combustibile** (JOG, FAE, accoppiamento creep-sweeling)

3. Analisi di **performance della barretta della nuova configurazione** di ALFRED e **ulteriori feedback per il design**





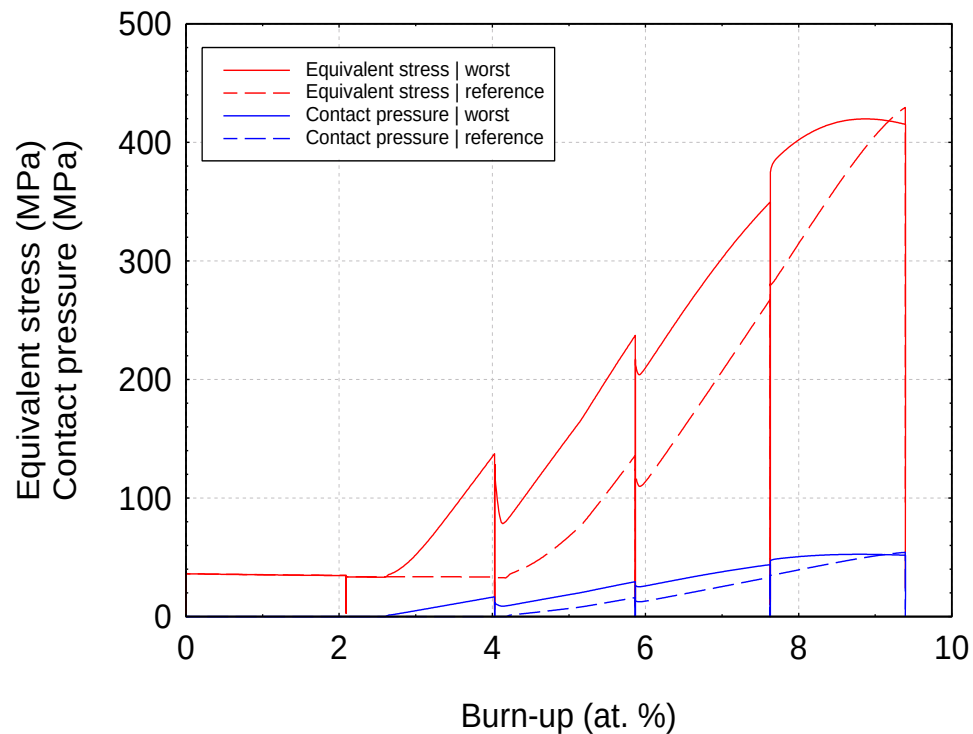
Fission Gas Release



Internal pressure well below the design limit

Sforzi nella guaina

ALFRED HC | Slice 14 | $z = 337.5$ mm



Rispetto al reference case HC

1. Aumento della pressione di contatto
2. Alti stress ma rilassamento verso la fine dell'ultimo ciclo



Sviluppo dei sistemi LFR: strategie e prospettive

P.Agostini

Brasimone, 20 Novembre 2015

Strategia per ALFRED

European frame: ALFRED in ESNII

2025

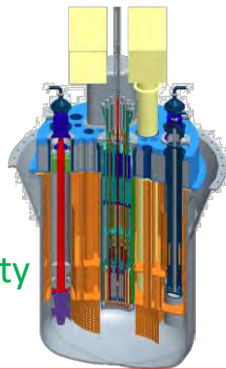
ASTRID
SFR
Prototype



Reference Technology
Design, Construction &
Commissioning

MYRRHA

Irradiation Facility



Supporting Infrastructure
Design, Construction &
Commissioning

ALFRED

LFR Demonstrator



Short-term alternative Technology
Conceptual design, siting, & supporting R&D

ALLEGRO

GFR Demonstrator

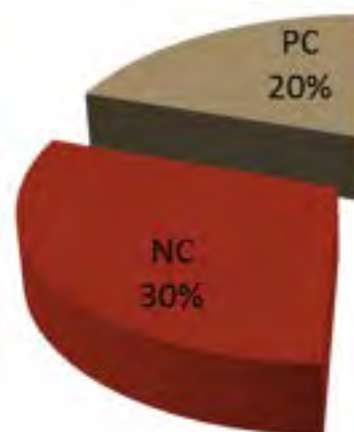
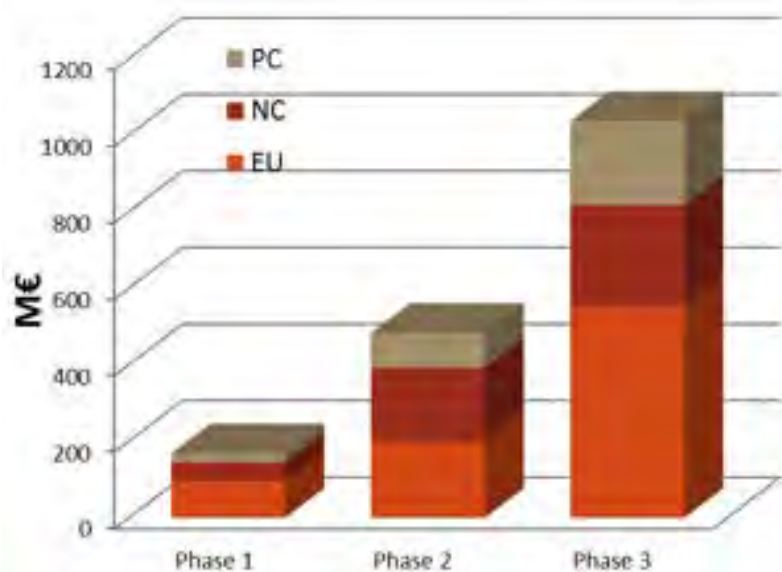
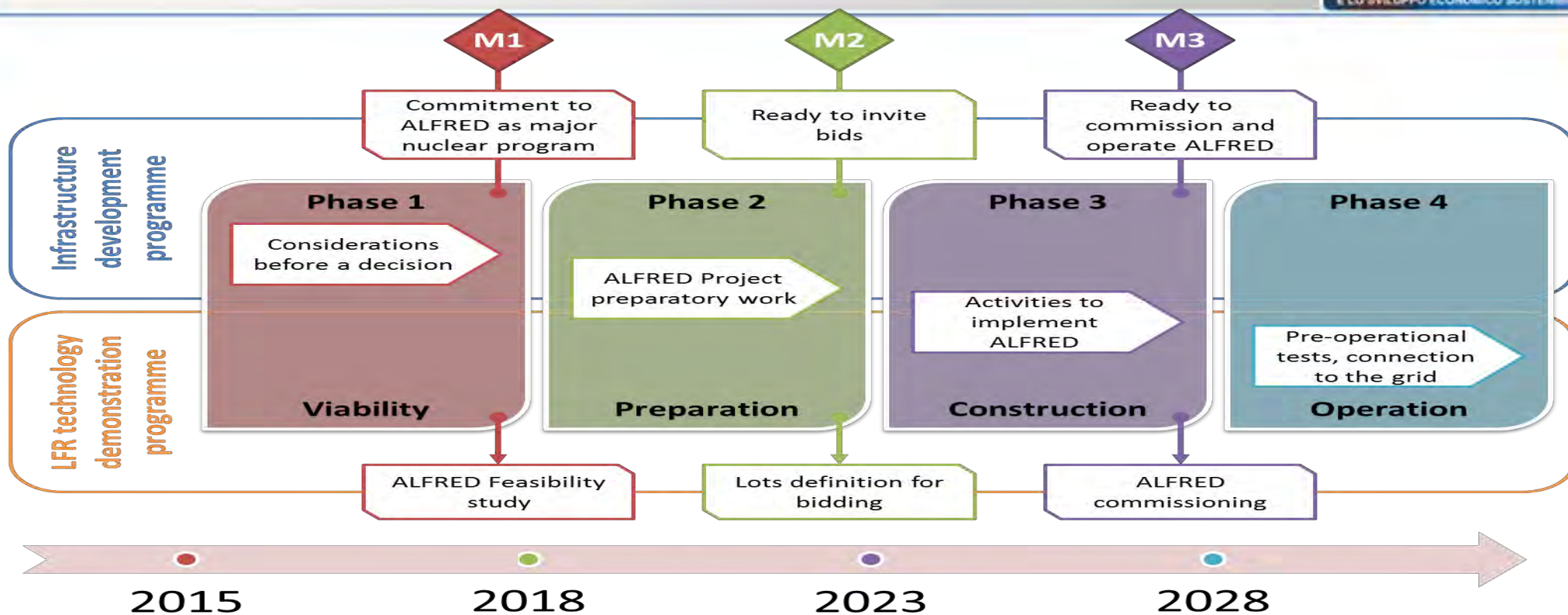


Long-term alternative Technology
Conceptual design, siting, & supporting R&D

ESNII is the European
Sustainable Nuclear
Industrial Initiative

Participation to EU projects
in GEN IV is facilitated by
the participation to ESNII

ALFRED ROADMAP



THE FALCON CONSORTIUM



Fostering **AL**fred **CON**struction



Signature ceremony
Dec 18th 2013

PHASE
1

- 30 months
- Unincorporated consortium
- In-kind contributions
- Optimize the cooperation
- Areas: strategic, management governance, financial and technical aspects

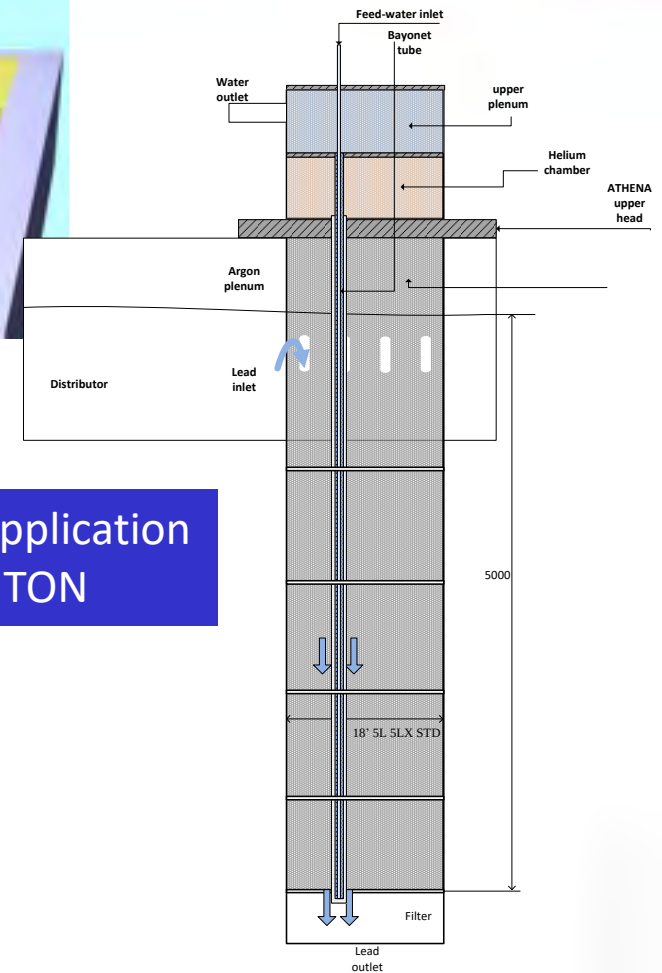
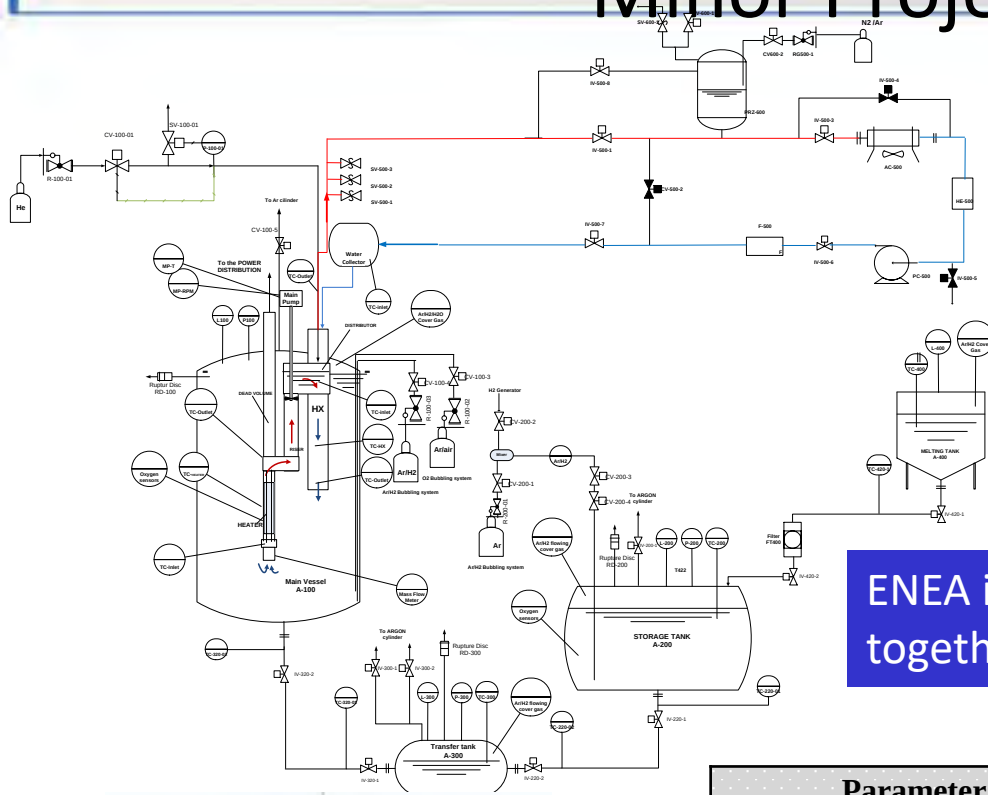
PHASE
2

- Detailed agreement
- R&D needs management
- Engineering design
- Licensing, and
- Commit the construction

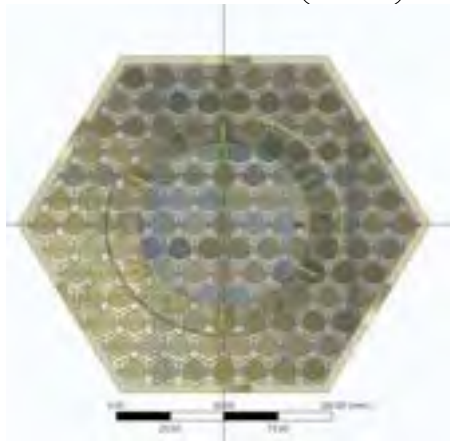


THE FALCON CONSORTIUM IS EXTENDED TO JUNE 2016

Applicazione al grant rumeno per Minor Projects (20 Meuro)



ENEA is carrying on the application together with ICN and CITON



Assembly of fuel pin simulators

Parameter	Quantity
Total power	2.21MW
Total mass flow rate	189 kg/s
FPS inlet temperature	400 °C
FPS outlet temperature	480 °C
Rod diameter (D)	10.5 mm
Pitch (P)	13.86 mm
P/D	1.32
Hexagonal key	166 mm
Wrapper width	4 mm
Active length	600 mm
Average linear power	29 kW/m
number of pins	127
Total power	2.21 MW
Mass flow rate	189 kg/s
Average velocity	1.7 m/s

Heat exchanger

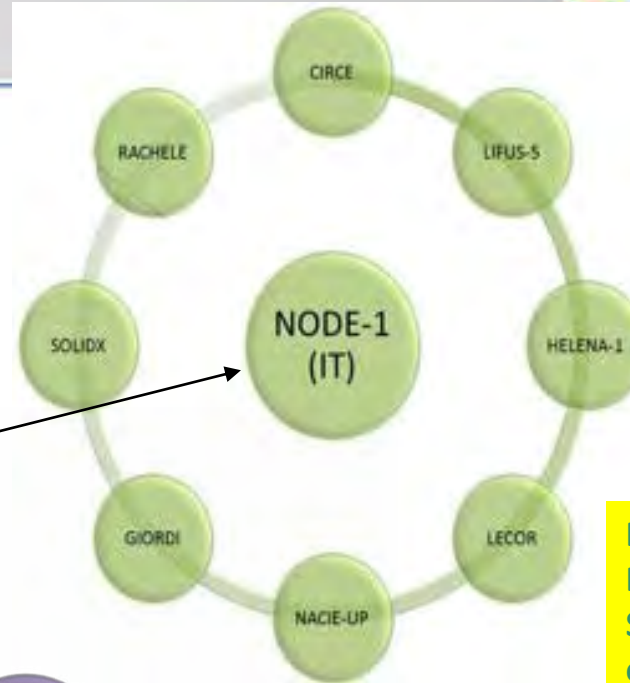
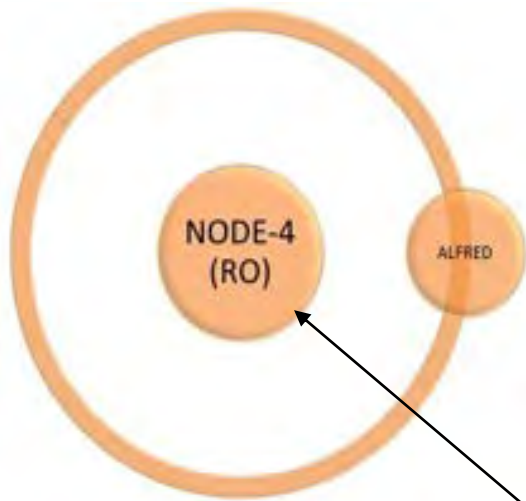
Richiesta che ALFRED venga classificato come Major Project (oltre 50Meuro)



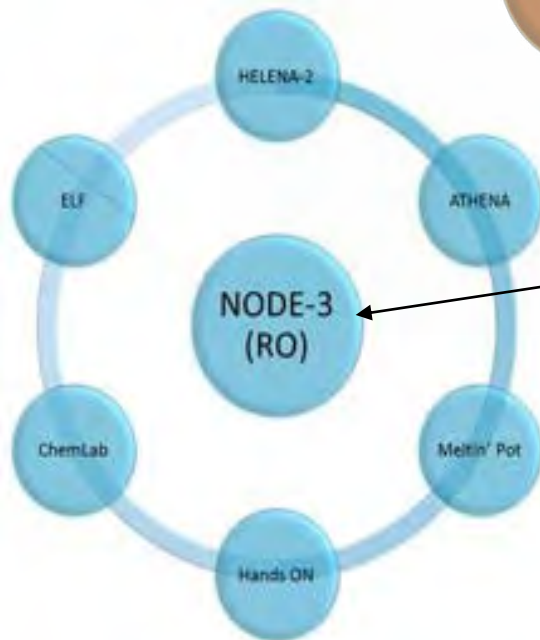
- Il 29 Ottobre, G.Villabruna di Ansaldo ha incontrato il ministro rumeno dell'Energia e la D.G. Elena Popescu
- Nella riunione G.V. ha sollecitato l'inserimento di ALFRED tra i "Major Projects" ricevendo un feedback positivo
- Il 4 Novembre, a causa delle dimissioni del primo ministro, il Memorandum, già firmato dal ministro dell'Energia e da quello dell'Educazione/Ricerca, si è arrestato presso il ministero dei fondi europei.
- Il 13 Novembre il Memorandum firmato dai tre Ministri e' stato portato alla riunione del Consiglio dei Ministri, ma, su indicazione del Ministero della Giustizia, non e' stato discusso in quanto essendoci un Governo ad interim non poteva essere approvato.
- Attendiamo la formazione del nuovo governo in Romania

iCRADLE in ESFRI

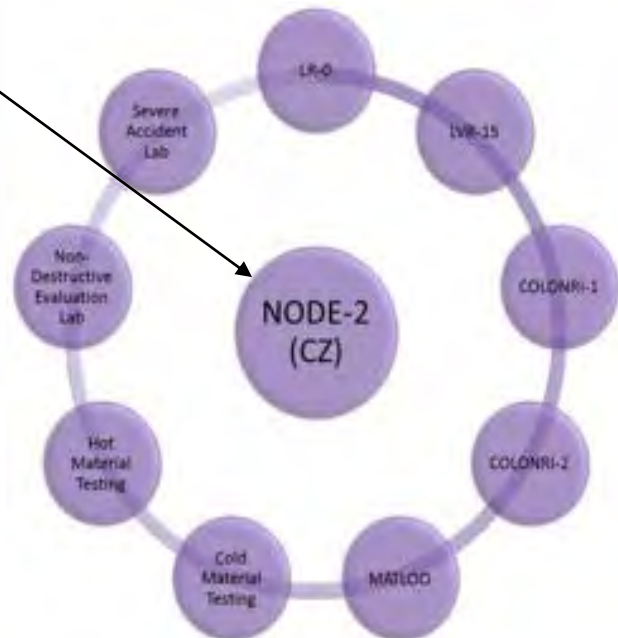
*"The iCRADLE proposal consists of a **Distributed Research Infrastructure (D-RI)** for research, development and qualification of the Heavy Liquid Metal (HLM) technology aimed to LFR reactor development"*



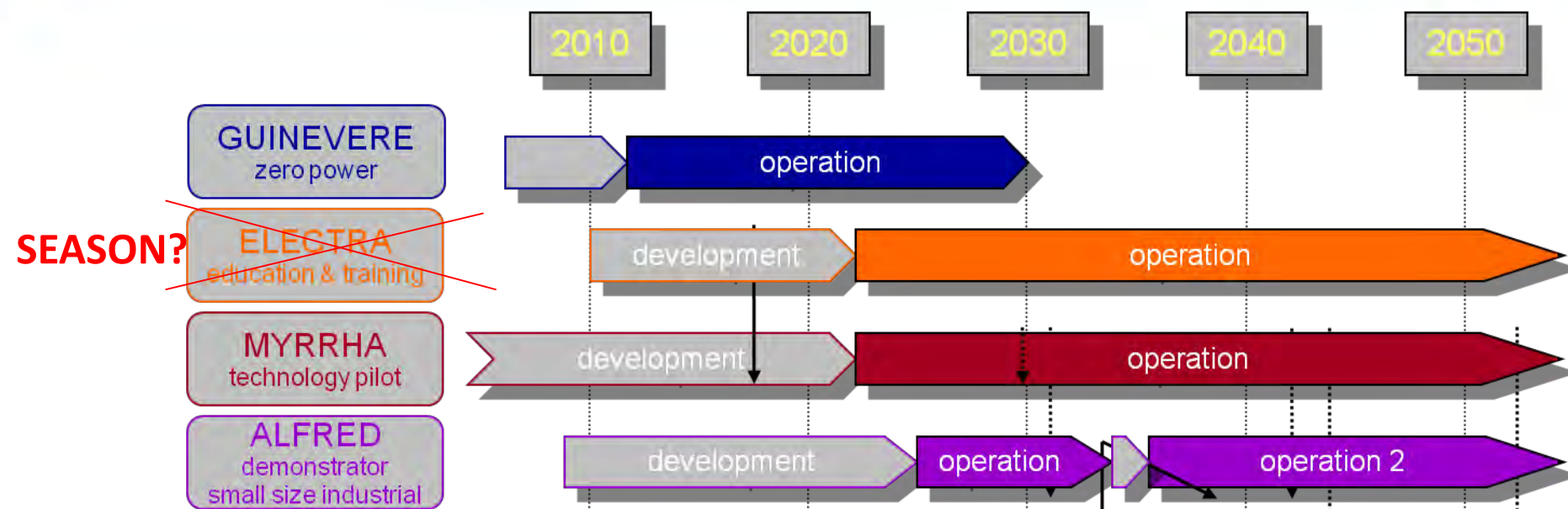
ESFRI is the European Strategy Forum on Research Infrastructures



Inclusion in ESFRI facilitates the access to European structural funds



Inserimento di un piccolo reattore nella strategia complessiva



- Il piccolo reattore svedese (ELECTRA) era già presente nella roadmap LFR.
- Nel 2013 il finanziamento fu cancellato dal governo svedese
- Il 20 Ottobre ENEA è stato contattato da Janne Wallenius, CEO della Lead Cool inc. per collaborare allo sviluppo del progetto **SEASON**: Small, Efficient And Safe Options for Nuclear
- Viene proposto di applicare ad NFRP 4 della recente call EURATOM

Prossime azioni nel Consorzio FALCON



- Sussistono ancora incertezze sulle modalità di accesso ai fondi strutturali europei ed incertezza sull'entità richiedibile. **Saranno intensificati i contatti con le autorità Rumene**
- Sono stati accumulati ritardi sull'avviamento delle attività tecniche incluse negli agreement of collaboration. **E' urgente definire e pianificare le attività in kind da affidare ai sottoscrittori**
- Sono in preparazione le proposte per i progetti di R&D della call EURATOM Fissione. **E' necessario armonizzare in essa i contenuti degli agreement of collaboration**
- Si prevede partecipazione significativa a progetti su:
 - **sicurezza, gen IV**
 - **materiali,**
 - **SMR.**

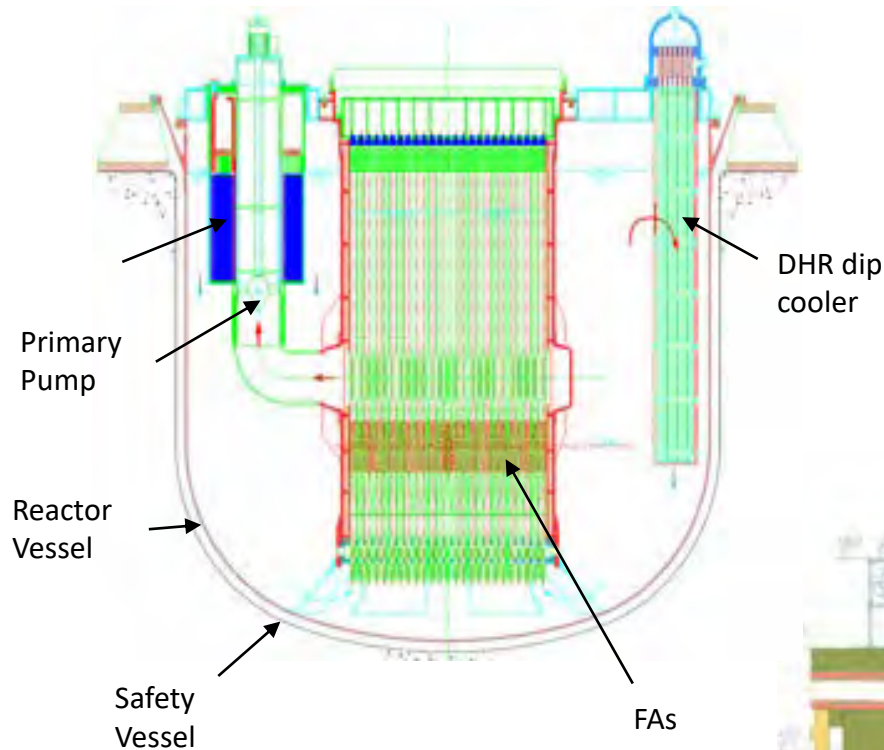


Stato delle collaborazioni in corso

Partecipazione a GIF -GEN IV Forum-

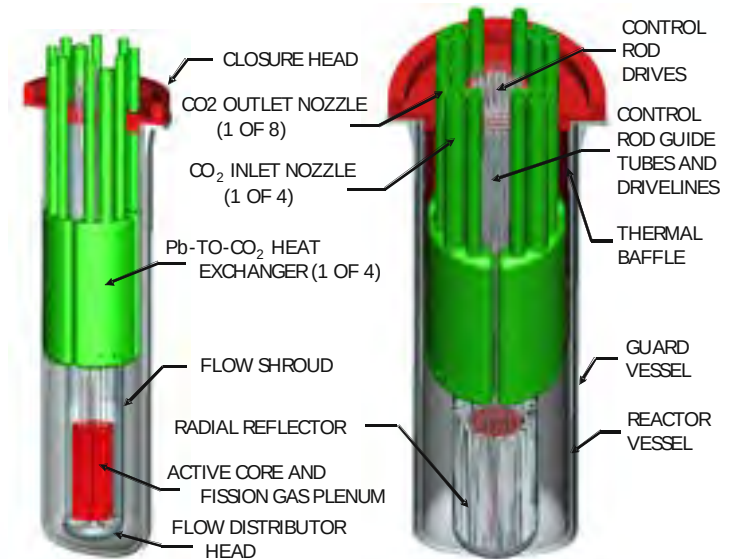
I paesi con interesse LFR in GIF sono: Europa, Russia, USA, Giappone, Corea

ELFR (600 MWe), BREST (300 MWe), and SSTAR (small size)

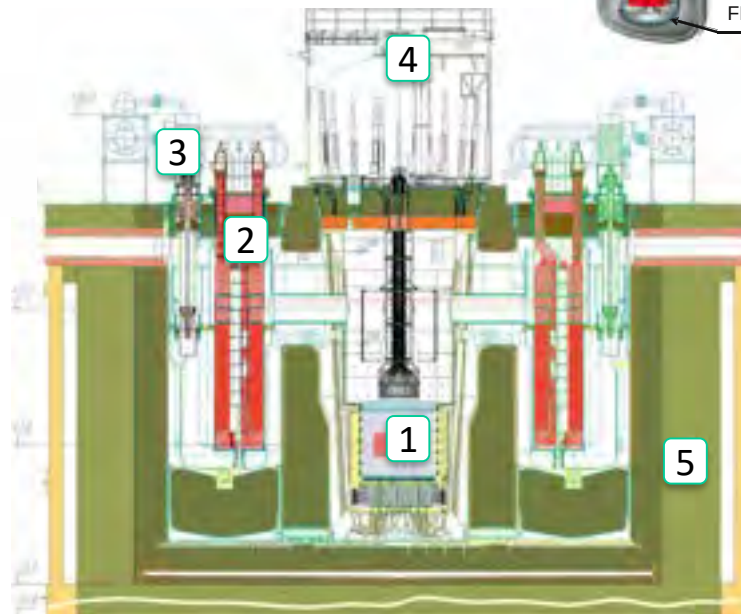


ELFR
system for central station
power generation

BREST
system of
intermediate size



SSTAR
system of small size with
long core life



- 1 - Core
- 2 - Steam Generator
- 3 - Pump
- 4 - Refueling Machine
- 5 - Reactor Vault

Collaborazione con USA

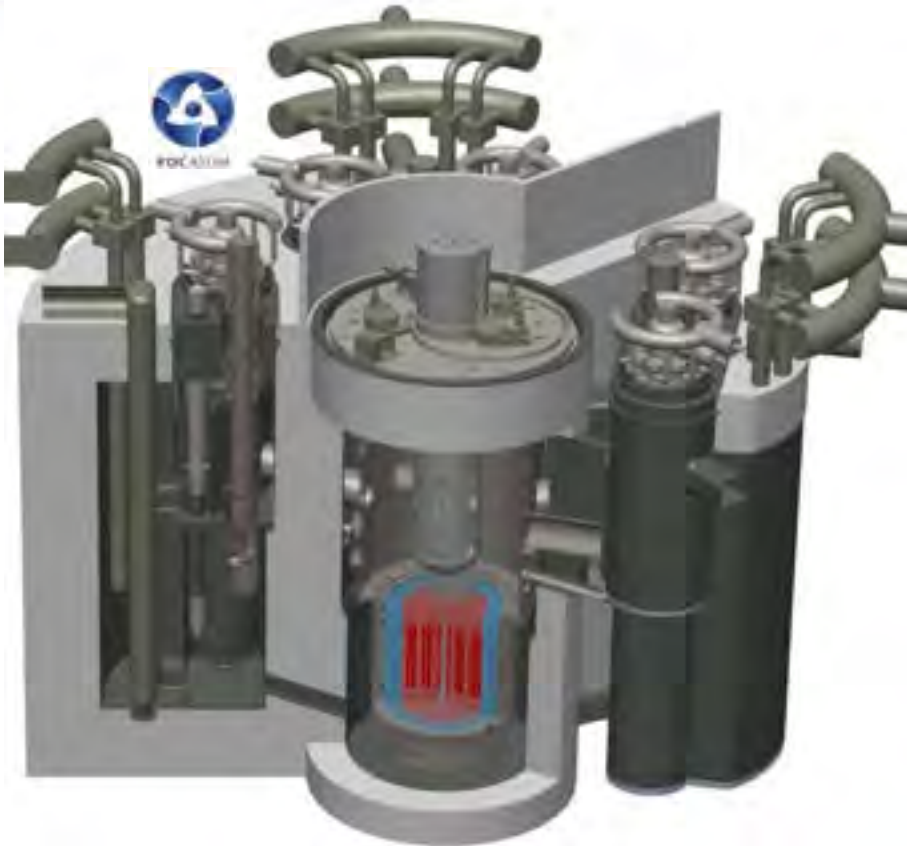


Fiscal Year 2016 Request: \$908M

- **Reactor Concepts** (\$108M)—Expands light water reactor sustainability efforts to maintain carbon free generation of the current fleet and supports development of non-water cooled reactor systems.
- **Small Modular Reactors** (\$63M)—Continues technical support for licensing SMRs.
- **STEP R&D** (\$5M) —Initiates multi-program effort to accelerate commercialization of sCO₂ Brayton cycle energy conversion technologies with a 10MW demonstration project.
- **Fuel Cycle R&D** (\$218M)—Expands effort to develop commercial used nuclear fuel disposal solutions; maintain schedule for 2016 selection of accident tolerant fuel candidates for further development and testing.
- **Nuclear Energy Enabling Technologies** (\$86M)—Continues Energy Innovation Hub for Modeling and Simulation for second 5-year period; advanced modeling and simulation for NE R&D programs.
- **Idaho National Laboratory** (\$338M) —Modernization of facilities and security capabilities.

- Nell'ambito dei bandi DOE 2016, WESTINGHOUSE ha applicato per una proposta LFR.
- L'unico partner non USA invitato a collaborare è stato ENEA
- ENEA partecipa alla proposta con una quota dell'8.5%
- Gli ambiti di partecipazione ENEA sono la progettazione del nocciolo e la tecnologia dei materiali
- Il consortium agreement tra ENEA e Westinghouse è attualmente in revisione presso ENEA

Collaborazione con la Russia



BREST-OD-300 SCHEDULE:

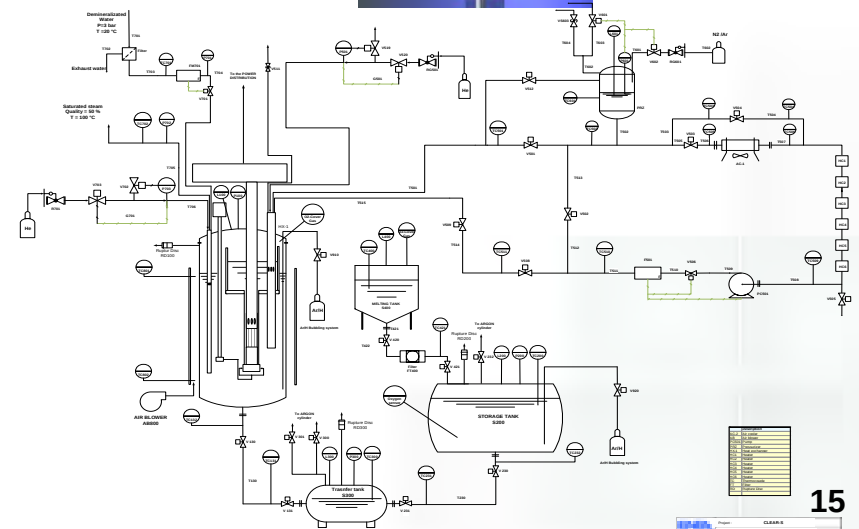
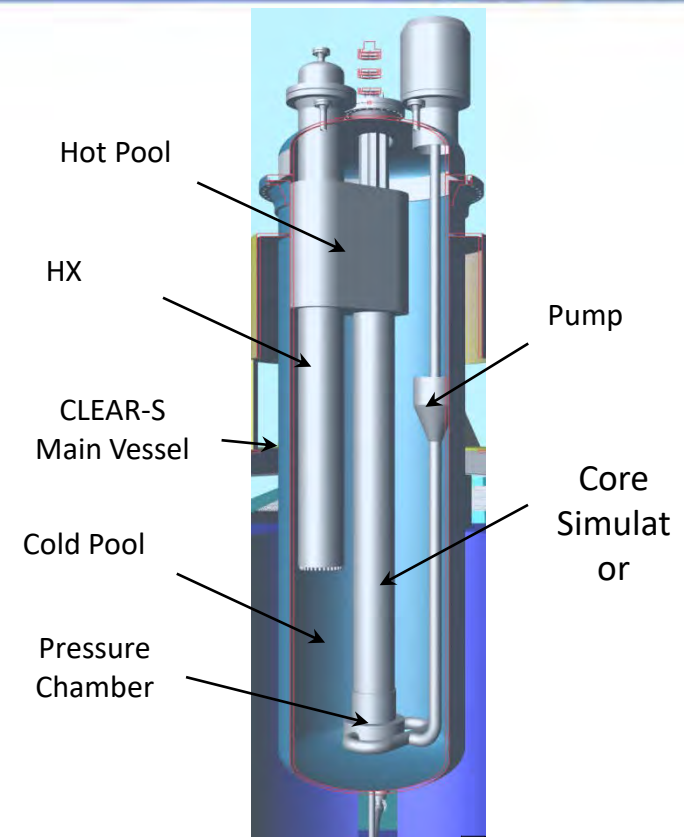
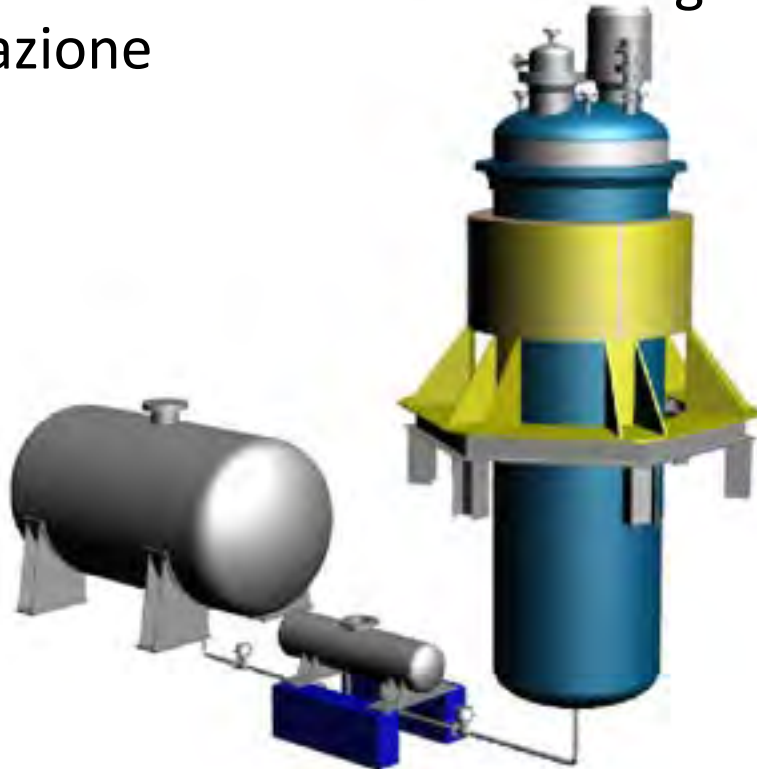
Design completed	2014
License approval	2015
Start of construction	2016
Commissioning	2020-2022

**Seminar on thermal-hydraulics of lead-cooled reactors
Ansaldo Nucleare HQs – December 2-3, 2015**

- Safety Approach for LFR.
- CFD modeling of mixing of heavy metal model flows
- 3D simulation of turbulent heat transfer in a swirling flow
- Study of partial blocking the flow cross section at the coolant inlet

Collaborazione con la Cina

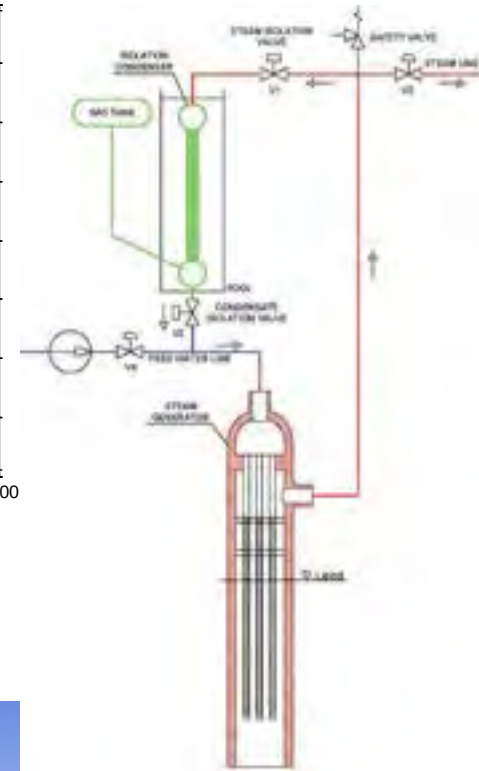
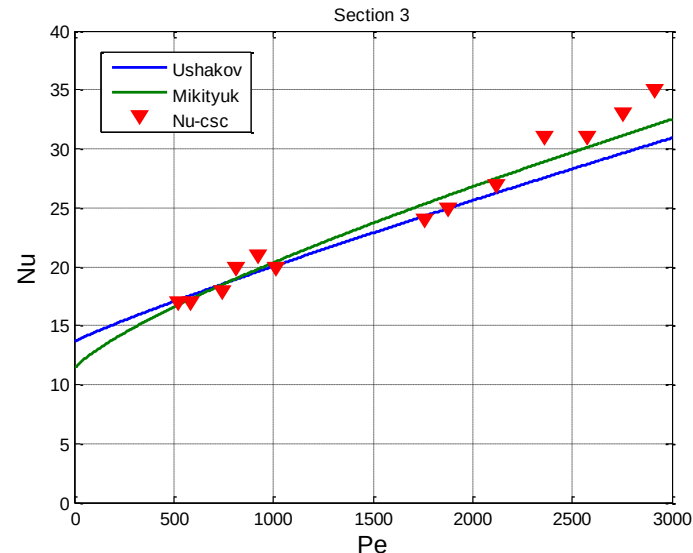
- ENEA Brasimone fornirà all' Accademia Cinese delle Scienze nel 2016 l'impianto CLEAR-S per la qualificazione sperimentale del prototipo di trasmutatore CLEAR I.
- La fornitura ha un valore di circa 6 Meuro
- L'accordo comprende anche assistenza nella fase di commissioning e sperimentazione nonché nella definizione della strategia di sperimentazione



Prospettive tecnologiche

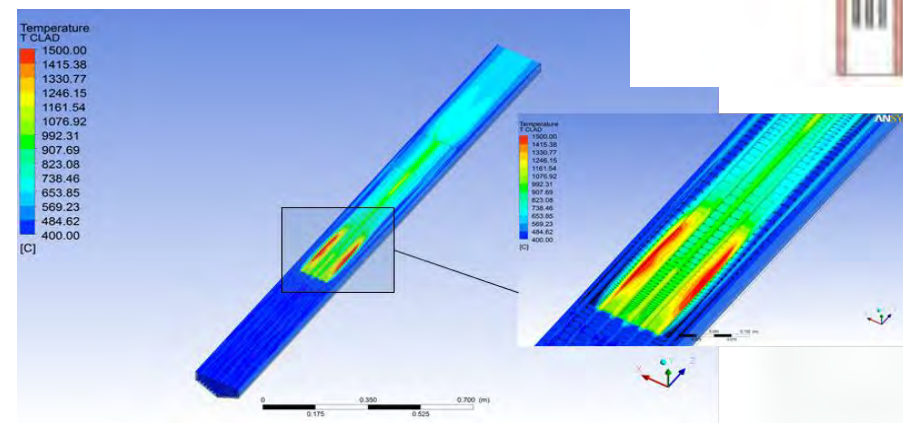
Termoidraulica

- Dal 2008 ad oggi sono state risolte molte incertezze grazie agli impianti del Brasimone.
- In particolare sono state fatte misure del numero di Nusselt ed è stata dimostrata l'efficacia di raffreddamento della **convezione naturale** in condizioni di emergenza.
- Sono stati **validati i codici di calcolo termofluidodinamico** rendendo credibile l'impiego di tali strumenti



Le prospettive future riguardano argomenti mirati a dimostrare la sicurezza del LFR :

- La dimostrazione dei **dispositivi di emergenza** (isolation condenser e DHX)
- L'approfondimento delle **conseguenze del freezing** e misure correttive
- L'approfondimento del **flow blockage**



- [illegible]

1 year

Pb penetration

316L

A black and white micrograph of a 20Ni AFA surface. A white arrow points to a dark, irregular line along the top edge, labeled "Pb penetration". The text "20Ni AFA" is printed in the bottom left corner.

L'acciaio dei fuel cladding è il 15-15 Ti, in quanto qualificato, ma si tende ad un **austenitico a basso swelling**.

L'acciaio dei componenti (GV) è il 316 ma si tende ad un AFA.

Ancora **R&D da condurre** e necessità di facility di irraggiamento.



DEMO-LFR ALFRED: Technical Overview

WORKSHOP LFR-GEN IV - STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO

Brasimone, 19-20 Novembre, 2015 - Centro Ricerche ENEA Brasimone

Michele Iamele

Michele.iamele@ann.ansaldo.it



CONTENTS

- Introduction and Design Guidelines
- Overview of Main Primary System Components
 - Reactor Assembly Configuration
 - Reactor Vessel
 - Inner Vessel and Upper/Lower Core Support Plates
 - Steam Generator
 - Primary Pump
 - Decay Heat Removal Systems
 - Reactor Building
- Conclusions & Open issues



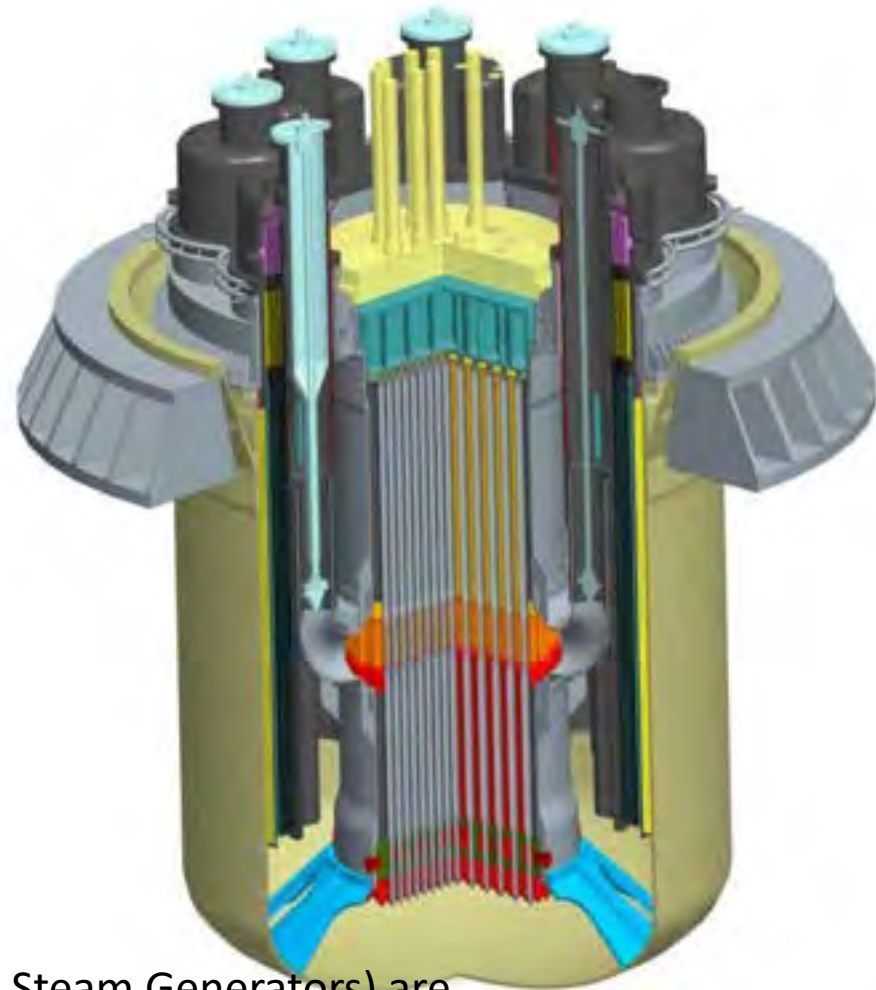
Main Design Guidelines

Top-level Technical Requirements

- ALFRED will be connected to the electrical grid (Reactor Power ~130 MWe)
- ALFRED design should be based on available technology as much as possible, in order to speed up the construction time
- ALFRED shall use structural materials compatible with the corrosive Lead used as coolant (Selected material AISI 316LN, T91, 15-15/Ti)
- ALFRED design shall limit coolant flow velocity to values compatible with the erosive Lead used as coolant
- ALFRED design solutions shall allow components to be removed from the Reactor Vessel to facilitate inspection, maintenance, replacement
- ALFRED design solutions (especially for Safety and Decay Heat Removal function) should be characterized by very robust and reliable choices to smooth the licensing process
- ALFRED Decay Heat Removal Systems shall be based on passive technology to reach the expected high Safety level



- Pool type primary system
- Relatively Low Power: 300 MWth (130 Mwe)
- Compact Design based on:
 - simple and removable components
 - proven technologies and materials
- The primary coolant is molten lead, which is characterized by good Nuclear and chemical properties
- The hot pool is enclosed by the Inner Vessel that feeds the suction pipes of the Primary Pumps and Steam Generators integrated into a single vertical unit.
- The Reactor assembly presents a simple flow path of the primary coolant, the position of the heat source (the Core) and the heat sink (the Steam Generators) are studied to allow an efficient natural circulation of the coolant.

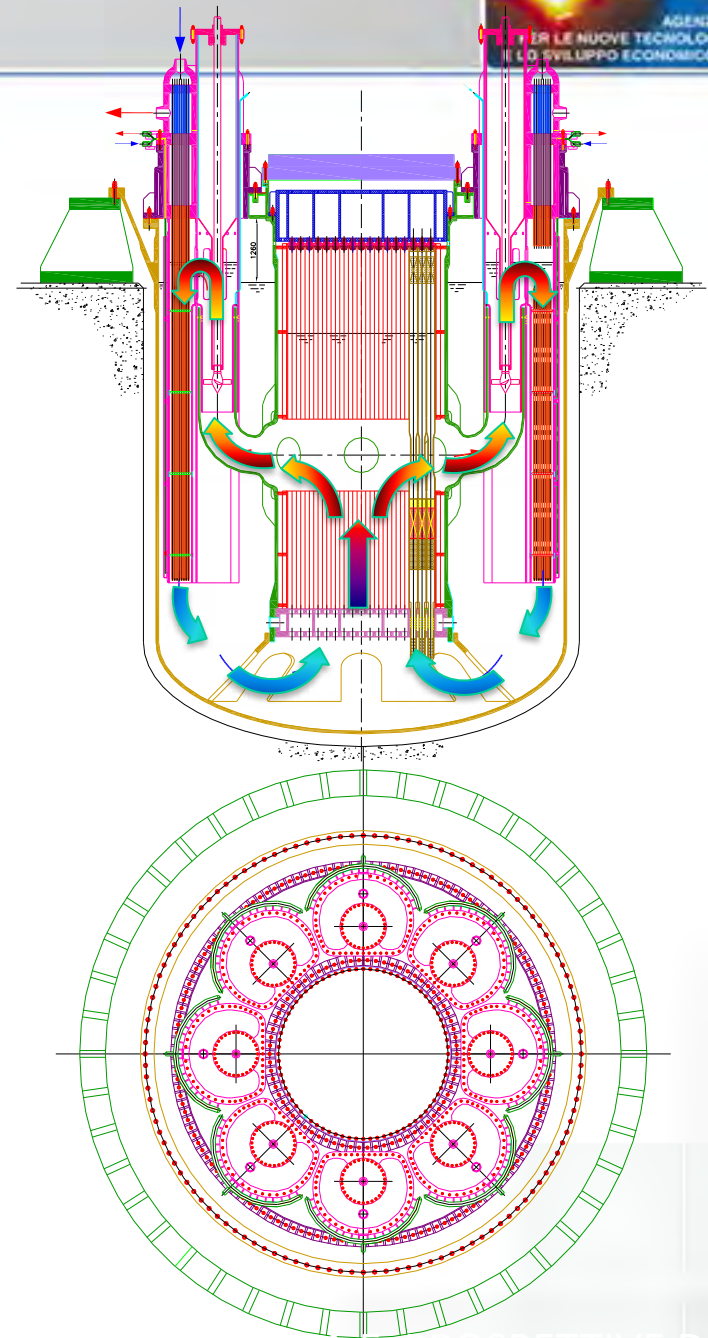


ALFRED - Reactor Configuration from LEADER

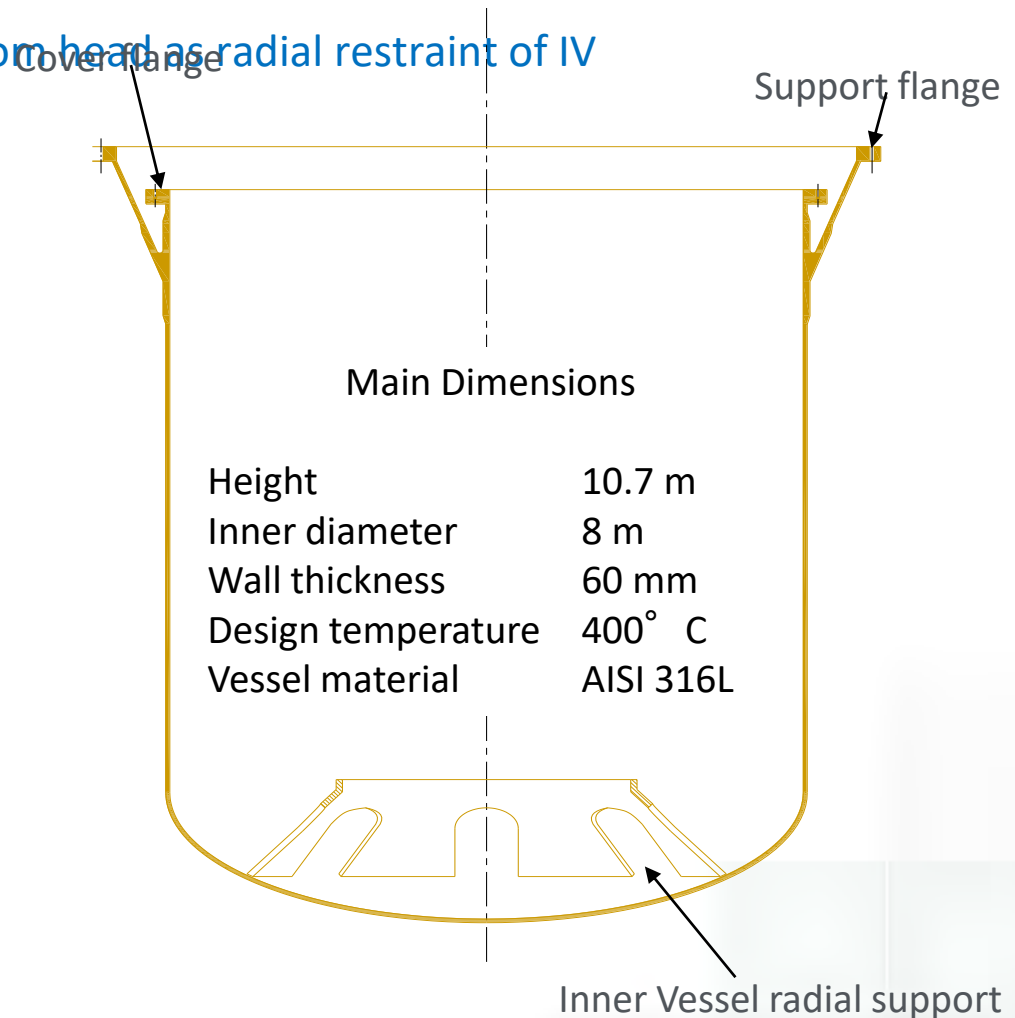


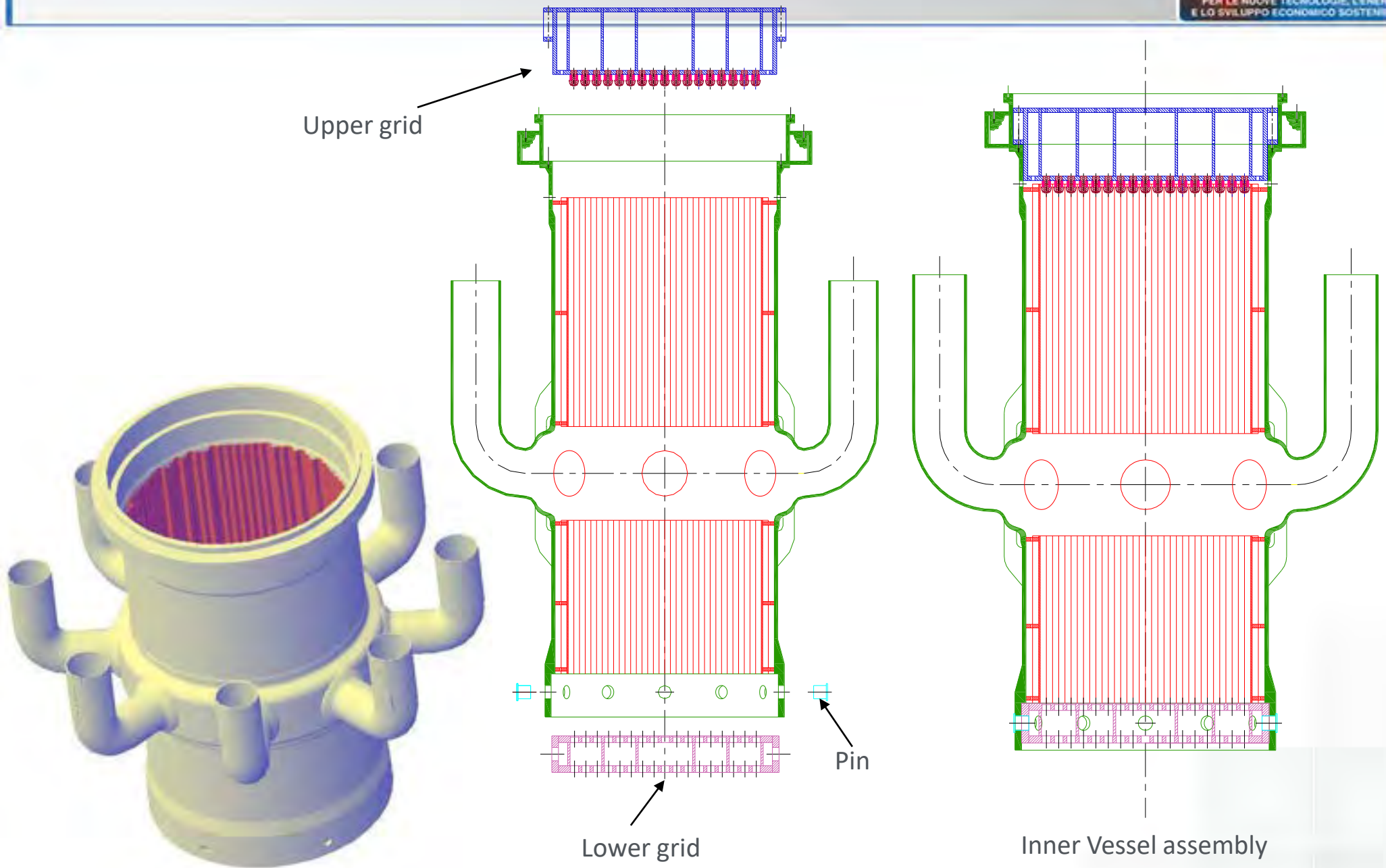
Main Design Data

Core power / Electrical Power	300 MW _t / 130 Mwe
Primary Coolant	Pure Lead
Reactor vessel	Austenitic SS Height = 10,7 m Inner diameter = 8 m
Safety Vessel	Anchored to reactor pit
Inner Vessel	Cylindrical, Height = 9.7 m Inner diameter = 3.3 m
Core Inlet/Outlet Temperatures	400° C / 480° C
Steam generators	8 units, bayonet tubes type, integrated in the reactor vessel, removable
Fuel Assembly	Closed (with wrapper), Hexagonal,
Refuelling System	No refuelling machine stored inside the Reactor Vessel
DHR System	2 separate and redundant systems of 4 Isolation Condensers connected to the Steam Generator (actively actuated, passively operated)



Cone frustum welded to the bottom head as radial restraint of IV





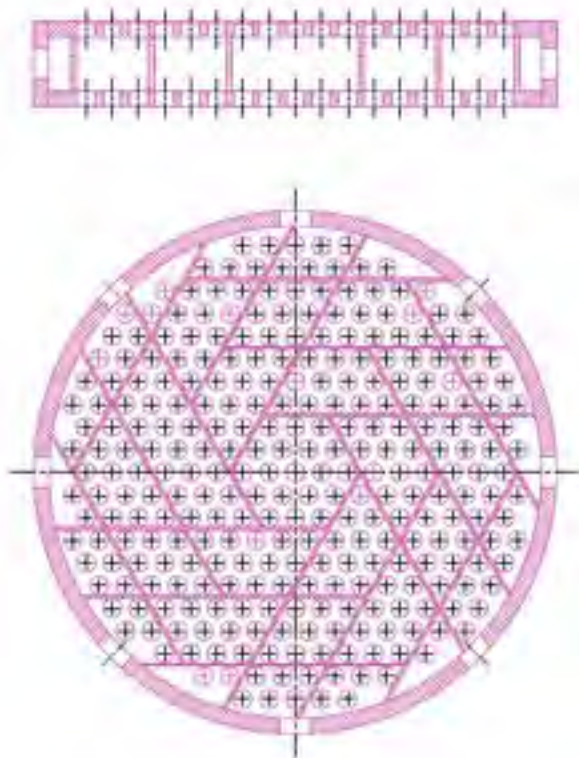
UPPER AND LOWER CORE SUPPORT PLATES

Lower core support plate

Box structure with two horizontal perforated plates connected by vertical plates.

Plates holes are the housing of FAs foots.

The plates distance assures the verticality of FAs

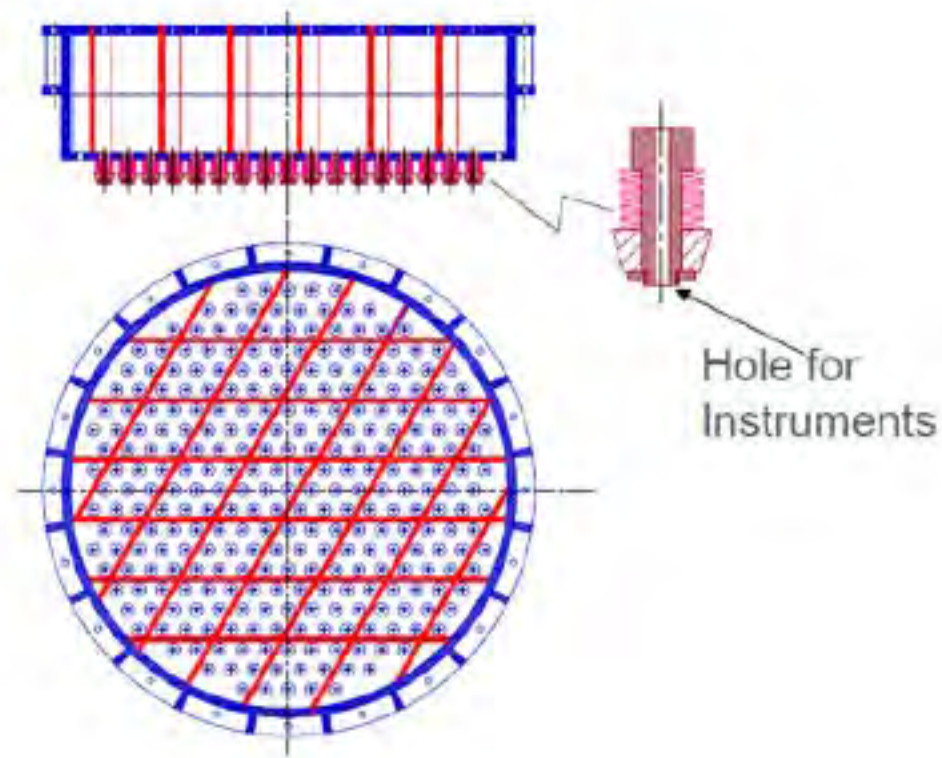


Upper core support plate

Box structure as lower grid but more stiff

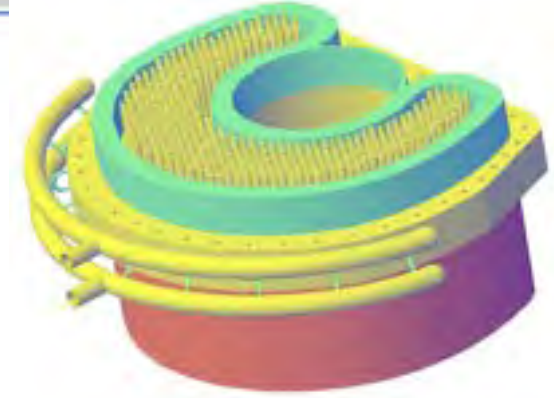
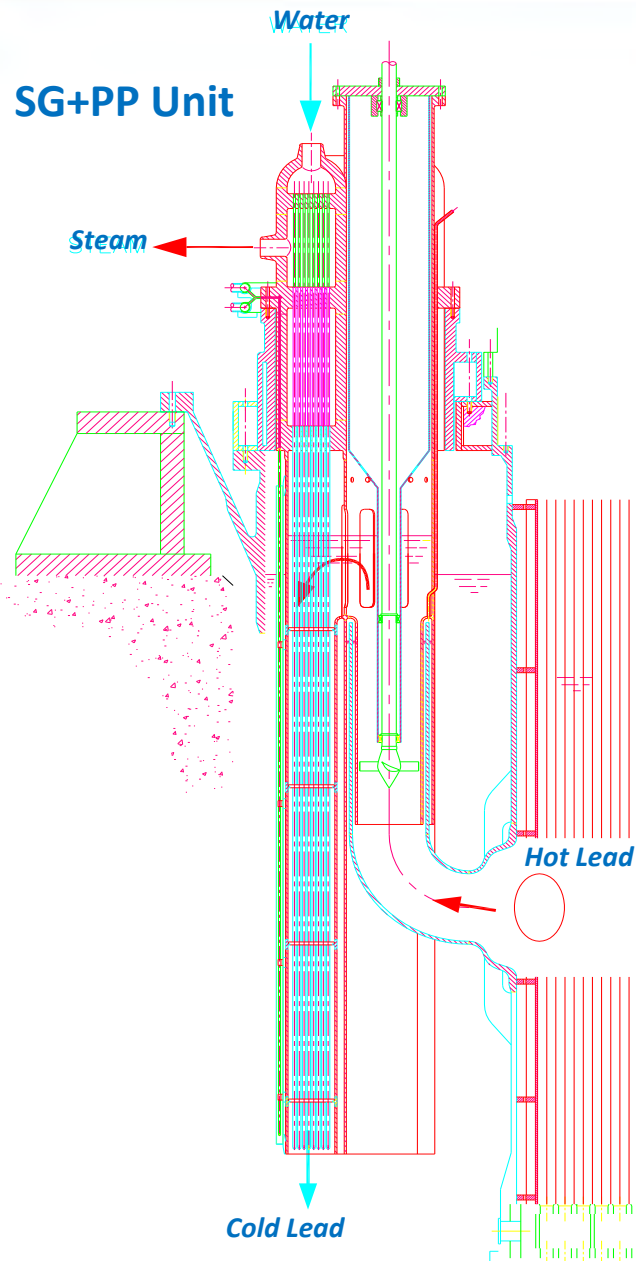
It has the function to push down the FAs during the reactor operation

A series of preloaded disk springs presses each FA on its lower housing

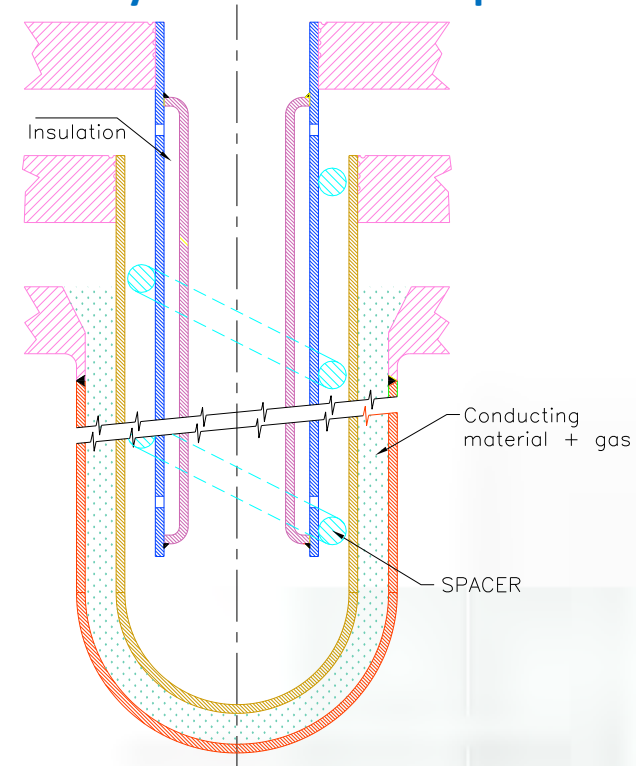


STEAM GENERATOR

Auxiliary cooling collector



Bayonet Tube Concept





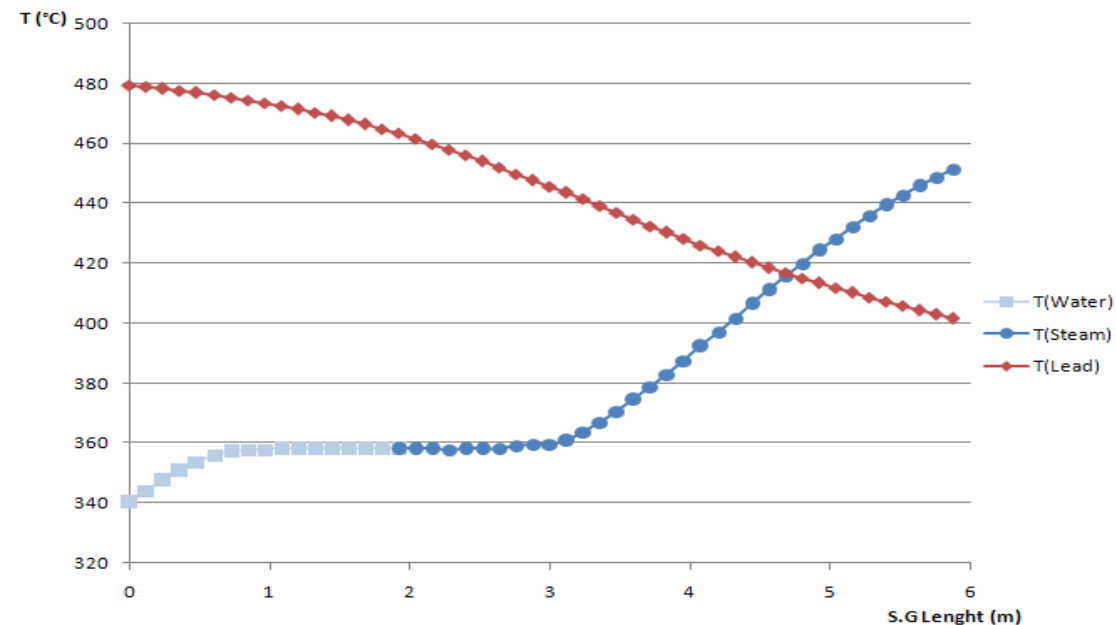
Steam Generator Geometry

Number of coaxial tubes	4
Slave tube O.D	9.52 mm
Slave tube thickness	1.07 mm
Inner tube O.D	19.05 mm
Inner tube thickness	1.88 mm
Outer tube O.D	25.4 mm
Outer tube thickness	1.88 mm
Outermost tube O.D	31.73 mm
Outermost tube thickness	2.11 mm
Length of exchange	6 m
Number of tubes	510

Steam Generator Performance

Removed Power [MW]	37.5
Core outlet Lead Temperature [°C]	480.0
Core inlet Lead Temperature [°C]	401.5
Feedwater Temperature [°C]	335.0
Immersed bayonet steam outlet T [°C]	451.5
Steam Plenum Temperature [°C]	450.1
SG steam/water side global Δp [bar]	3.3

Steam Generator Thermal Cycle



Primary pump is an axial mechanical pump, always running at constant speed, with blade profile designed to achieve the best efficiency



Parameters	Value
Flow rate	3247.5 kg/s
Head	1.5 m
Outside impeller diameter	0.59 m
Hub diameter	0.39 m
Impeller speed	315 rpm
Number of vanes	5
Vane profile	NACA 23012
Suction pipe velocity	1.12 m/s
Vanes tip velocity	9.8 m/s
Meridian (at impeller entrance and exit) velocity	2.0 m/s

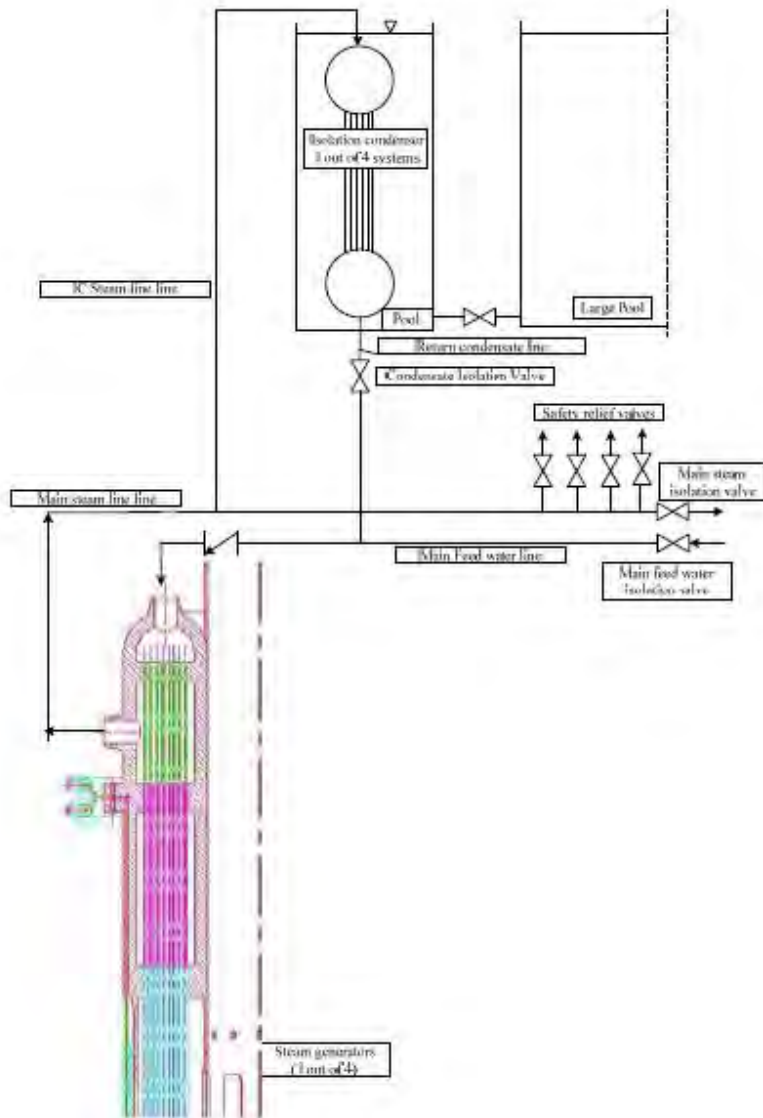
DHR Systems

One non safety-grade system, the secondary system, used for normal decay heat removal

Two independent, high reliable passive and redundant safety-related DHR systems:

in case of unavailability of the secondary system, the DHR1 is called to operate and

in the unlikely event of unavailability of the first two systems, the DHR2 is called to operate



DHR-1:

Isolation Condenser system connected to 4 out of 8 SGs

DHR-2:

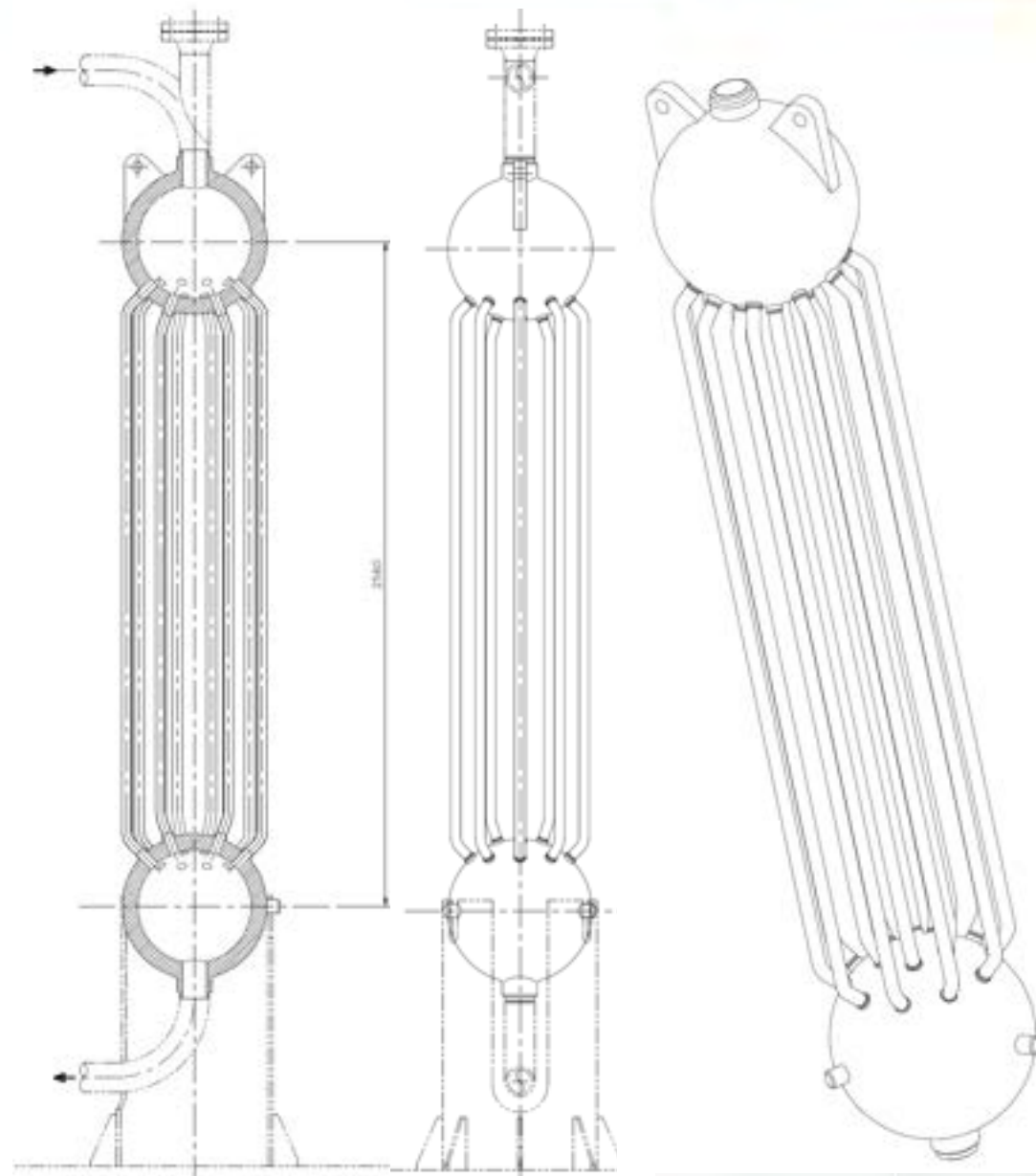
Isolation Condenser system connected to the other 4 SGs

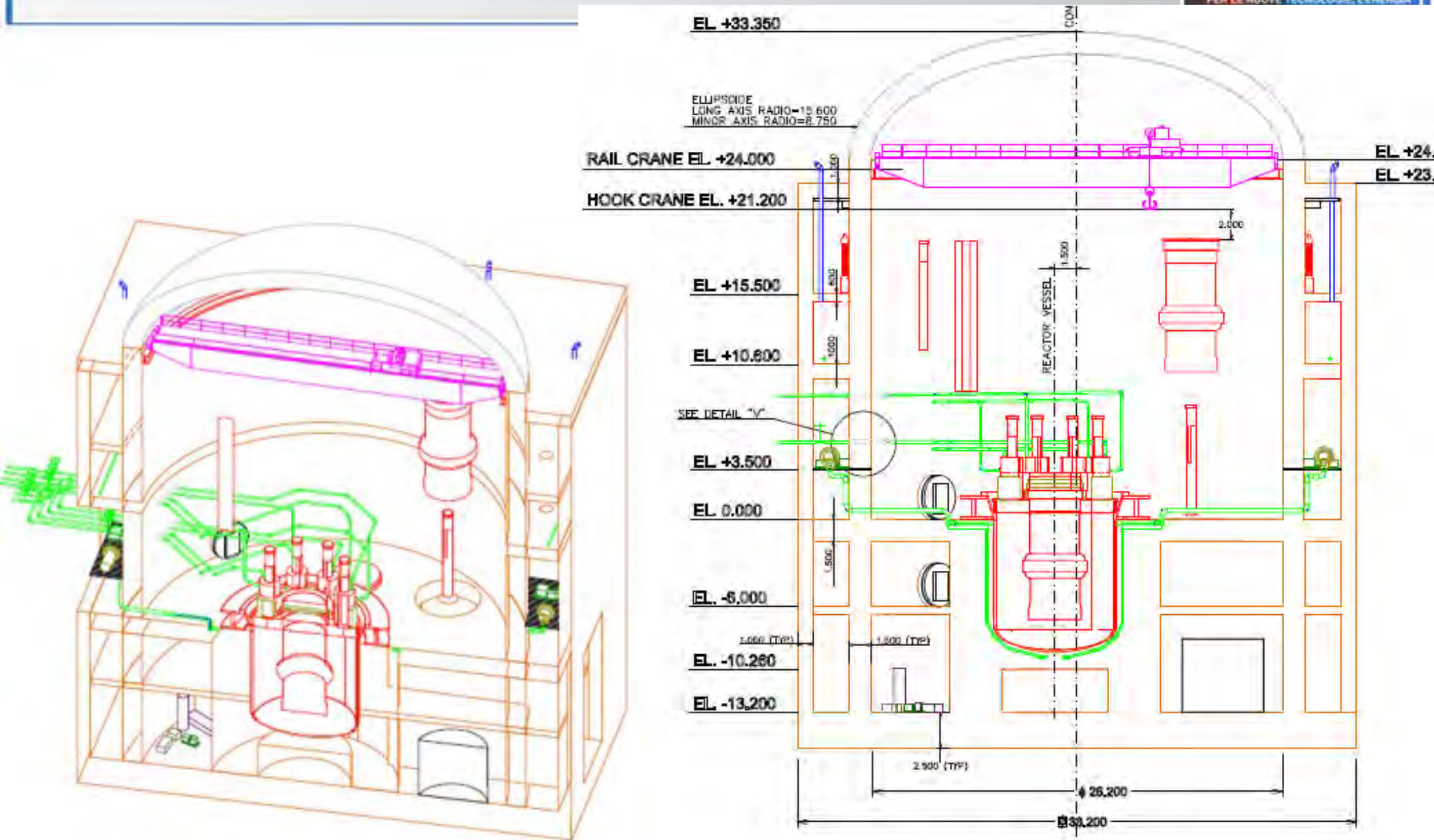
Considering that, each SG is continuously **monitored**, ALFRED is a **demonstrator** and a redundancy of **266%** is maintained, the Diversity concept could be relaxed

DHR Systems features:

- **Independence:** two different systems with nothing in common
- **Redundancy:** three out of four loops (of each system) sufficient to fulfil the DHR safety function even if a single failure occurs
- **Passivity:** using gravity to operate the system (no need of AC power)

Parameter	Value
Upper and lower spherical header diameter	560 mm
Tube diameter	38.1 mm
Number of tubes	16
Average tube length	2 m
Material Inconel	600





ALFRED Technical Review...

Open issues that need to be carefully addressed before defining the reference conceptual design:

- Upper part of the “cold plenum” could result stagnant

 - Stratification

 - Smaller fluid volume participating to the natural circulation phase

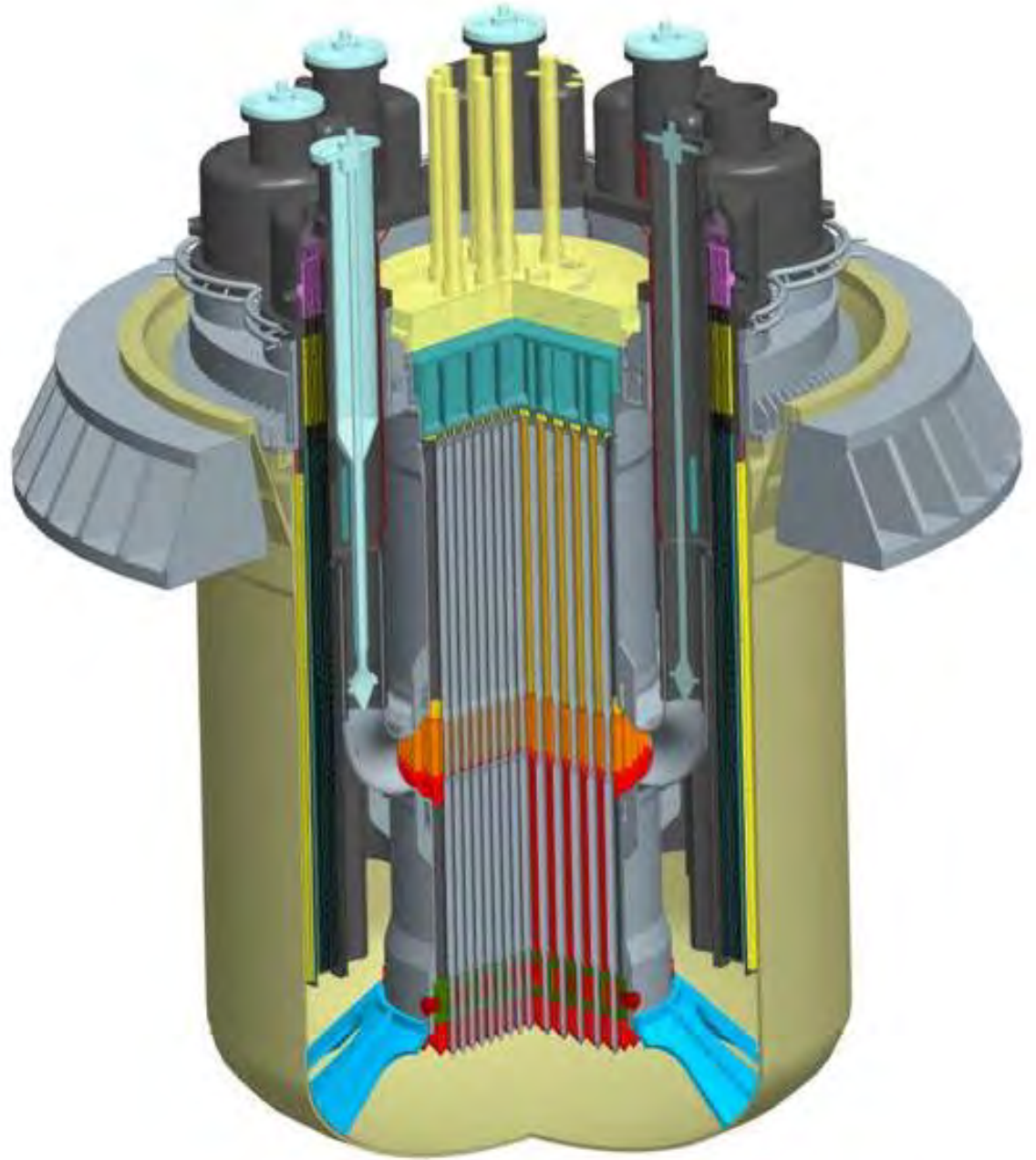
 - Oxygen/Chemical Control Issue

- SG design: by pass flow & mechanical issues.

- Need of two diverse DHR systems

The LEADER Project was able to give a reference configuration but much work has yet to be done before a final configuration is available.

*Thank you
for your attention*





TAPIRO Fast Reactor.

Feasibility study of minor actinides irradiation campaign

M. Carta*, P. Console Camprini, V. Fabrizio, A. Grossi, V. Peluso (ENEA)

P. Blaise, B. Geslot, A. Gruel (CEA)

F. Boccia (Università di Roma "La Sapienza")

C. Bethaz (Politecnico di Torino)

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Background



- The reduction of the nuclear waste is one of the most important nuclear issues.
- The high radiotoxicity of the spent fuel is due to plutonium and some minor actinides (MAs) such as neptunium, americium and curium, above all.
- To allow the MAs destruction an important effort have been done on the nuclear data due to the poor knowledge in this field.
- To improve MAs nuclear data, in the framework of the second *NEA Expert Group on Integral Experiments for Minor Actinide Management* an analysis of the feasibility of MAs irradiation campaign in the TAPIRO fast research reactor is in progress. The work is performed in close collaboration with *CEA*.
- Some preliminary results have been obtained by calculations modelling the irradiation, in different TAPIRO irradiation channels, of some CEA samples coming from the French experimental campaign *OSMOSE*.
- On the basis of neutron transport calculation results, obtained by both deterministic *ERANOS* and Monte Carlo *Serpent* calculation tools, an estimate of the irradiated samples counting levels has been obtained.
- The experimental campaign is named *AOSTA* (*Activation of OSMOSE Samples in TAPIRO*).



Background



Time integrated flux

$$\bar{\phi} T \sim \left[\frac{N_{Nd8}(T)}{N_{U5}(T)} \right]_m \frac{1}{\gamma_{Nd8} \bar{\sigma}_{U5}^f}$$

At TAPIRO core center this value is $1.265 \pm 3.5\%$ (barns).

MA capture x-section

$$\left[\frac{N_{A+1}(T)}{N_A(T)} \right]_m \equiv [R_{A+1}(T)]_m$$

$$\bar{\sigma}_A^c \sim \frac{[R_{A+1}(T)]_m - [R_{A+1}(0)]_m}{[\bar{\phi} T]_m}$$

Reasonable irradiation times?

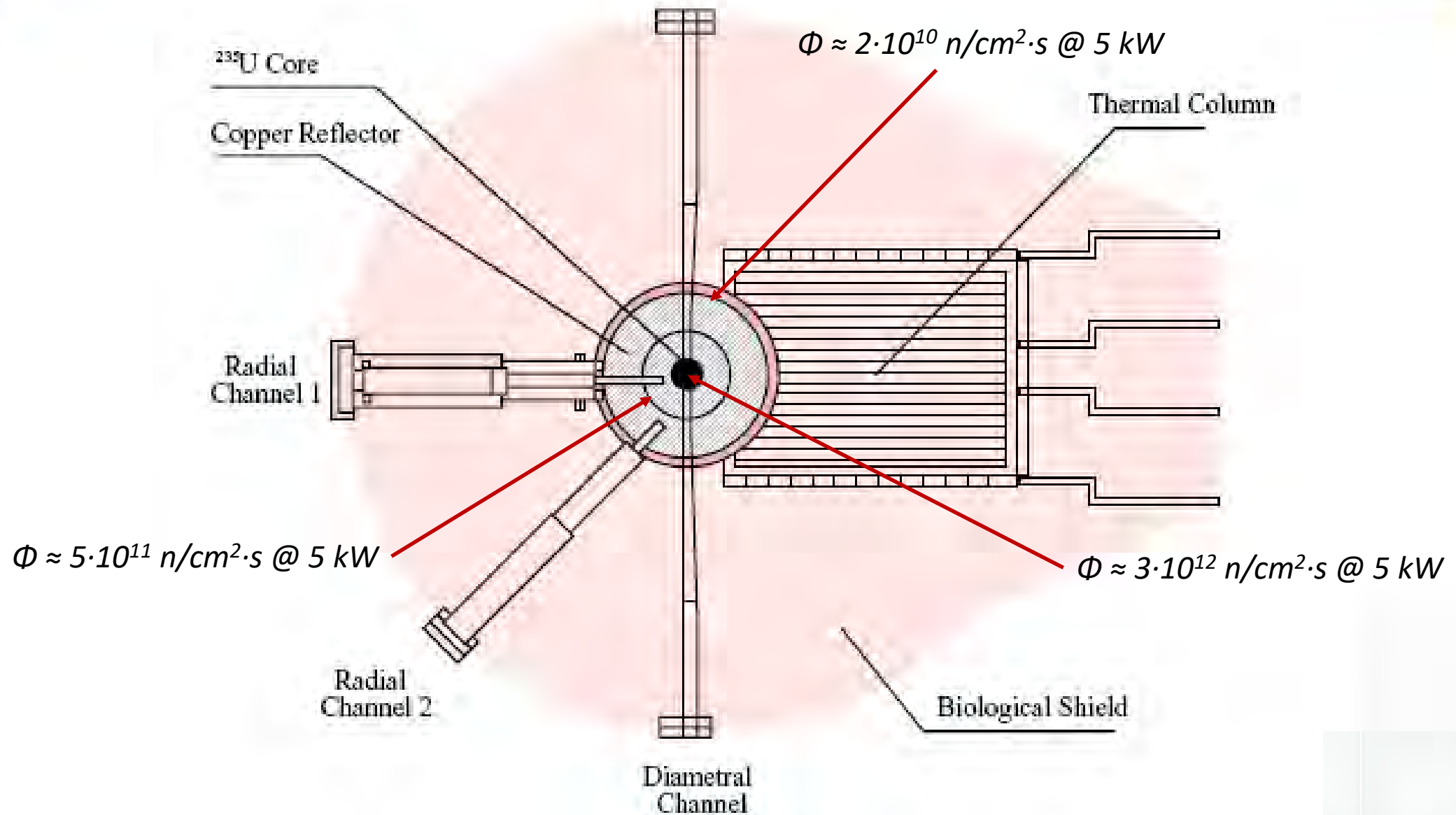
$$\bar{\sigma}_{A+1}^c \sim 2 \frac{[R_{A+2}(T)]_m}{[R_{A+1}(T)]_m [\bar{\phi} T]_m}$$

$$\bar{\sigma}_{A+2}^c \sim 3 \frac{[R_{A+3}(T)]_m}{[R_{A+2}(T)]_m [\bar{\phi} T]_m}$$



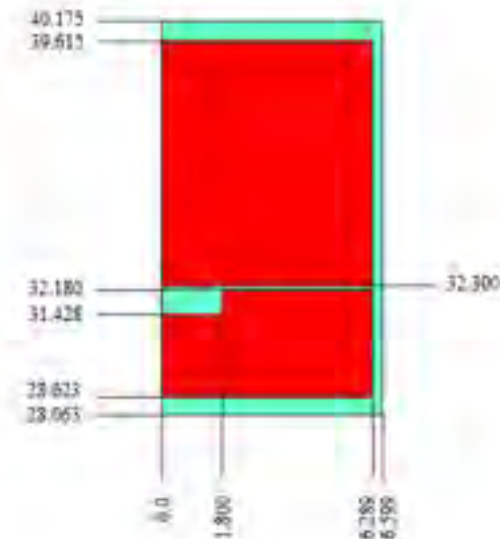
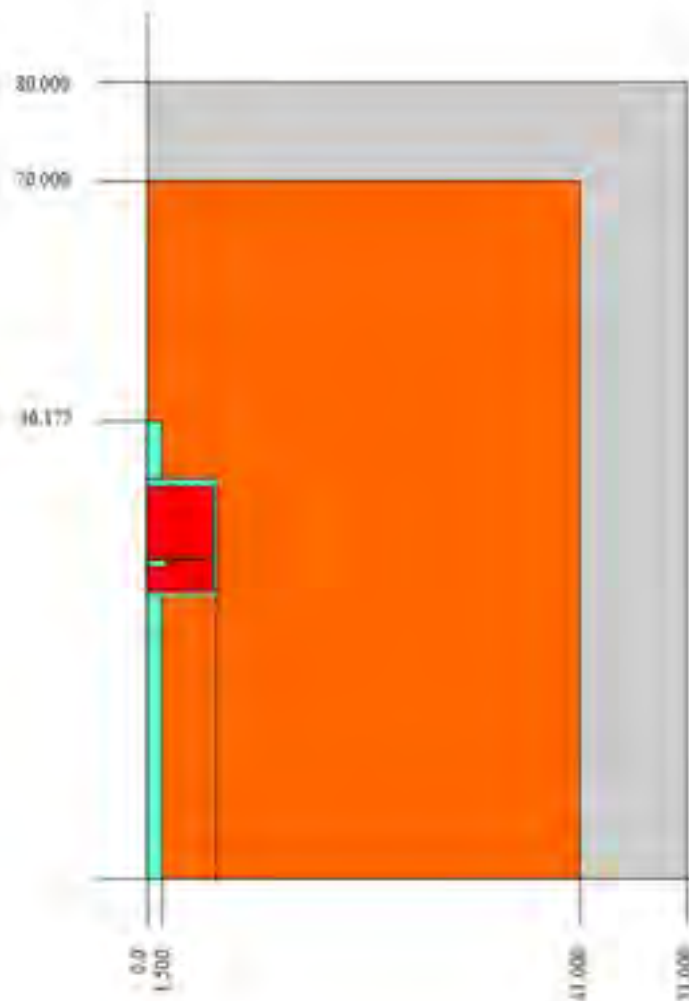
The TAPIRO reactor

Main characteristics





The TAPIRO reactor ERANOS RZ model



***TAPIRO is a simple system to model in view of benchmarking
among calculation tools and data libraries (IRPhE)***



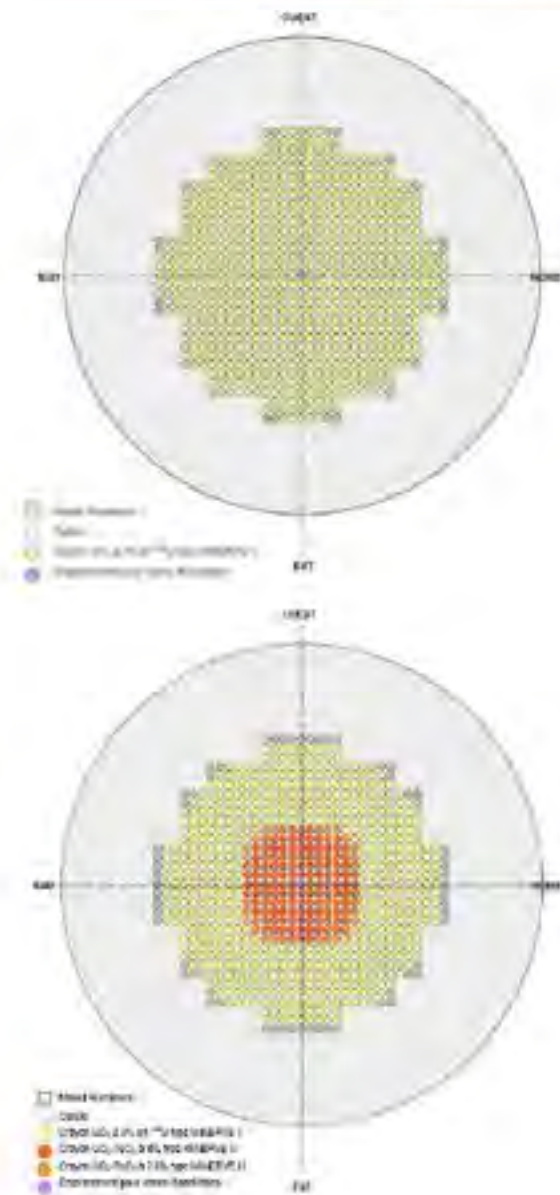
TAPIRO channels and OSMOSE samples

The OSMOSE programme



The OSMOSE programme in MINERVE

- Sample oscillation programme in MINERVE (2005 – 2010)
- In collaboration with DOE (INERI collaboration)
- Objectives :
 - Pu recycling in LWR
 - MA transmutation
 - Waste disposal and storage
- Two MINERVE configurations:
 - R1-UO₂ (REP-UO₂ spectrum)
 - R1-MOX (REP-MOX spectrum)
 - An over-moderated spectrum was foreseen but abandoned
- Main benefit: uncertainty reduction on nuclear cross sections of ^{237}Np , ^{238}Pu , ^{242}Pu , ^{241}Am , ^{243}Am et ^{245}Cm
- Sample Manufacturing (CEA Marcoule):
 - UO₂ or U₃O₈ pills (sintered or compacted)
 - Reprocessed uranium
 - Pure ThO₂





TAPIRO channels and OSMOSE samples

OSMOSE samples



Dimensions

- Internal sheath (Zy4): 9,56 mm
- External sheath (Zy4): 10,6 mm
- Length : 103.5 mm



Precise Material certificate are available

Actinide	Sample n°1 (g)	Sample n°2 (g)	Matrix
Unat	48	/	/
Np237	0.1	0.6	UO2 nat
Pu242	0.5	/	UO2 nat
U236	0.6	2	UO2 nat
Am241	0.06	0.2	UO2 nat
Am243	0.1	0.5	UO2 nat
U234	0.3	/	UO2 nat
Pu238	0.4	/	UO2 nat
Pu240	0.15	/	UO2 nat
Pu239	0.6	/	UO2 nat
U233	0.5	/	UO2 nat
Th232	2	/	UO2 nat
Th232	48	/	/
Pu241	0.1	0.5	UO2 nat



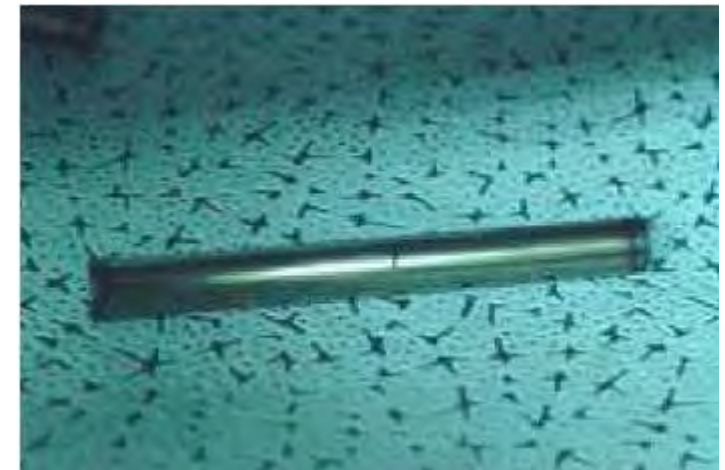
TAPIRO channels and OSMOSE samples Compatibility



Name	Position	Penetration	Useful diameter
Diametral channel (D.C.)	Piercing. Horizontal. Diametral in the core.	Inner and outer fixed reflector. Core.	10 mm in core
Tangential channel	Piercing. Horizontal. 50 mm above core mid-plane. Parallel to D.C. 106 mm from core axis.	Inner and outer fixed reflector.	30 mm in reflector
Radial channel 1 (R.C.1)	Radial. Horizontal on core mid-plane, at 90° with respect to D.C.	Inner and outer fixed reflector, up to 93 mm from core axis.	56 mm in reflector
Radial channel 2	Radial. Horizontal on core mid-plane, at 50° with respect to R.C.1.	Outer fixed reflector, up to 228 mm from core axis.	80 mm in reflector
Grand Horizontal Channel (G.H.C.)	Radial. Concentric with R.C.1.	Up to reflector outer surface	400 mm near reflector
Grand Vertical Channel (G.V.C.)	Above core, on the same axis.	Outer fixed reflector, up to 100 mm from upper core base.	800 ÷ 900 mm in reflector
Thermal column	Horizontal.	Shield, up to outer reflector	110x116x160 cm ³
Irradiation cavity	On safety plug upper base.	7.4 mm	33 mm

Dimensions

- Internal sheath (Zy4): 9,56 mm
- External sheath (Zy4): 10,6 mm
- Length : 103.5 mm



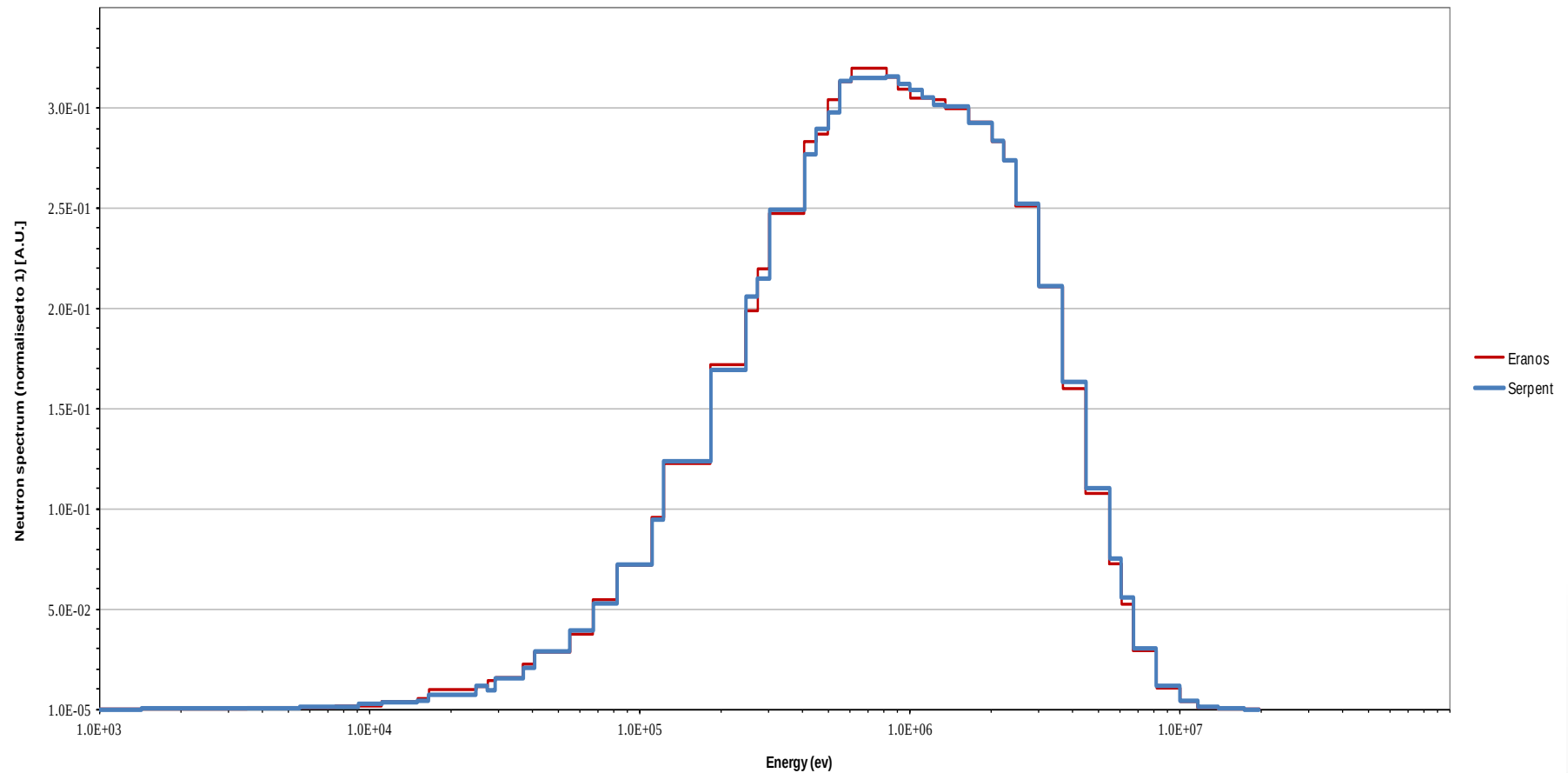


TAPIRO neutronic field analyses

ERANOS vs. Serpent



CORE CENTER ERANOS/SERPENT COMPARISON



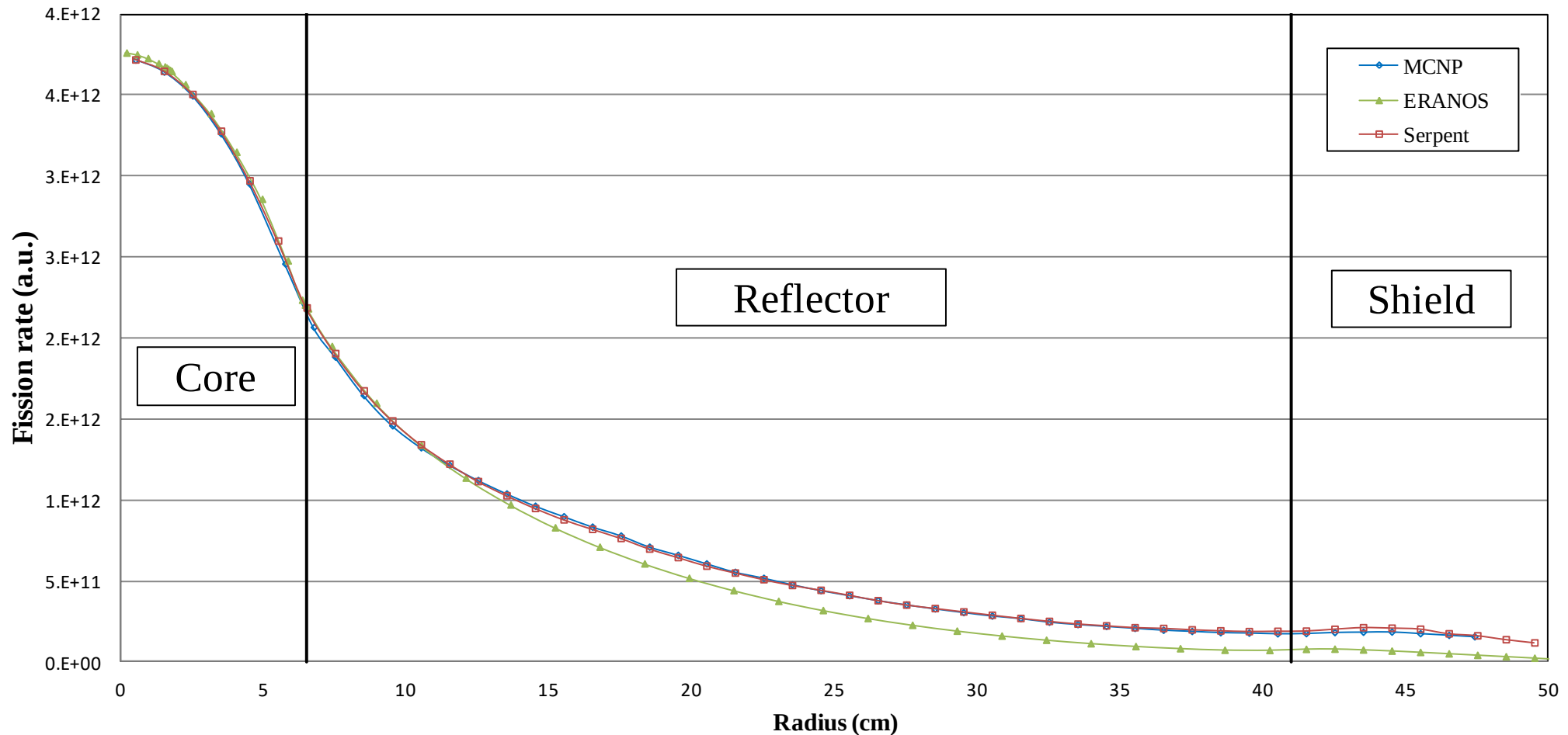


TAPIRO neutronic field analyses

ERANOS vs. Serpent/MCNP



Fission Rate U^{235} diametral channel



Per i risultati MCNP si ringrazia il CRESCO team, nelle persone dei colleghi Guido Guarnieri e Agostino Funel, che sono stati di grande supporto nella preparazione e ottimizzazione dell'ambiente di calcolo CRESCO per MCNP.



TAPIRO neutronic field analyses

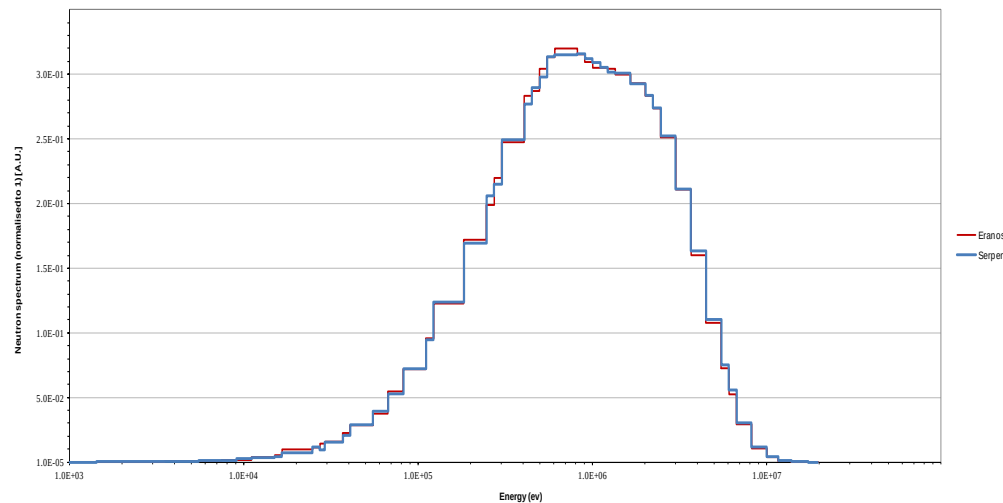
Average capture cross sections (JEFF 3.1)



$$\overline{\sigma_c(\mathbf{r})} = \frac{\langle \sigma_c(\mathbf{r}, E) \phi(\mathbf{r}, E) \rangle_E}{\langle \phi(\mathbf{r}, E) \rangle_E}$$



CORE CENTER ERANOS/SERPENT COMPARISON

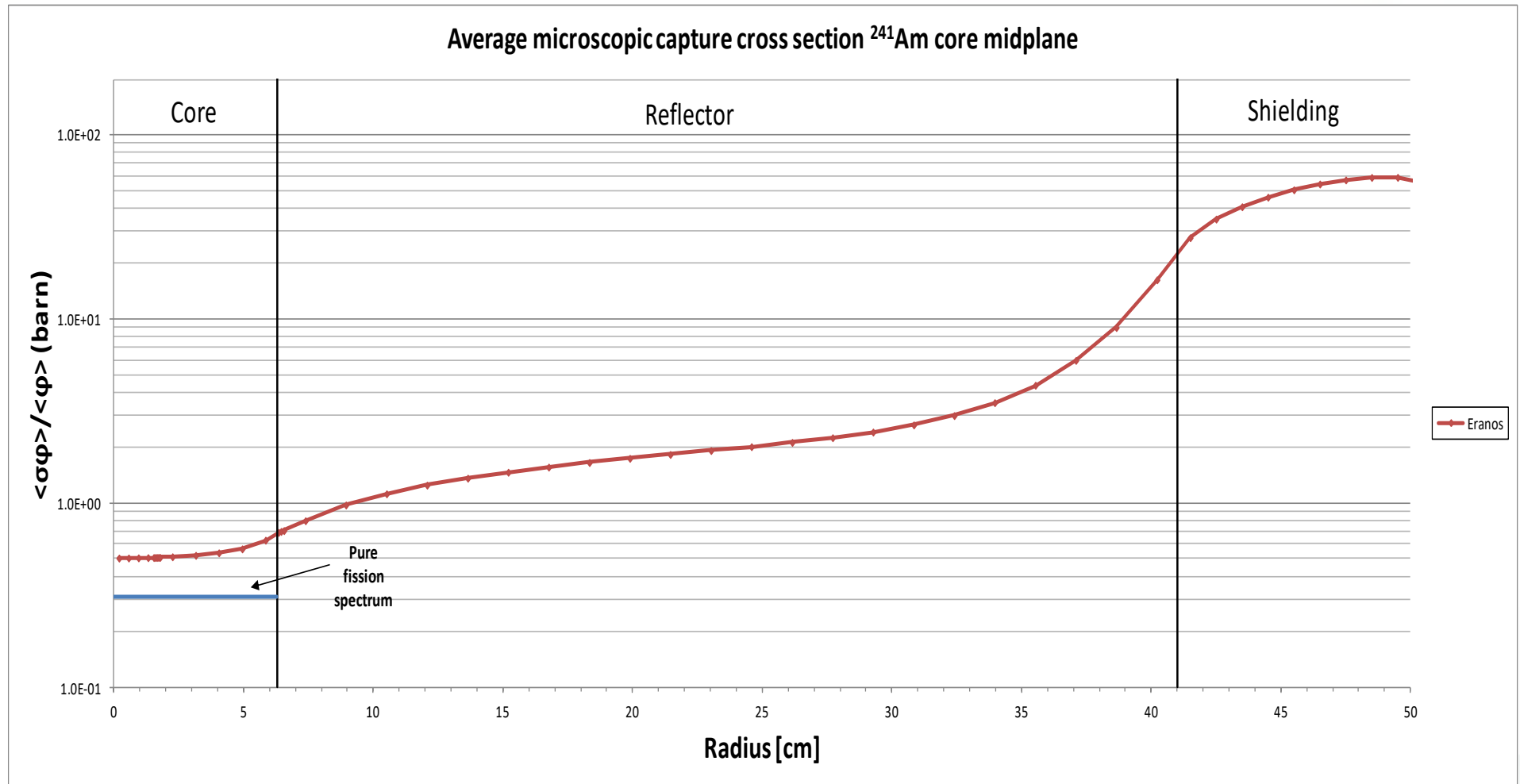


Isotopes considered: Np^{237} , Pu^{242} , Am^{241} , Am^{243}



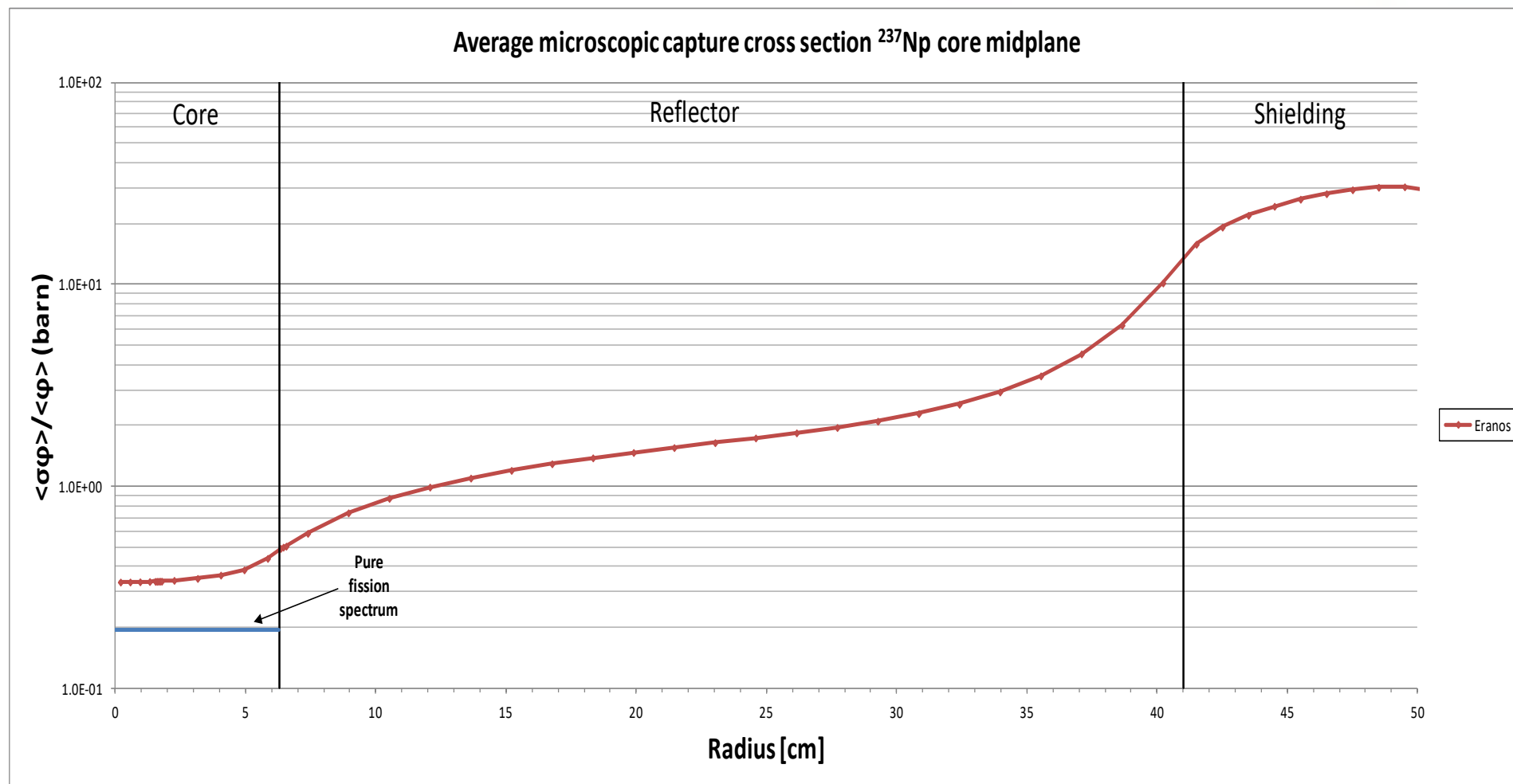
TAPIRO neutronic field analyses

Average capture cross sections (JEFF 3.1)



TAPIRO neutronic field analyses

Average capture cross sections (JEFF 3.1)



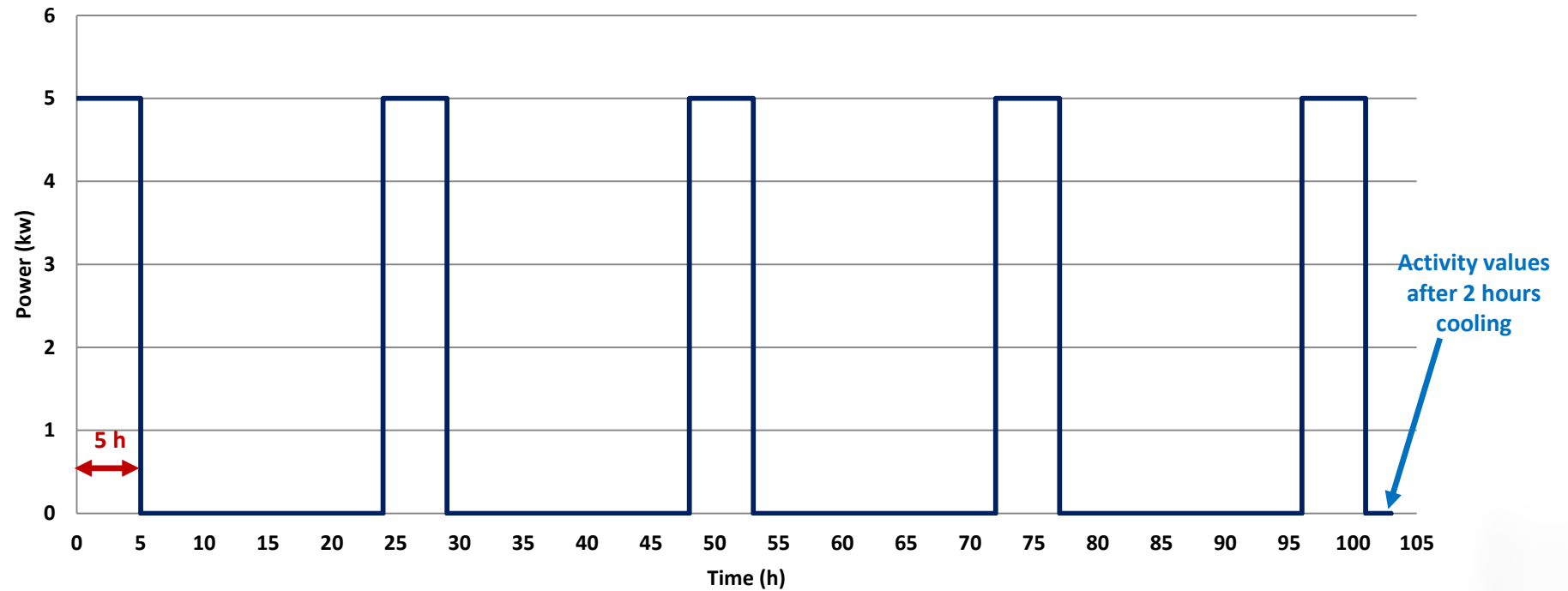


Results

Irradiation scheme for activities (@ 5kW)



1 week irradiation scheme





Results

FISPACT results (analytically checked...)

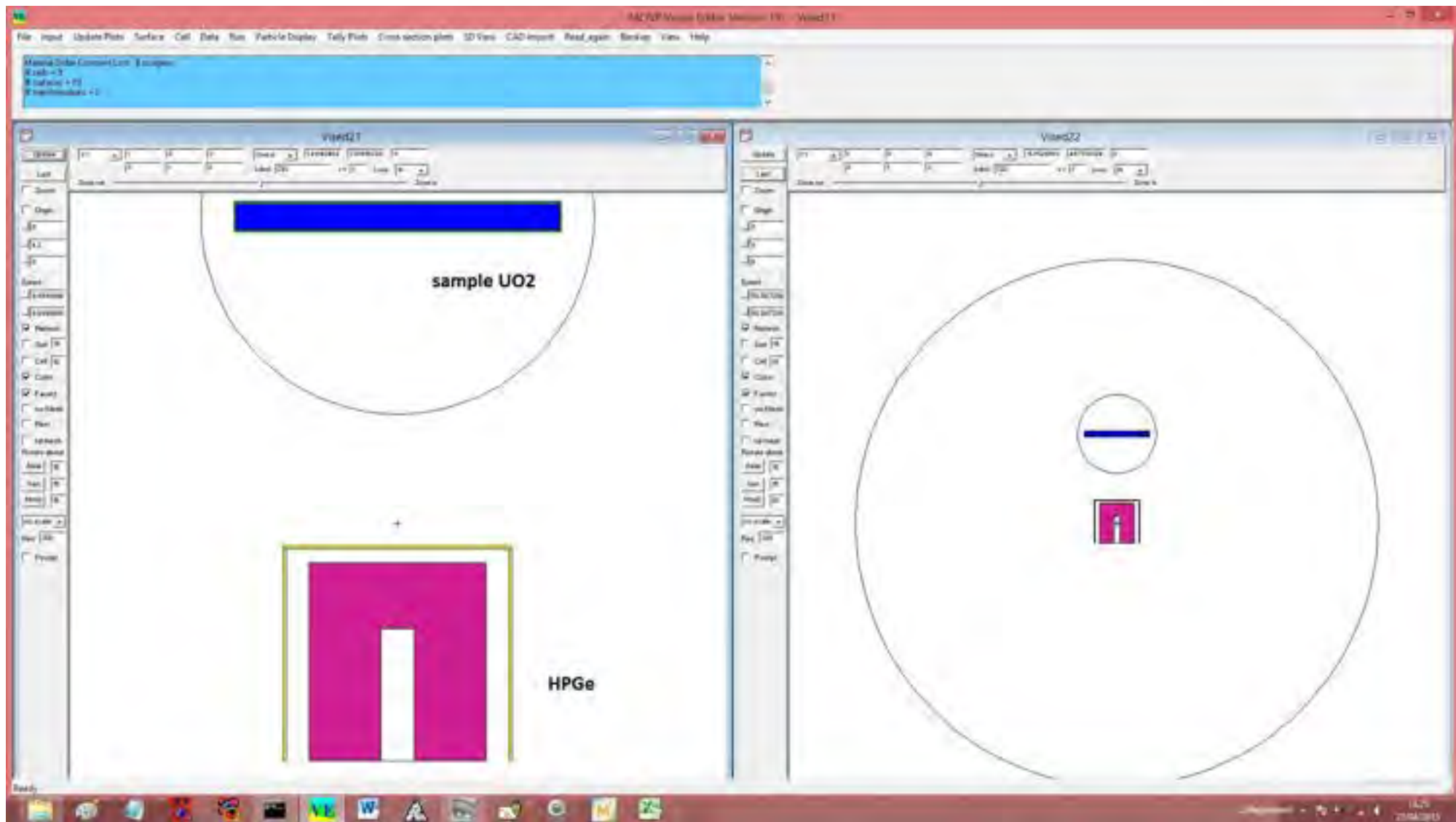


	Position	r = 12.07 cm	r = 24.58 cm	r = 45.5 cm
OSMOSE Samples	ϕ (n·cm ⁻² ·s ⁻¹)	6.94E+11	1.74E+11	8.79E+09
Np237	$\sigma_{c,Np237}$ (barn)	1.04	1.73	19.57
	A (Bq)	2.04E+08	8.49E+07	4.85E+07
Pu242	$\sigma_{c,Pu242}$ (barn)	0.34	0.62	22.48
	A (Bq)	1.15E+08	5.30E+07	9.68E+07
Am241	$\sigma_{c,Am241}$ (barn)	1.32	2.06	32.61
	A (Bq)	1.15E+08	4.50E+07	3.61E+07
Am243	$\sigma_{c,Am243}$ (barn)	1.13	1.83	33.40
	A (Bq)	2.10E+07	8.10E+06	7.14E+06



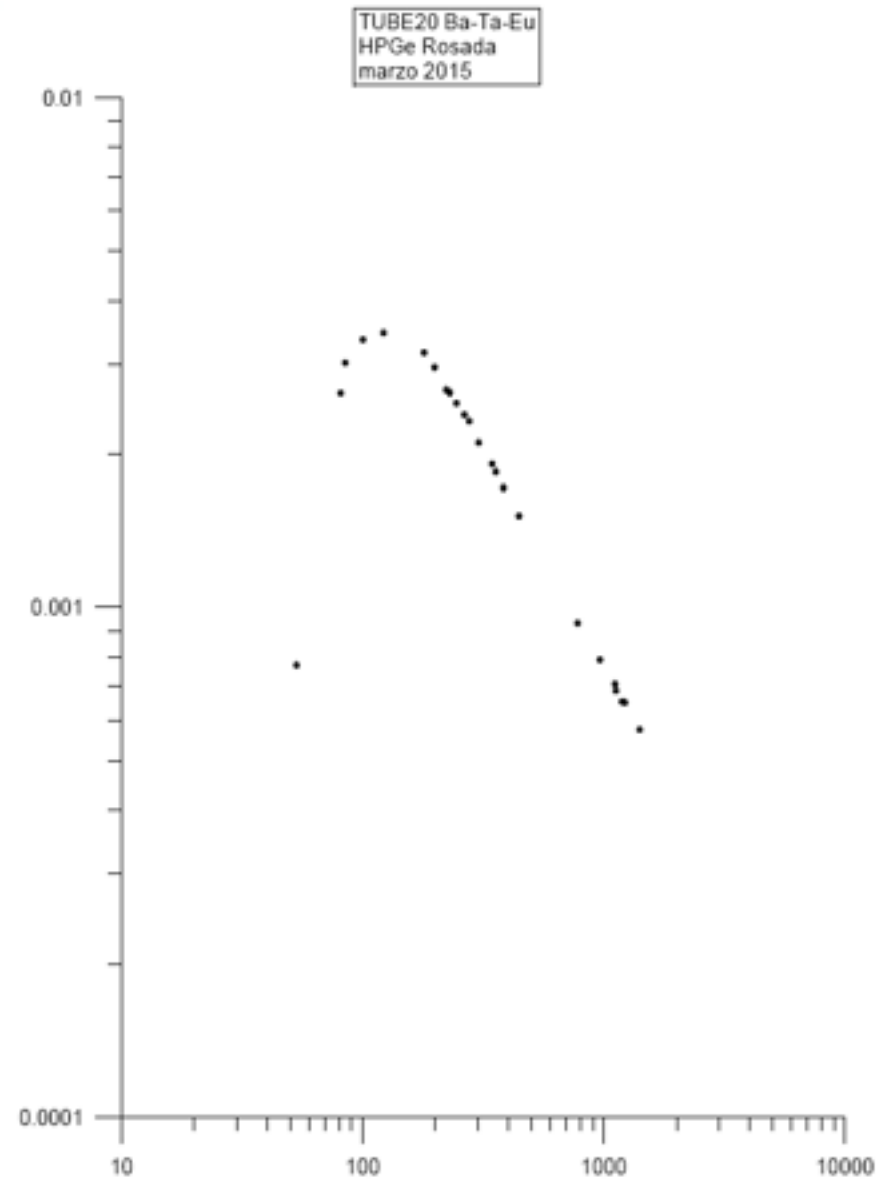
Results

Detection efficiency - MCNP evaluation





HPGe efficiency





Results

Counts estimate



$$\text{CPS (counts/s)} \approx \text{Activity (Bq)} \times$$
$$\gamma \div X \text{ Intensity (line appearance/ disintegration)} \times$$
$$\varepsilon (\gamma \div X \text{ detected/ } \gamma \div X \text{ emitted})$$



Results

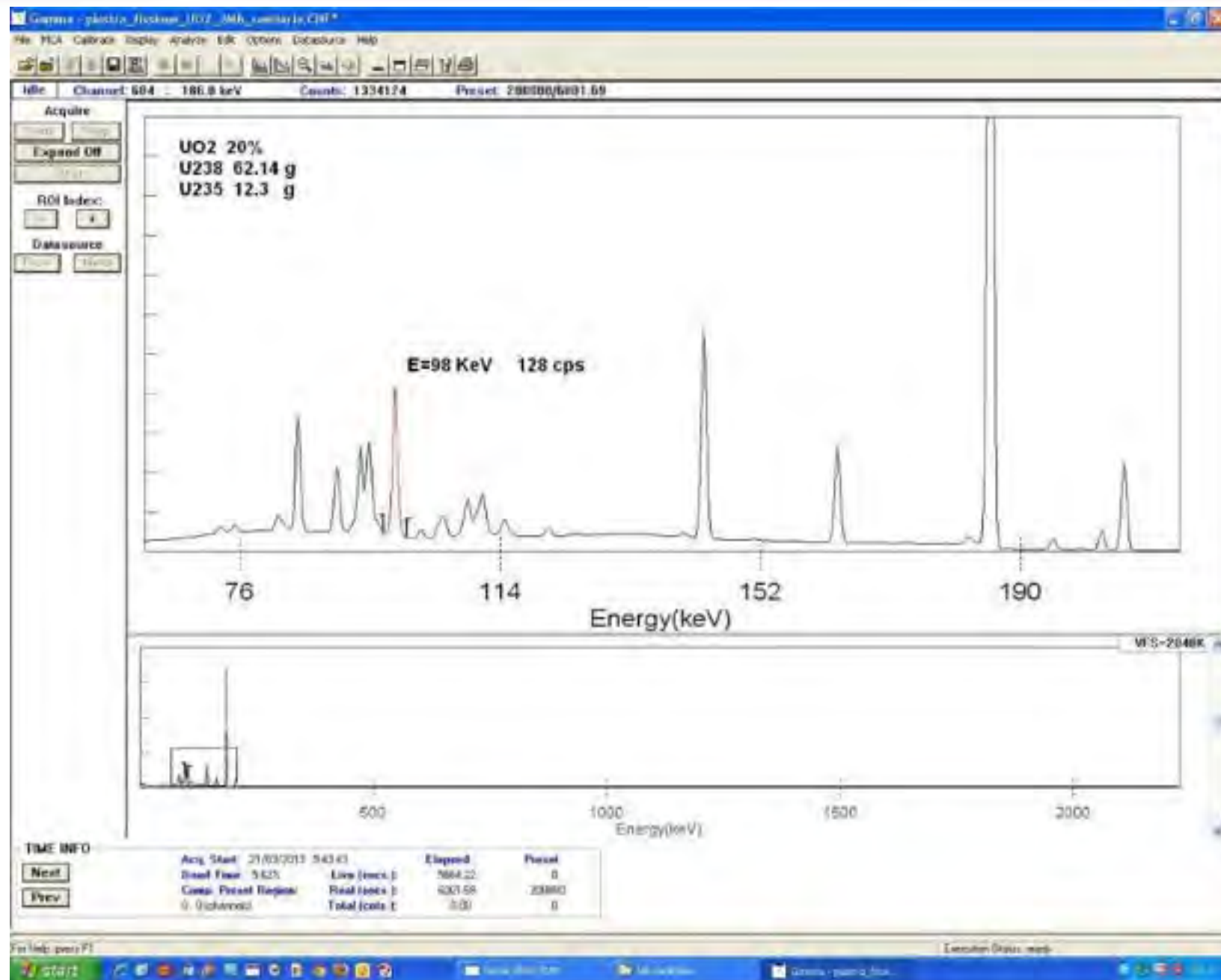
Counts estimate



	Position	r = 12.07 cm	r = 24 .58 cm	r = 45.5 cm
OSMOSE Samples	ϕ (n·cm ⁻² ·s ⁻¹)	6.94E+11	1.74E+11	8.79E+09
Np237/2	Np238 E γ (keV)	984.45	984.45	984.45
	γ Intensity (%)	25.19	25.19	25.19
	ϵ Detection (%)	0.186	0.186	0.186
	C (cps)	95487	39779	22738
Pu242	Pu243 E γ (keV)	84	84	84
	γ Intensity (%)	23.10	23.10	23.10
	ϵ Detection (%)	0.530	0.530	0.530
	C (cps)	140305	64912	118561
Am241/1	Am 242 E X _{Kα1} (keV)	103.374	103.374	103.374
	X _{Kα1} Intensity (%)	5.70	5.70	5.70
	ϵ Detection (%)	0.107	0.107	0.107
	C (cps)	2104	823	661
Am241/2	Am 242 E X _{Kα1} (keV)	103.374	103.374	103.374
	X _{Kα1} Intensity (%)	5.70	5.70	5.70
	ϵ Detection (%)	0.107	0.107	0.107
	C (cps)	7014	2745	2204
Am243	Am244 E γ (keV)	743.971	743.971	743.971
	γ Intensity (%)	66.00	66.00	66.00
	ϵ Detection (%)	0.213	0.213	0.213
	C (cps)	29466	11391	10032



Not overlapping lines with UO₂ lines





NEA framework actions chronology since April 2015



- **EGIEMAM-II-02 (29-30 Apr. 2015). List of Actions connected to AOSTA program:**
 - ✓ All to provide information of the FCs to NEA Secretariat [as soon as possible].
 - ✓ NEA Secretariat to send the list of FCs to M. Carta [by the end of May 2015].
 - ✓ M. Carta, P. Blaise, B. Geslot, and G. Imel to consider detailed experimental programs at TAPIRO using the FCs and OSMOSE samples
- **What has happened since then:**
 - ✓ **22 June.** NEA sends list of **SCK•CEN** FCs available for the measurements in TAPIRO (contribution by **Anatoly Kochetkov**).
 - ✓ **6 July.** NEA sends material concerning **CEA** FCs available for the measurements in TAPIRO + papers about FCs manufacturing, spectral indexes measurements and calibration issues (contribution by **Benoit Geslot**) .
 - ✓ **6 July.** NEA sends material concerning **JAEA** FCs available for the measurements in TAPIRO (contribution by **Kazufumi Tsujimoto**).
 - ✓ **May ÷ September.** ENEA checks some aspects regarding FCs and measurement chains available in house. Checks are made also with the Italian National Institute for Environmental Protection and Research (ISPRA) about eventual constraints under the safety point of view. ENEA prepares a first scheduling of a preparatory program to the AOSTA campaign. Collaboration with CEA continues (Serpent TAPIRO input sent from ENEA to CEA).



From ENEA side



- **First of all thanks to all the contributors!**
- **ENEA checks some aspects regarding FCs and measurement chains available at home.**
 - ✓ Available FCs: #3 U235 (different characteristics) ; #5 U238 (different characteristics); #1 Np237; #1 Pu239. All chambers (except one) have to be checked. Calibration??? 😞
 - ✓ Measurement chains exist and are complete. 😊
- **Checks are made also with the Italian National Institute for Environmental Protection and Research (ISPRA) about eventual constraints under the safety point of view:**
 - ✓ Only reactivity margins, regardless the kind of material, have to be taken into account. 😊
- **ENEA prepares a first scheduling of a preparatory program to the AOSTA campaign:**
 - ✓ TAPIRO will come back to its original configuration within this year.
 - ✓ A measurement campaign with some detectors in different positions (in collaboration with CEA, but of course all the volunteers are very welcomed!) has to be performed before AOSTA. Detectors calibration issues must be solved to obtain spectral indexes of interest.
 - ✓ A calculation benchmark has to go along with this experimental phase (→ IRPhE).
 - ✓ During this preliminary phase, but also in parallel to AOSTA, other experiments can be performed (George Imel proposals).



THANK YOU GEORGIOS!

Verifica di fattibilità di sonde commerciali per la misura dei flussi neutronici in reattori raffreddati al piombo. Proposta di studio teorico-sperimentale di SPND innovativi ottimizzati per reattori LFR.

(ADPFISS-LP2-089)

by L. LEPORE¹, R. REMETTI¹, M. CAPPELLI²

C.R. ENEA Brasimone, November, 19th 2015

1: Sapienza, University of Rome

2: ENEA, UT-FISST\MEPING

AIM OF THE WORK

The work faces neutron instrumentation issues for Lead Fast Reactor oriented to the control of the plant. Neutron flux detectors used in Sodium Fast Reactor could not completely fit the needs of LFRs.



AIM OF THE WORK

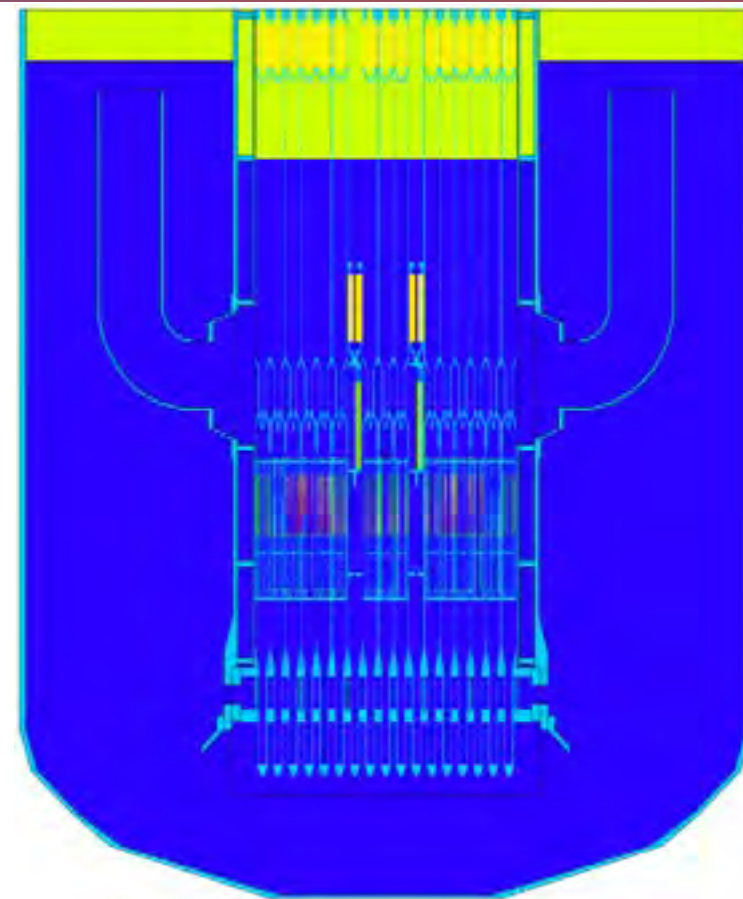
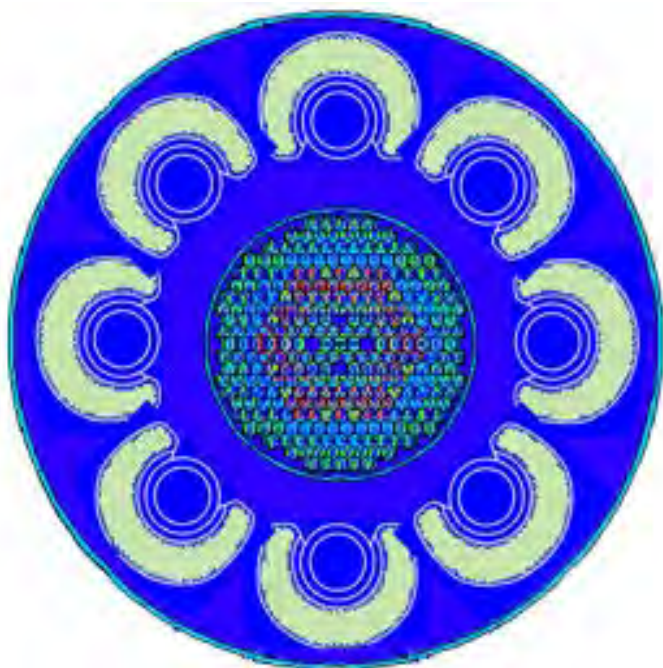
I&C OPEN ISSUES:

- What is the **best control strategy (in/out-of-core; in/out-of-vessel) for LFR? Core neutron-monitoring-needs and instrumentation technology?**
- SFR and LFR reference spectra are not so different, but **spectral differences must be evaluated** in the positions where instrumentation is supposed to be installed.
- Instrumentation & control issues may need to come in parallel with neutronics and thermal-hydraulics issues, in order to optimize the I&C instrumentation/system alongside the other customization processes on reactor design.

REFERENCE REACTOR

The LFR reactor modeled into MCNPX is based on **LEADER Project (ALFRED)**.

The MCNPX input deck now includes the 8 bayonet steam generators, having reached ~50000 lines.

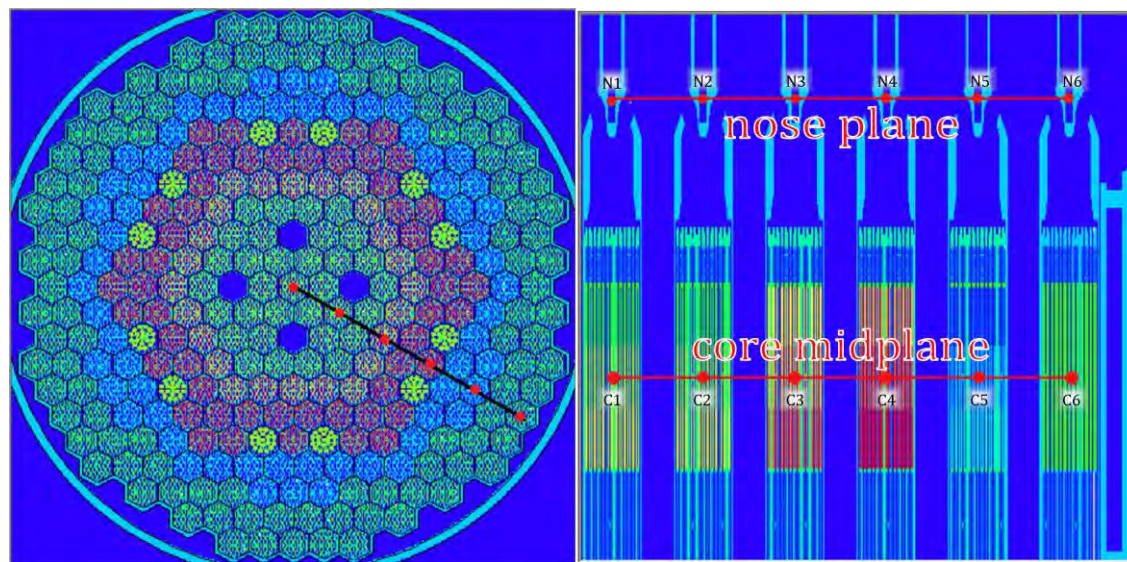


Instrumentation selected for neutron flux:

- **Fission Chambers (FC)**
- **Self Powered Neutron Detectors (SPND)**

RESULTS:

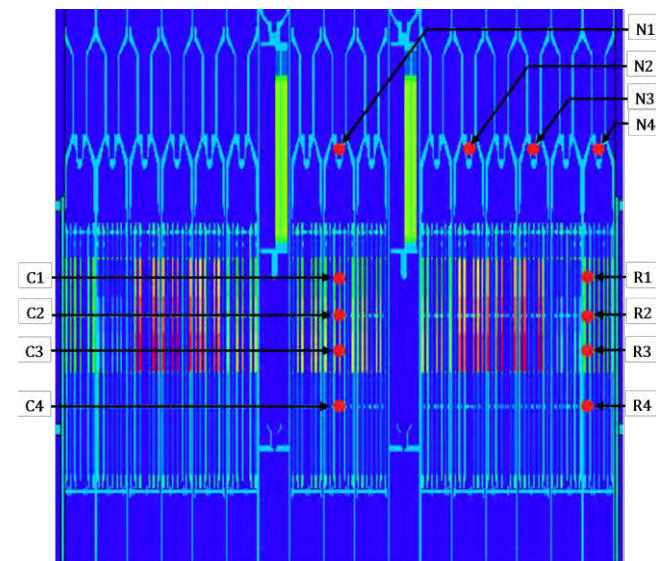
REFERENCE LFR REACTOR ENVIRONMENT



OLD CONFIGURATION:

12 in and out-of-core position are studied:

- 6 radial POINTS on core plane
- 6 radial POINTS on nose plane



CURRENT CONFIGURATION:

12 in and out-of-core position are studied:

- 4 axial POINTS in the reactor central element
- 4 axial POINTS in a reflector element
- 4 radial POINTS on nose plane, along a traverse

RESULTS :

SELECTED INSTRUMENTATION, CALCULATION STEPS

Instrumentation analyzed consists of:

➤ Fission Chambers (FC):

Manufacturer: **PHOTONIS**

- 1 CFUE32

➤ Self Powered Neutron Detectors (SPNDs):

Manufacturer: **ThermoCoax**

- 1 Co-type
- 1 Pt-type

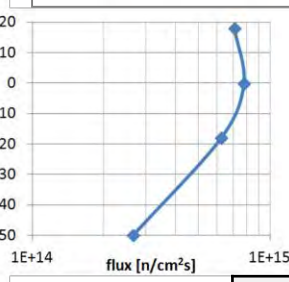
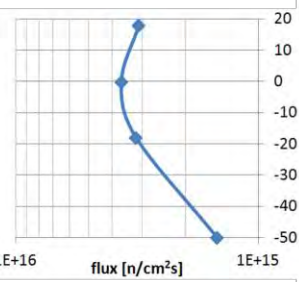
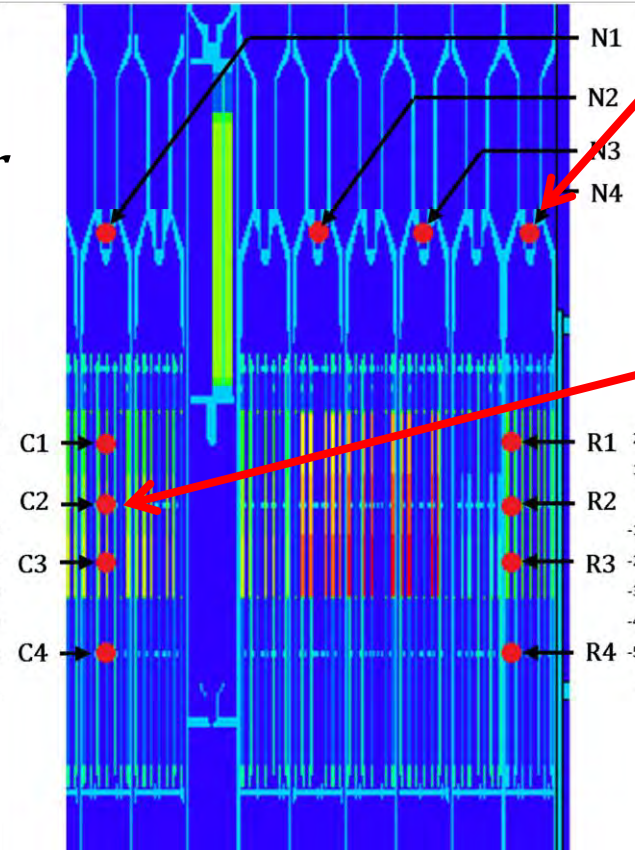
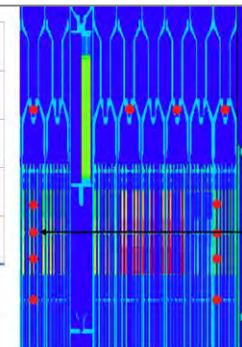
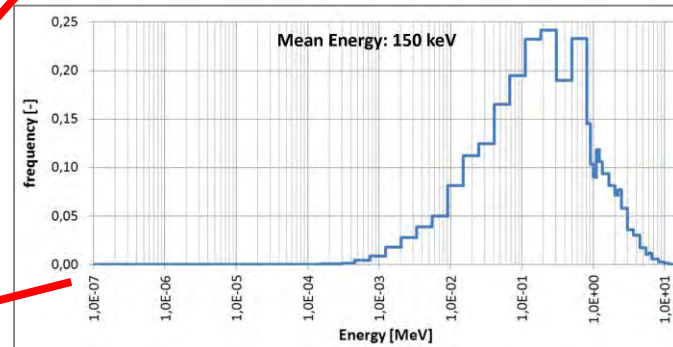
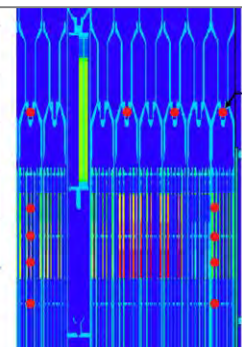
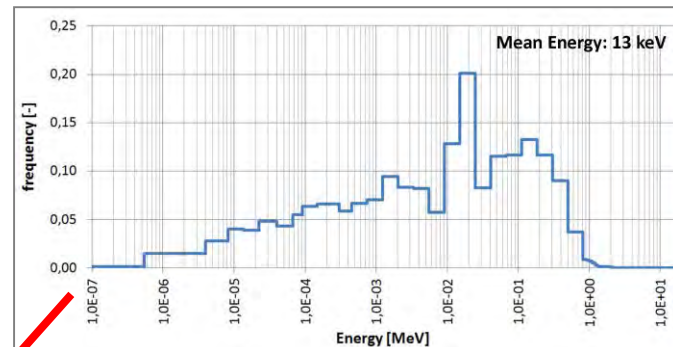
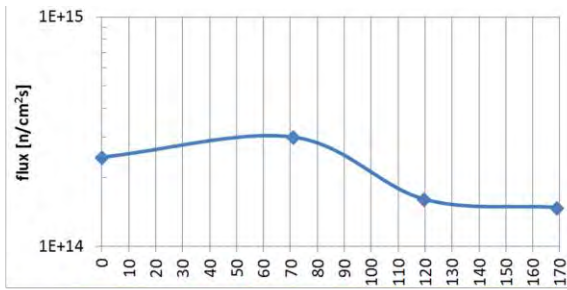
Cresco4 allowed:

- Calculation of the neutron fluxes at Points Of Interest (POI);
- Calculation of the neutron spectra at POI;
- Calculation of the gamma background at POI;
- Update of detector's sensitivities [1] to neutron and gamma;
- Calculation of detector's responses at POI.

RESULTS:

REFERENCE LFR REACTOR ENVIRONMENT BY MCNPX

*Neutron
flux at
full power*



	Energia γ media [keV]	Rapporto γ/n
R1	500	0.1986
R2	600	0.1881
R3	450	0.2585
R4	900	0.0154

	Energia γ media [keV]	Rapporto γ/n
N1	950	0.0067
N2	1450	0.0009
N3	1250	0.0039
N4	900	0.0272
C1	500	0.1365
C2	450	0.1456
C3	500	0.1464
C4	900	0.0569

RESULTS:

DETECTOR'S KIND vs. REACTOR POWER and POSITION

“Neutronics should need some detectors to be installed into the core or near the edge of the active length” [2][3]

If the statement is true, detector's kind vs. power and positioning could be different, due to neutron and gamma flux magnitudes and spectra. Indeed,

- **Fission Chambers** with their **higher sensitivities**, can follow the reactor evolution from **zero power to 1-10% of full power**.
Pulse, MSV and Current mode are exploited.
- **SPNDs** with their **lower sensitivities**, can follow the reactor at **full power** without suffering an excessive burn-up.
Current mode is exploited.

A superimposition region between those classes is foreseen for the switching during the power evolution

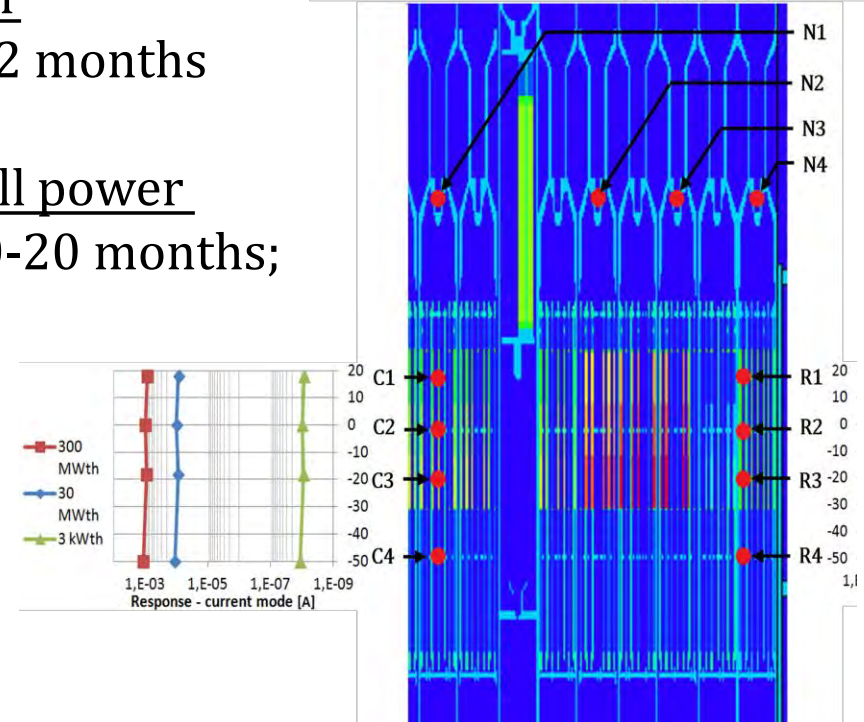
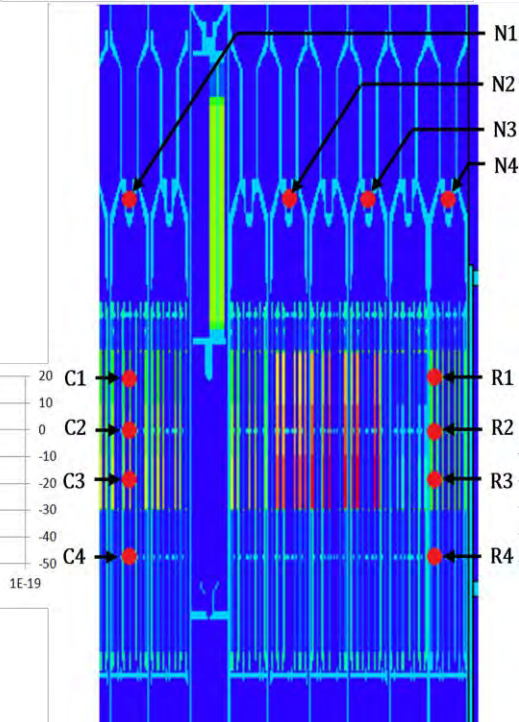
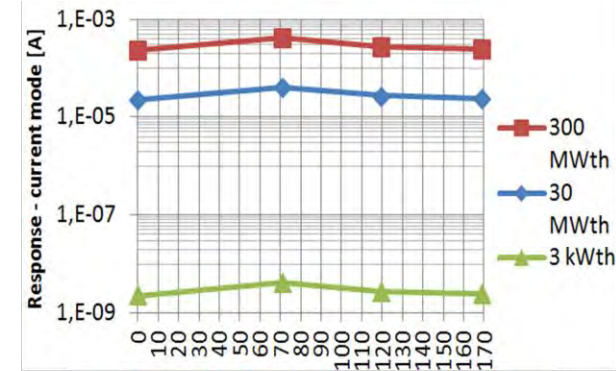
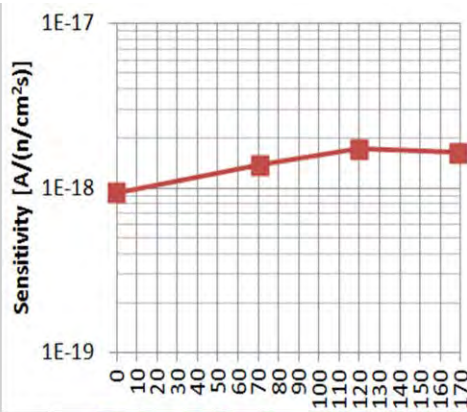
RESULTS :

PHOTONIS CFUE32 SENSITIVITY AND RESPONSE (in CURRENT MODE)

$$R(\vec{r}) = S_{fast}(\vec{r}) \cdot \varphi(\vec{r})$$

Durability:

- Full power
1-2 months
- 10% of full power
10-20 months;



RESULTS :

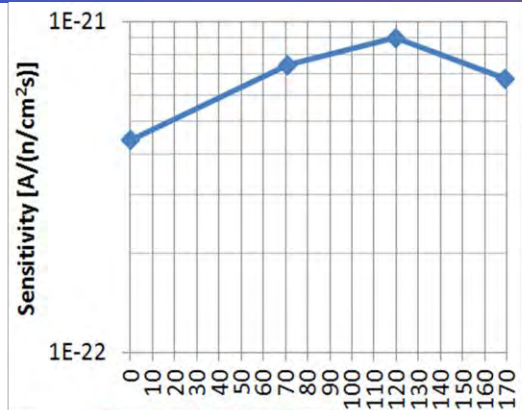
PHOTONIS CFUE32 FISSION CHAMBER USABILITY in ALFRED

Key points:

- CFUE32 can follow the reactor power **till 1-10% of full power**;
- Neutron fluxes corresponding to reactor power **>10% of full power burn the device too fast**;
- When reactor power **>0.1% of full power**, devices too close to the active length suffer **an excessive gamma bombardment**; such a noise has to be studied;
- **Replacement devices** has to be foreseen inside the reactor design to **insert the instrument** as close as possible to the active length at start-up and **remove** it when neutron or gamma fluxes become unsustainable.

RESULTS :

THERMOCOAX SPND Pt-type SENSITIVITIES and RESPONSES (in CURRENT MODE)

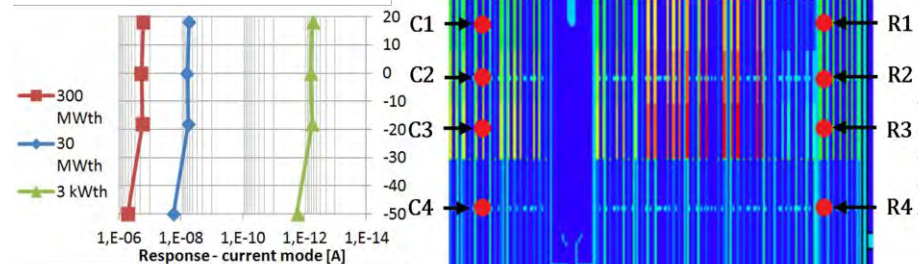
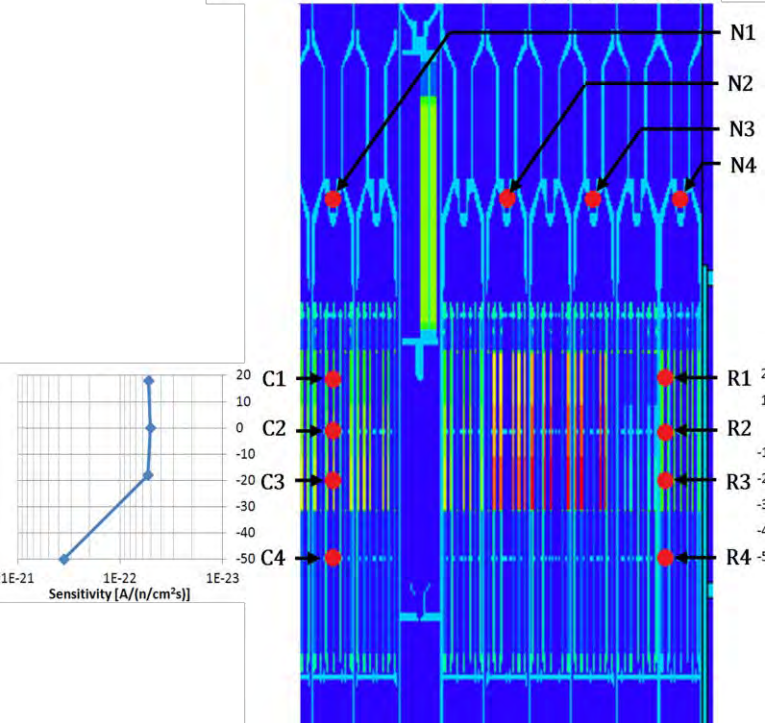
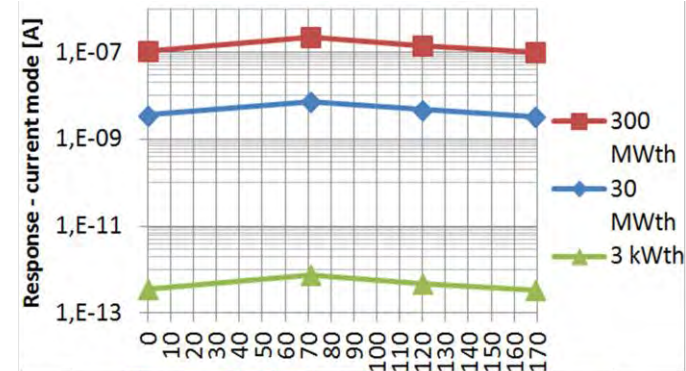


$$R(\vec{r}) = S_{fast}(\vec{r}) \cdot \varphi(\vec{r})$$

Burn-up:

• Full power

1%/ months



RESULTS :

THERMOCOAX SPND Pt-type USABILITY in ALFRED

Key points:

- SPND **do not follow lower decades** of reactor power;
- They can monitor from **10% to 100% of full power**, according to positioning;
- **Low Burn-up rate** allow the device to **endure** for the whole irradiation campaign foreseen for the elements;
- They can be installed as a **fixed component** into fuel and reflector elements: **no replacement is needed**;
- They could **suffer some gamma noise** at installation sites within the fuel.
- **Maximum limits on burn-up** has to be investigated.

RESULTS :

MAJOR REMARKS

- **Fission Chambers** seem to be the only devices capable in monitoring the reactor power range **0-10% of full power** as **in-core-instrumentation**;
- **SPNDs** seem to be the only devices capable in monitoring the reactor power range **10-100% of full power** as **in-core-instrumentation**;

Prompt-SPNDs are never been used as control instrumentation

At the state-of-the-art, ALFRED could suffer the lack of a suitable instrumentation for in-core monitoring at full power.

It must be noted that ALFRED is a Demonstrator Reactor at reduced power, 300 MW_{th} . What to do with a 3000 MW_{th} -sized reactor?

FUTURE WORKS :

MCNPX AS A DESIGN TOOL FOR NEW SPNDs DESIGNS

R&D on SPND is strongly suggested, in both **theoretical** and **experimental** approaches.

*According to the **spectral characteristics of the neutron flux**, SPNDs for full power monitoring can be **optimized in materials and geometries**.*

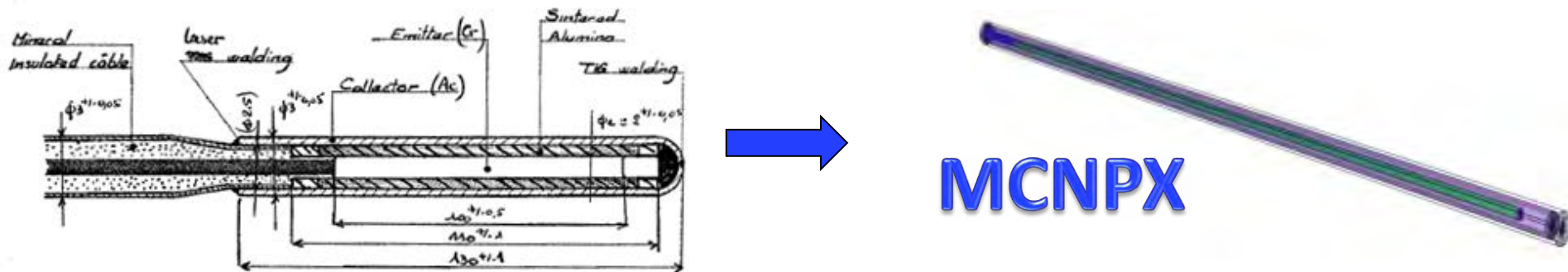
*MCNPX can represent an useful **design tool** to conceive and test in simulation **innovative SPNDs**.*

⇒ MCNPX for SPND modeling has to be validated first

*⇒ An **irradiation experience on SPNDs in TAPIRO** has been reconstructed to validate MCNPX as a design tool for SPNDs*

FUTURE WORKS :

MCNPX AS A DESIGN TOOL FOR NEW SPNDs DESIGNS



The SPNDs model in **MCNPX** reproduces detectors' thermal sensitivities as rated by manufacturer in factory conditions [4].

The irradiation experience in TAPIRO by Angelone et al. [5] has been reconstructed into MCNPX.

The experiment used a **Rh-type SPND** (not a prompt detector).

At the maximum reachable power for TAPIRO, the **detector response** was **~17 pA**.

The SPNDs model into MCNPX reproduces **~4.4 pA**.

The **order of magnitude** of the detector's response is **well reproduced** [4].

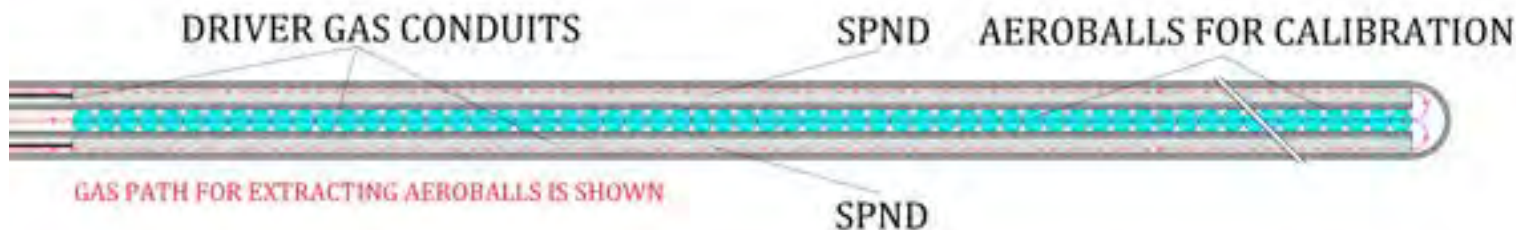
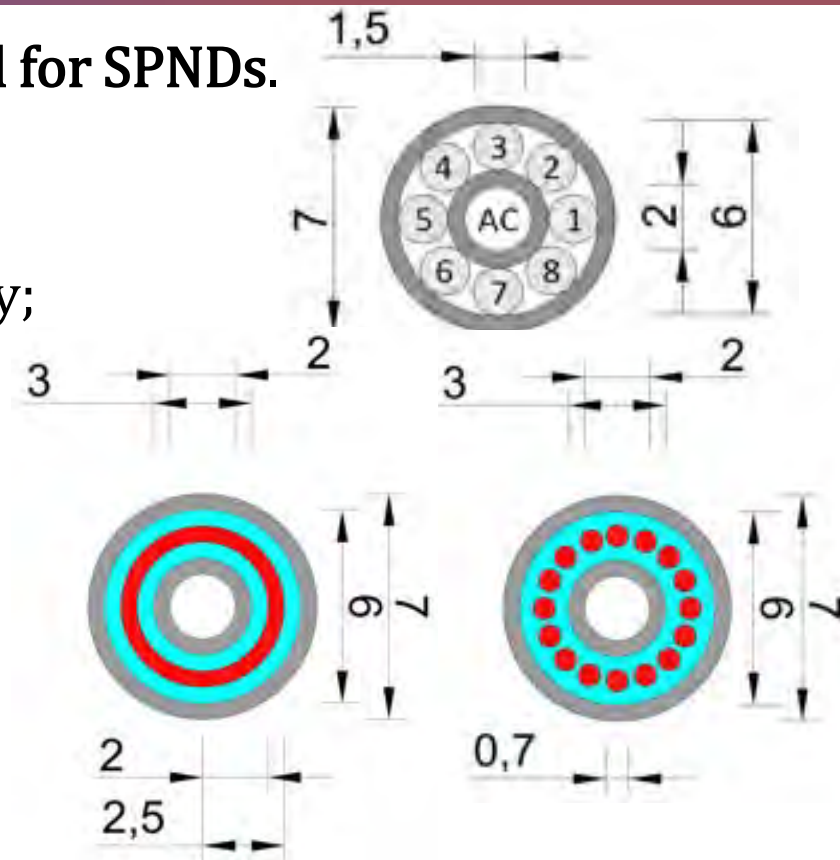
FUTURE WORKS :

MCNPX AS A DESIGN TOOL FOR NEW SPNDs DESIGNS

MCNPX now can be used as a **design tool for SPNDs**.

➤ SPND modification:

- prompt-commercial-SPND assembly;
- innovative geometries for sensitive volumes;
- innovative sensitive materials;
- innovative study on a special SPND assembly for real-time neutron spectra measurement.



STUDY SCHEDULE

STUDY SCHEDULE

1st year: - ***analysis of performances of current instrumentation (PAR 2013) in LFR environment (ALFRED) by MCNPX.*** ☒

2nd year: - *completing the ALFRED MCNPX input deck;* ☒
 (PAR 2014) - ***validation of simulation technique by means of reproduction into MCNPX of experimental irradiations in TAPIRO.*** ☒

3rd year: - *customization of **new detectors and I&C***
 (PAR 2015?) ***prototyping;*** ☐
 - *feasibility study and **experimental procedure for detector irradiation and testing in TAPIRO;*** ☐
 (future work) - ***detector prototype construction and irradiation.*** ☐

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- [3] J. C. Perrigreur, C. Berlin, J. C. Gauthier e J. Gourdon, «In core neutronic measurements in an industrial environment. Assessment of the performances of the in-vessel neutronic measurements chains of SUPER-PHENIX 1,» in *Proceedings of the Specialists' Meeting on IN CORE INSTRUMENTATION AND REACTOR ASSESSMENT*, 1989.
- [4] L. Lepore, R. Remetti and M. Cappelli "Verifica di fattibilità di sonde commerciali per la misura dei flussi neutronici in reattori raffreddati al piombo. Proposta di studio teorico-sperimentale di SPND innovativi ottimizzati per reattori LFR." ADPFISS-LP2-089, 2015.
- [5] M. Angelone, A. Klix, M. Pillon, P. Batistoni, U. Fischer e A. Santagata, «Development of self-powered neutron detectors for neutron flux monitoring in HCLL and HCPB ITER-TBM,» *Fusion Engineering and Design*, vol. 89, p. 2194–2198, 2014.

**Thank you
for your attention!!!**

WORKSHOP TEMATICO
**LFR-GEN IV: STATO ATTUALE DELLA TECNOLOGIA E
PROSPETTIVE DI SVILUPPO**

ADP ENEA-MSE (PAR2014-LP2)



POLITECNICO
MILANO 1863



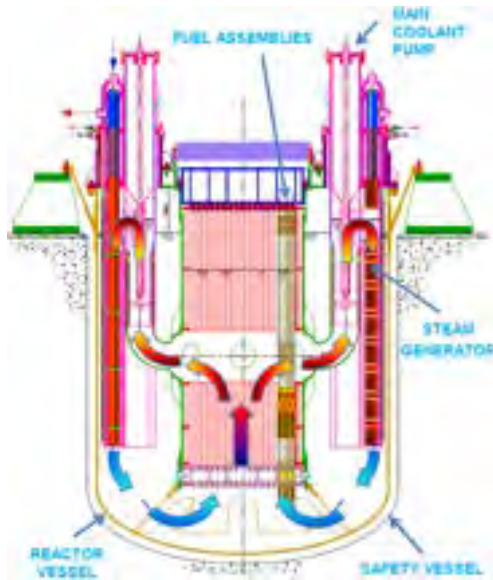
Dipartimento di Energia - CeSNEF
Laboratori Integrati di Ingegneria Nucleare

Interazione chimica tra combustibile e refrigerante in sistemi LFR

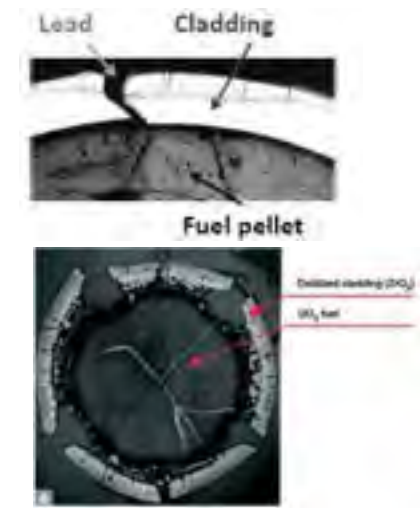
E. Macerata, M. Mariani, M. Cerini, M. Negrin, E. Mossini, M. Giola
Laboratorio di Radiochimica e Chimica delle Radiazioni



Brasimone, 19-20 Novembre, 2015



*Interazione chimica
tra combustibile e piombo liquido
dovuta all'evento di fessurazione
della guaina (failure event)*



Scenario complesso



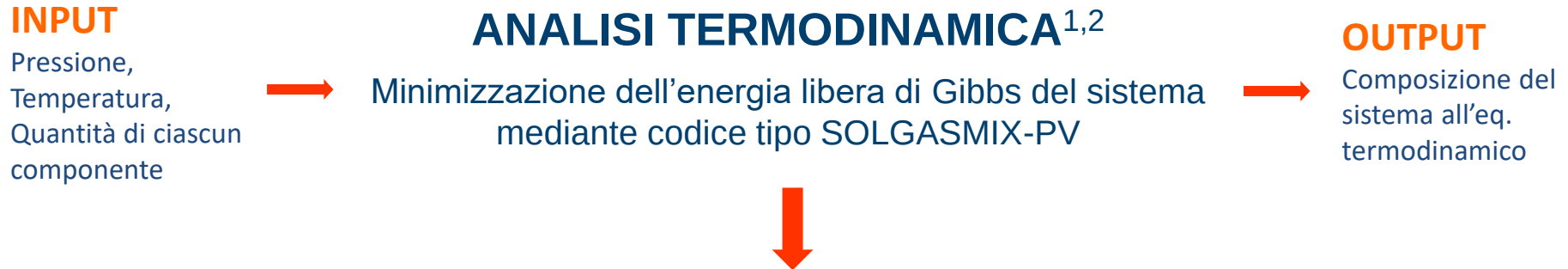
Composizione del combustibile
Coinvolgimento della guaina
Temperatura del sistema
Dimensione della fessurazione
Presenza di ossigeno nel refrigerante

Studio sperimentale



Studio teorico-computazionale

Sistema FUEL-COOLANT = sistema multi-componente e multi-fase a T e p



DATABASE contenente i **dati termochimici** di componenti e prodotti di reazione

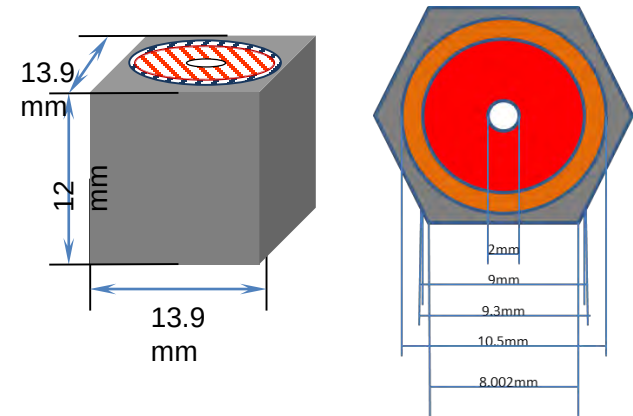
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1. S. Imoto, *J. Nucl. Mater.*, **1986**, 140, 19-27.

2. E.H.P. Cordfunke, R.J.M. Konings, *J. Nucl. Mater.*, **1988**, 152, 301-309.

ANALISI TERMODINAMICA

- Reattore di riferimento: ELSY, ALFRED
- Volume di riferimento
- Temperature operative (funzionamento nominale e caso incidentale ULOF)
- Sistemi binari con combustibile metallico
- Validazione su sistema U-Pb



Dati in INPUT

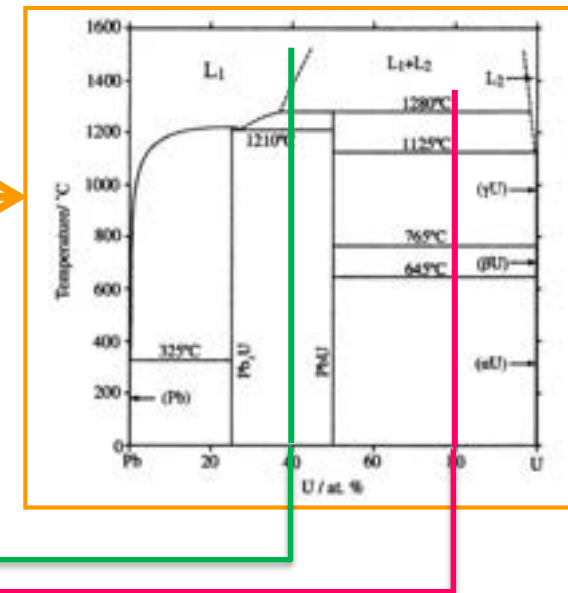
T [K]: 500, 800, 1100, 1400, 1700

U [mol]: 0.2, 0.4, 0.6, 0.8

P [atm]: 1

Iterazioni: 5000

U 0.8 mol			Pb 0.8 mol				
Temperatura	K	500	800	1100	1400	1700	
U^{liq}	mol	-	-	-	-	0.8	
Pb^{liq}	mol	-	-	-	-	0.8	
PbU	mol	0.6	0.6	0.6	0.6	-	
Pb_3U	mol	0.2	0.2	0.2	0.2	-	



ANALISI TERMODINAMICA

UO₂ - Pb

Sistema

**Chimicamente
stabile**

T [K]	700	800	900	1050	1250	1450
Pb _{liq} [mol]	0.4295	0.4295	0.4295	0.4296	0.4295	0.431
U _{liq} [mol]	0	0	0	0	0	5.00E-04
PbU [mol]	1.69E-07	4.86E-08	3.57E-06	4.26E-05	-	-
Pb ₃ U [mol]	5.00E-04	5.00E-04	4.96E-04	4.57E-04	5.00E-04	-
UO ₂ [mol]	0.1895	0.1895	0.1895	0.1895	0.1895	0.1895

Pu_{metallico} - Pb → Pb₅Pu₄ (98.8 %) e Pb₄Pu₅ (1.2 %)

modesta instabilità a T ≥ 1250 K con possibile formazione di ossidi di U e Pu

(U_{0.8}Pu_{0.2})O₂-Pb

Caso nominale

T [K]	700	750	800	850	900	950
Pb _{liq} [mol]	0.4255	0.4255	0.4255	0.4255	0.4255	0.4255
UO ₂ [mol]	0.1533	0.1533	0.1533	0.1533	0.1533	0.1533
PuO ₂ [mol]	0.0382	0.0382	0.0382	0.0382	0.0382	0.0382
U ₄ O ₉ [mol]	Presenti in tracce <10 ⁻⁶				9.34·10 ⁻⁶	
Pu ₂ O ₃ [mol]					1.05·10 ⁻⁵	

Caso incidentale

T [K]	1050	1150	1250	1350
Pb _{liq} [mol]	0.4219	0.4219	0.4182	0.4218
PbO _{liq} [mol]	-	-	0.0037	0.0001
UO ₂ [mol]	0.1543	0.1543	0.1541	0.0805
PuO ₂ [mol]	0.0384	0.0384	0.0309	0.0012
Pb ₃ U [mol]	0	0	0	1.51·10 ⁻⁶
U ₃ O ₈ [mol]	0	0	6.57·10 ⁻⁶	<10 ⁻⁶
U ₄ O ₉ [mol]	Presenti in tracce <10 ⁻⁶		4.00·10 ⁻⁵	0.0185
Pu ₂ O ₃ [mol]			0.0038	0.0186

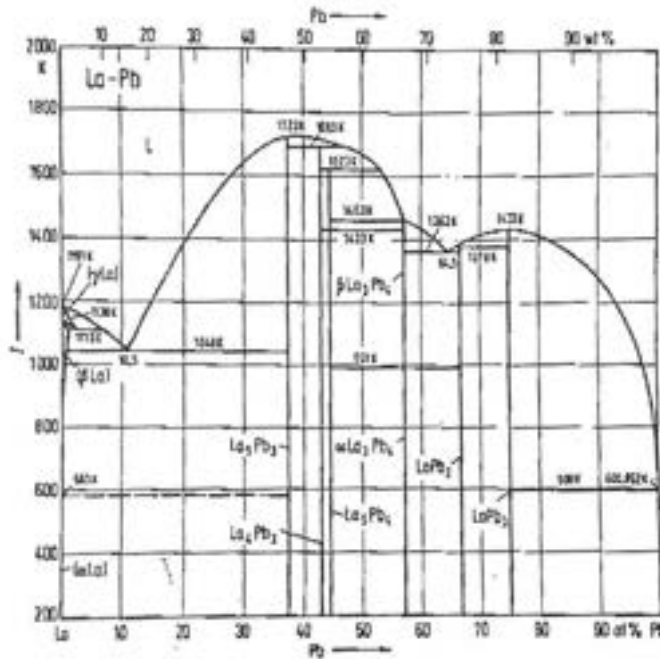
Negrin, M., Interazione tra combustibile e termovettore in sistemi LFR di IV generazione: analisi termodinamica preliminare, [Tesi di Laurea Specialistica in Ingegneria Nucleare](#), A.A. 2011-2012;

M. Negrin, E. Mossini, E. Macerata, M. Cerini, M. Giola, M. Mariani and L. A. Pellegrini, *Proc. Int. 23rd International Conference Nuclear Energy for New Europe-NENE 2014*, p. 1211, Nuclear Society of Slovenia (2014) (CD-ROM), ISBN 978-961-6207-37-9

...per simulare il sistema $\text{MOX}_{\text{irr}}\text{-Pb}$...

Sistema La-Pb

il codice descrive correttamente la composizione del sistema all'equilibrio in termini sia di quantità sia di stato fisico



Moli La	0.8	0.6	0.5	0.4	0.2
Moli Pb	0.2	0.4	0.5	0.6	0.8
Temperatura	600 K				
Fase Solida					
La ₂ Pb ₃	0.0667	0.0667			
La ₃ Pb ₂		0.0665			
La ₂ Pb ₃			0.0625		
La ₃ Pb ₂			0.0625	0.1000	
LaPb ₂				0.0999	
LaPb ₃					0.2
La	0.4667				
Pb					0.2
Temperatura	800 K				
Fase Liquida					
Pb					0.2
Fase Solida					
La ₂ Pb ₃	0.0667	0.0667			
La ₃ Pb ₂		0.0666			
La ₂ Pb ₃			0.0625		
La ₃ Pb ₂			0.0625	0.1000	
LaPb ₂				0.0999	
LaPb ₃					0.2
La	0.4667	0.2			
Temperatura	1200 K				
Fase Liquida					
La	0.4667				
Pb					0.2
Fase Solida					
La ₂ Pb ₃	0.0667	0.0667			
La ₃ Pb ₂		0.0667			
La ₂ Pb ₃			0.0625		
La ₃ Pb ₂			0.0625	0.1	
LaPb ₂				0.1	
LaPb ₃					0.2

Sistema MOX-La-Pb

- Comportamento simile al sistema MOX -Pb
- Già a 900K si formano ossidi di U, Pu e Pb con elevato contenuto di O
- No formazione di composti La-U/Pu

Open issues...

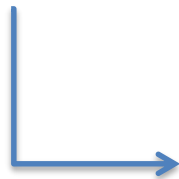
Limitazione del codice

- Composti che decompongono;
- Composti non stechiometrici;
- Curve di miscibilità e punti eutettici.



Compilazione del Database

Mancanza di dati termodinamici sperimentali

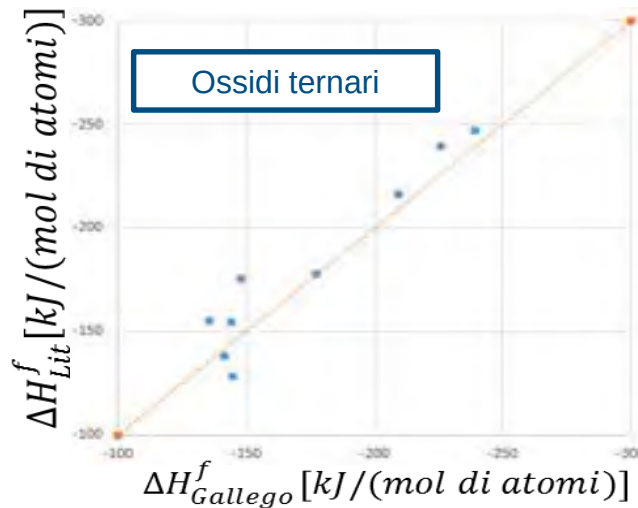
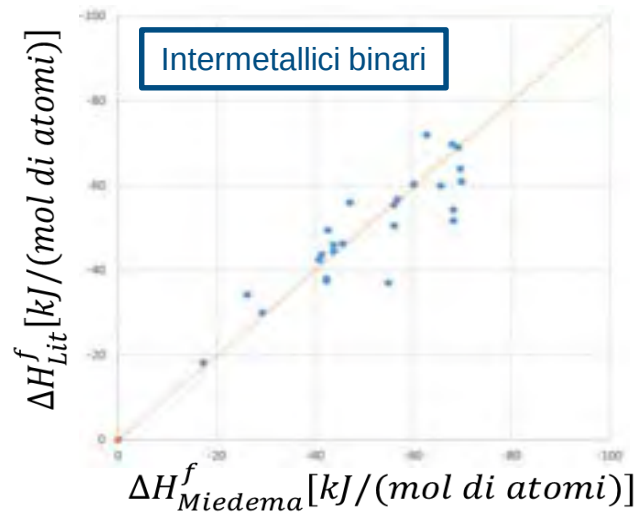


- *Metodi semi-empirici*
 - costi computazionali ridotti
 - sviluppati per il calcolo di numerose grandezze
 - “spesso” in buon accordo con i dati sperimentali
- *DFT - Density Functional Theory*
 - relativamente poco oneroso
 - può trattare gli attinidi

Stima mediante metodi semi-empirici:

- **Entalpia di formazione ΔH^f e entalpia di soluzione ΔH^{sol}** mediante metodo Miedema e sua estensione (di Neuhasen) al gruppo dei calcogeni ¹
- Entalpia di formazione ΔH^f per ossidi e intermetallici ternari con l'estensione di Gallego

Entalpia di formazione



A. Tosolin, *Interazione tra combustibile e termovettore in sistemi LFR di IV generazione: stima di grandezze termodinamiche tramite metodi semi-empirici*, Tesi di Laurea Specialistica in Ingegneria Nucleare, A.A. 2012-2013;

A. Tosolin, E. Macerata, E. Mossini, M. Cerini, M. Giola and M. Mariani, *Proc. Int. 23rd International Conference Nuclear Energy for New Europe-NENE 2014*, p. 1212, Nuclear Society of Slovenia (2014) (CD-ROM), ISBN 978-961-6207-37-9

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Stima mediante metodi semi-empirici:

- **Entropia** mediante il metodo di Witusiewicz-Sommer per intermetallici binari²
- **Calore specifico** per intermetallici binari mediante la legge di Kopp modificata

Entropia

Composto	Entropia totale, S_{tot} [J/Kmol]	
	calcolata	sperimentale
AuSn	75.83	98.115
AuSn ₂	115.23	135.562
AuSn ₄	193.98	250.622
Cu ₂ Sb	108.01	126.482
CdSb	89.13	94.558
InSb	66.47	86.199
Mg ₂ Pb	84.59	110.876

Entropia totale in fase solida per i sistemi La-Pb, Fe-Pu, Sr-Pb e Cs-Pb.

Calore specifico

$c_p(T)$ degli intermetallici:
U-Pb, Pu-Pb, Fe-Pb, La-Pb, Fe-Pu, Sr-Pb e Cs-Pb.

Non sono stati individuati metodi per la stima di Entropia e Calore specifico di ossidi e composti ternari.



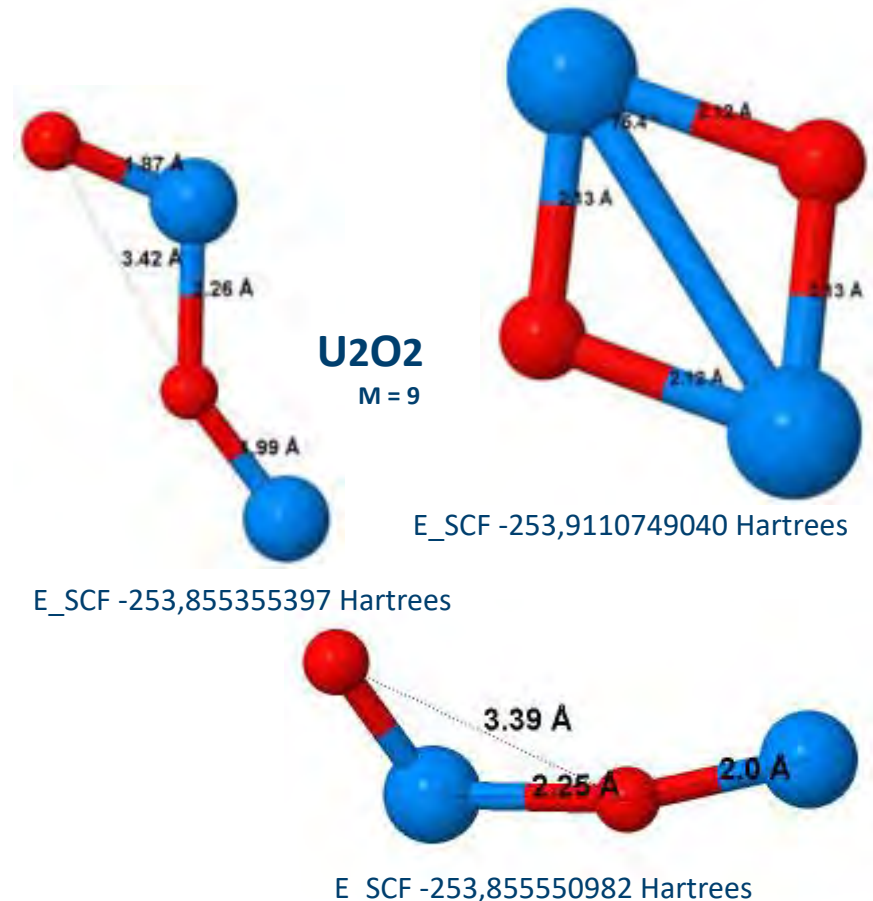
2. V.T. Witusiewicz, F. Sommer, *Journal of Alloys and Compounds*, **2000**, 312, 228-237

Stima di entalpia, entropia e calore specifico mediante DFT-GGA

- Studio preliminare **in fase gas**¹⁻²:

Simulatore Gaussian09 / **Basis-set** RECP –
Relativistic Effective Core Potential / **Funzionale**
ibrido-GGA (*Generalized Gradient Approximation*)

- È stata selezionata e validata una combinazione **funzionale/basis-set** per un approccio semi-sistematico;
- Ottimizzazione della geometria per ricavare la configurazione di minima energia;
- Nella configurazione di minima energia:
 - dalle frequenze vibrazionali sono state calcolate l' S_0 e il $c_p(T)$ in fase gas;
 - dai contributi energetici (energie SCF, ZPE e H_{corr} in output) è stata calcolata l'entalpia di formazione.



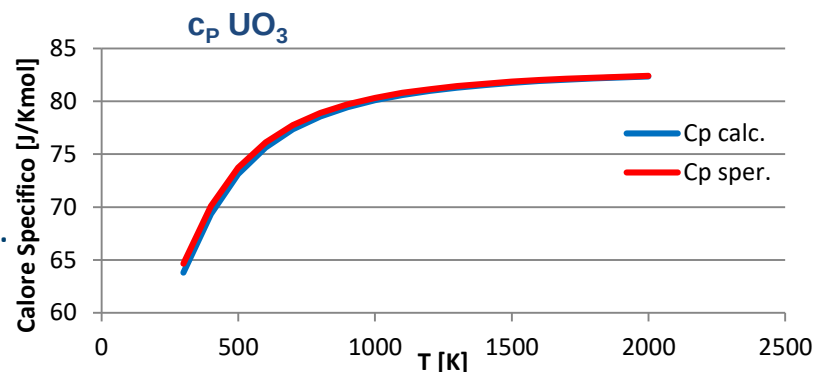
1. N. Tarrat, C. J. Marsden, *J. Phys. Chem. A*, **2008**, 112, 7632-7642

2. A. Kovacs, P. Pogany, J.M. Konings, *Inorganinc Chemistry*, **2012**, 51, 4841-4849

G. Dia, *Compatibilità chimica in reattori di IV generazione: studio preliminare tramite metodi ab-initio di composti Pb-An*, Tesi di Laurea Specialistica in Ingegneria Nucleare, A.A. 2012-2013.

Stima mediante simulazioni DFT-GGA:

- Ossidi di Pb: PbO , PbO_2 , Pb_3O_4 ;
- Intermetallici Pu-Pb: PuPb , PuPb_3 , Pu_3Pb ;
- Ossidi dell'Am, Np e Cm: AmO , AmO_2 , AmO_3 , Am_2O_3 , ...
- Intermetallici Pb-FP: LaPb_3 , SrPb_3 , Cs_2Pb_3 ;
- Intermetallici: UFe_2 , UNi_2 , PuFe_2 , PuNi_2 ;
- Intermetallici Am/Np/Cm-Pb: AmPb , AmPb_3 , Am_3Pb , ...
- Intermetallici Pb-guaina: PbFe_2 , PbAl_2 , PbAl_3 , PbNi_2 , PbNi_3 , PbNi_4 , PbCr , PbCrO_4



Molecule	Vibrational Frequency [cm ⁻¹]		Entropy [J/K·mol]		Formation Enthalpy [kJ/mol]	
	Calculated	Experimental	Calculated	Experimental	Calculated	Experimental
UO_2	807.8	820.0	251.013	263.554	-565.0	-477.8
UO_3	904.7	852.5	309.644	308.683	-892.1	-799.2
PuO_2	832.6	786.8	275.951	278.0 ± 5	-373.2	-410.2
UPb	93.3	-	295.341	-	501.6	-
UPb_3	135.6	-	444.145	-	88.9	-
PuPb	87.7	-	297.267	-	478.9	-
PbO	764.9	721.0	239.536	240.039	-84.5	70.2

Quantity	Δ % Exp-Calc
Entropy	+ 5
Specific Heat Capacity	+ 7
Formation Enthalpy	-20
Bond Dissociation Energy	-12

M. Cerini, G. Dia, E. Macerata, E. Mossini, M. Giola, M. Mariani, C. Cavallotti, *Proc. Int. 23rd International Conference Nuclear Energy for New Europe-NENE 2014*, Portorose, Slovenia, Settembre 8-11, 2014, p. 1209, Nuclear Society of Slovenia (2014) (CD-ROOM), ISBN 978-961-6207-37-9

M. Cerini, E. Macerata, M. Giola, M. Mariani, C. Cavallotti, *Advancing the chemistry of the f-elements, Dalton Discussion 14*, 28-30 July 2014, Edinburgh, UK

Stima di entalpia, entropia e calore specifico mediante DFT-GGA

- **In fase condensata** tramite il codice VASP (Vienna Ab-initio Simulation Package)¹:
 - Projector Augmented Wave potentials (PAW)
 - Generalized Gradient Approximation (GGA)
- **Procedura:**
 - Determinazione della cella cristallina;
 - Identificazione della posizione degli atomi nella cella unitaria;
 - Ottimizzazione dei parametri di reticolo in corrispondenza della configurazione di minima energia;
 - Valutazione delle proprietà (S , c_p , ΔH_f^0) dalle frequenze vibrazionali e dai contributi energetici mediante le relazione della termodinamica statistica.
- **Validazione:**
 - Parametri di reticolo, a_0 ;
 - Entalpia di formazione, Entropia e Calore specifico;
- Collaborazione col Centro di Supercalcolo CINECA:
 - Progetti LISA:
 - CHILDHOOD - Chemical issues in Lead Fast Reactors by theoretical methods
12 mesi (Maggio 2013 – Aprile 2014); Budget: 94000 stdhours su EURORA, PLX, FERMI
 - FueLead - Computational approach for fuel-coolant chemical compatibility in Lead-cooled Fast Reactors
6 mesi (Giugno 2014 –Dicembre 2014); Budget: 50000 stdhours su PLX
 - Progetto ISCRA:
 - ThermPro - Estimation of thermodynamic properties by theoretical approach within the development of Lead-cooled Fast Reactors
9 mesi (Aprile2015 –Dicembre2015); Budget: 50000 stdhours su Galileo



1. J. Hafner, *Journal of Computational Chemistry*, **2008**, 29, 2044

Stima di entalpia, entropia e calore specifico mediante DFT-GGA

Compound	a ₀ [Å]			Compound	a ₀ [Å]			c/a
	Calc.	Exp.	% deviation		Calc.	Exp.	% deviation	
UO ₂	5.43	5.47	-0.73%	UPb ₃	4.84	4.79	+1.04%	-
NpO ₂	5.42	5.43	-0.18%	Pu ₃ Pb	4.82	4.74	+1.69%	-
PuO ₂	5.41	5.40	+0.18%	LaPb ₃	4.96	4.90	+1.22%	-
AmO ₂	5.41	5.38	+0.56%	SrPb ₃	4.98	4.95	+0.61%	1.01
CmO ₂	5.42	-	-	CsPb	8.89	-	-	1.63
				BaUO ₄	5,8	5,75	0,87	

M. Cerini, *Fuel-Coolant Chemical Interaction for Lead-cooled Fast Reactors by a computational approach*, Tesi di Dottorato, II anno.

Compound	Entropy [J/(Kmol)]			Specific Heat Capacity [J/(Kmol)]			Formation Enthalpy [kJ/mol]		
	Calc.	Exp. ^[1]	% deviation	Calc.	Exp. ^[1]	% deviation	Calc.	Exp. ^[1]	% deviation
UO ₂	80.22	77.00	+4.18%	65.86	63.57	+3.60%	-1034.36	-1084.90	-4.66%
NpO ₂	80.27	80.33	-0.07%	65.94	63.72	+3.49%	-1069.74	-1029.26	+3.93%
PuO ₂	82.37	66.00	+24.80%	66.52	66.35	+0.41%	-1018.12	-1055.70	-3.55%
AmO ₂	80.06	75.50	+6.04%	65.96	66.17	-0.32%	-928.48	-932.3	-0.41%
CmO ₂	84.80	-	-	67.56	-	-	-763.66	-	-
UPb ₃	164.15	-	-	102.19	-	-	-70.82	-73.67	-3.87%
Pu ₃ Pb	172.74	-	-	103.76	-	-	-196.28	-	-
LaPb ₃	172.63	-	-	103.73	-	-	-193.07	-206.00	-6.28%
SrPb ₃	170.61	-	-	103.17	-	-	-150.60	-	-
CsPb	92.49	-	-	49.73	-	-	121.72	-	-
BaUO ₄	160,24	154	4,05	127,58	125,3	1,82	-1975,34	-1993,8	-0,93

M. Cerini, E. Macerata, M. Giola, M. Mariani, C. Cavallotti, *DFT-GGA Predictions of Thermodynamic Parameters in Solid Phase for Binary Compounds of Actinides and Fission Products*, GLOBAL 2015 International Conference, 20-24 September 2015, Paris, France

Confronto tra le stime con metodi semi-empirici e con DFT

Compound	Formation Enthalpy [kJ/mol]		
	DFT	Miedema	Exp.
LaPb₃	-193.07	-188.4	-206.00
UPb₃	-70.82	-68.8	-73.67
PbTiO₃	-1182.73	-1239.4	-1194.7
UO₂	-1097.99	-922.5	-1084.9
NpO₂	-1069.74	-836.17	-1029.26

Compound	Entropy [J/(K·mol)]		
	DFT	W-T	Exp.
UFe₂	109.7	83.22	104.6
LaAl₂	98.56	59.81	98.74
Mg₂Pb	109.63	92.02	110.88
Cu₂Sb	118.99	126.48	100.33

Compound	Specific Heat [J/(K·mol)]		
	DFT	W-T	Exp.
UFe₂	75.75	82.84	78.61
LaAl₂	73.63	96.95	73.72
YPb₃	103.36	128.12	104.83
Cu₂Sb	76.58	74.05	76.57

L'approccio DFT proposto è più accurato dei metodi semiempirici considerati.

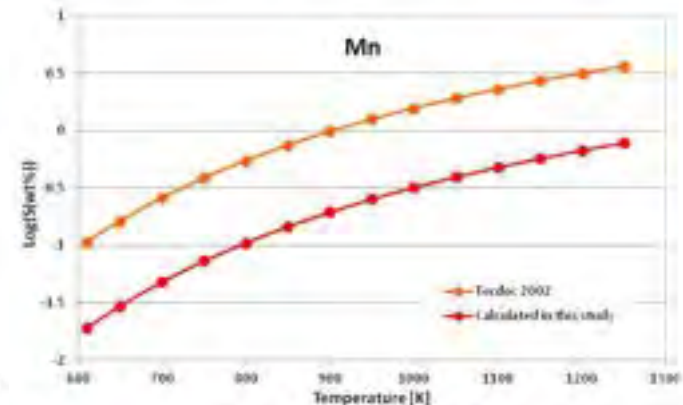
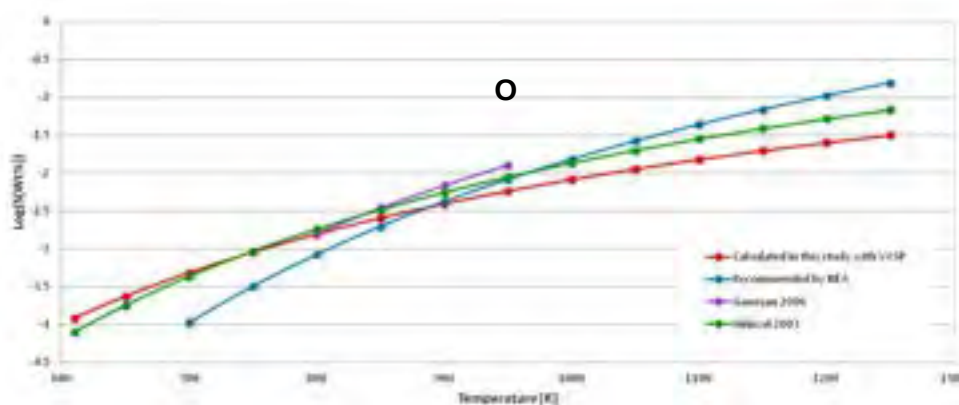
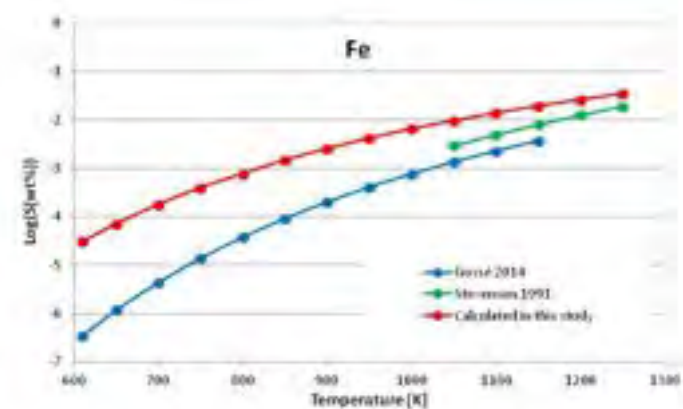
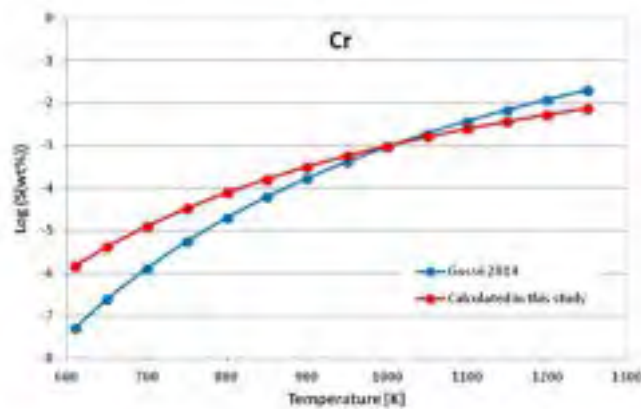
Database di dati termodinamici

È stato quindi possibile implementare un Database [12-14] di dati termochimici (entalpia di formazione e soluzione, entropia, calore specifico) in fase gas e condensata di:

- Ossidi binari di Pb, U, Pu, Am, Cm, Np, principali prodotti di fissione;
- Composti binari del Pb con U, Pu, Am, prodotti di fissione (Cs, Sr, Y, lantanidi, Pd, Zr);
- Composti ternari di Pb-U-Pu; Pb-Sr-Y, Pb-Cs-U, Pb-Cs-Pu, Pb-Sr-U, Pb-Sr-Pu, Pb-Y-U, Pb-Y-Pu; Pb-O-Cr/Mo/Ti;
- Uranati di Pb, Cs e Sr;
- Intermetallici di U/Pu con Fe/Ni: UFe_2 , UNi_2 , PuFe_2 , PuNi_2 .

Solubilità di elementi/composti in piombo liquido

- Simulazione DFT in VASP mediante modello a diluizione infinita;
- Calcolo di entalpia e entropia di dissoluzione;
- Correlazioni riportate nella pubblicazione della NEA n° 7268, 2015.



M. Cerini, E. Macerata, M. Giola, M. Mariani, C. Cavallotti, "Study of Fission Products solubility in liquid Pb by DFT approach", Submitted at *Scientific Basis for Nuclear Waste Management XXXIX*, Montpellier, France, 2-6 November 2015

Studio propedeutico all'attività sperimentale

- Progettazione di prove volte all'ottenimento di parametri termodinamici di interesse, utilizzabili per validare l'approccio computazionale sviluppato nei precedenti PAR;
- Studio del sistema La-Pb e Sr-Pb con Calorimetria a scansione differenziale (DSC):
 - sistemi di interesse per reattori LFR
 - sistemi facile da manipolare
 - mancanza di dati termodinamici (c_p , S_0 , ...)
- Obiettivo dell'esperimento: studiare il calore specifico degli intermetallici LaPb_3 e La_5Pb_3 (Sr-Pb)
- Preparazione campioni: miscela di polvere di Pb (99.99%) e di La (Sr) in proporzioni stechiometriche in atmosfera di Argon,
- Analisi termica: condizioni di temperatura in DSC; Indicazioni su reazioni eso- ed endo-termiche; calcolo del calore specifico; confronto dei dati sperimentali ricavati con quelli stimati - validazione metodi teorici
- Analisi in diffrazione a raggi X: informazioni strutturali su fasi intermetalliche, cfr con dati di letteratura;
- Collaborazione con ITU per ricavare informazioni sperimentali su sistemi U-Pb, Np-Pb e Pu-Pb (2016).

- Approccio promettente
- Limitazione del codice per l'analisi termodinamica
- Mancanza di dati sperimentali

- Metodo DFT per stima di parametri termodinamici
- Validazione = step difficile

- Complementarietà con l'attività sperimentale
- Attività sperimentale con elementi stabili e loro composti
- ...

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University of Pisa
Department of Civil and Industrial Engineering



LFR-GEN IV: Stato Attuale Della Tecnologia e Prospettive Di Sviluppo
ADP ENEA-MSE (PAR2014-LP2)

ANALYSIS OF THE CORE COMPACTION PHENOMENON

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Brasimone, 19-20 Novembre, 2015
Centro Ricerche ENEA Brasimone

CONTENTS

WHAT IS THE CORE COMPACTION

PHYSICAL PROBLEMS TO BE ADDRESSED

CORE COMPACTION MODELLING STRATEGY

ANALYSIS AND RESULTS

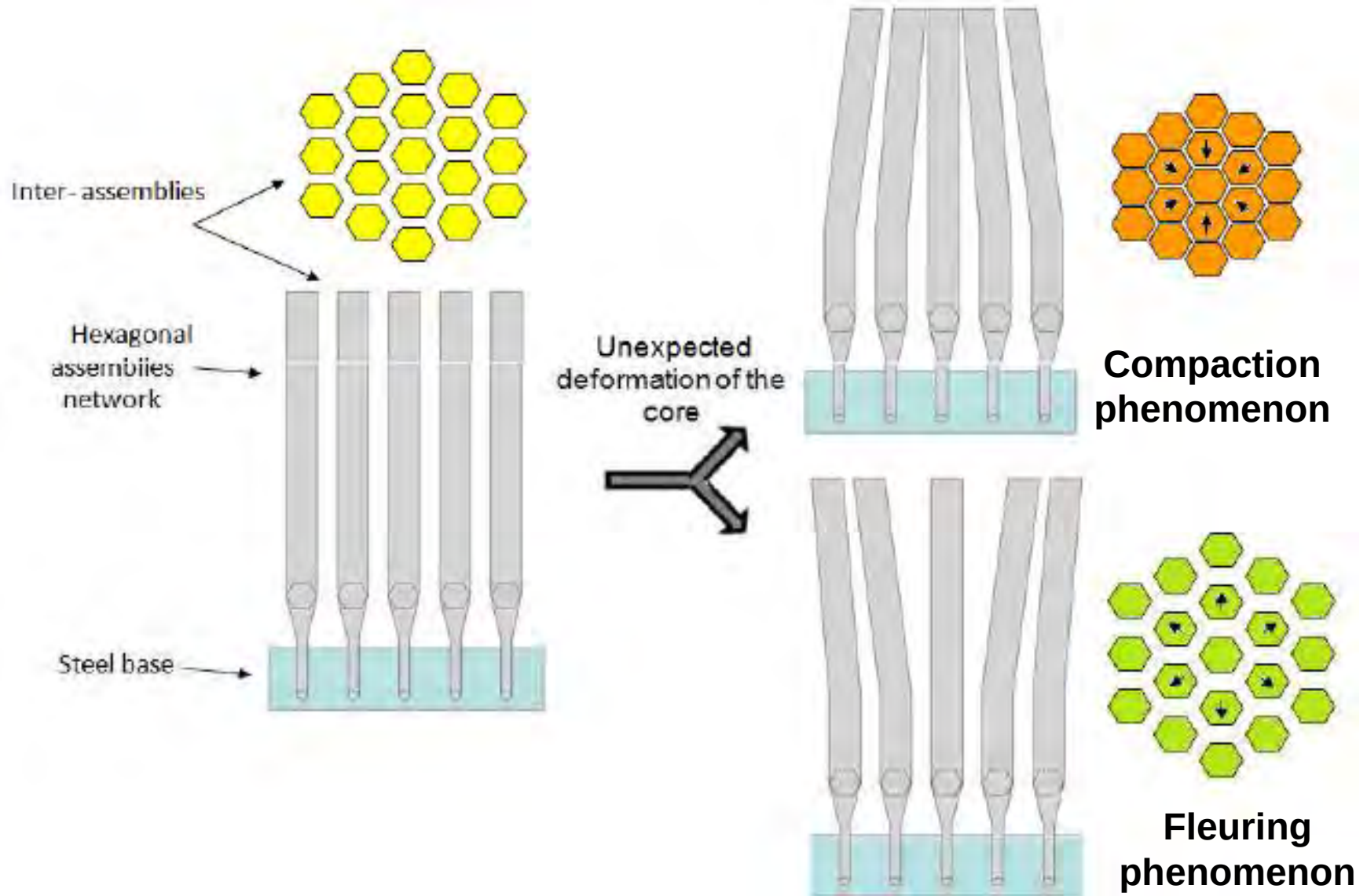
CONCLUSION

FURTHER DEVELOPMENTS

Why to investigate core compaction?

- ❑ The safety is the priority in any nuclear reactor: core compaction is a DBE in LFR
- ❑ Dynamic solicitation affects particularly the core design of LMR because of the high density of the primary coolant (convective mode according to ASCE rules), and the high temperature (operating condition).
- ❑ Nuclear stability dictates that the geometry of the core be closely controlled at all times: keep the reactivity known and controlled.
- ❑ Core deformation, caused by dynamic condition like the seismic motion, may determine to a large or small extent.
- ❑ Radial inward displacement (i. e. flexion + constraint on pads) could be accompanied by a localized surface bulging.
- ❑ Core compaction could cause severe and dangerous consequences particularly in the case of severe (and near fault) seismic event.

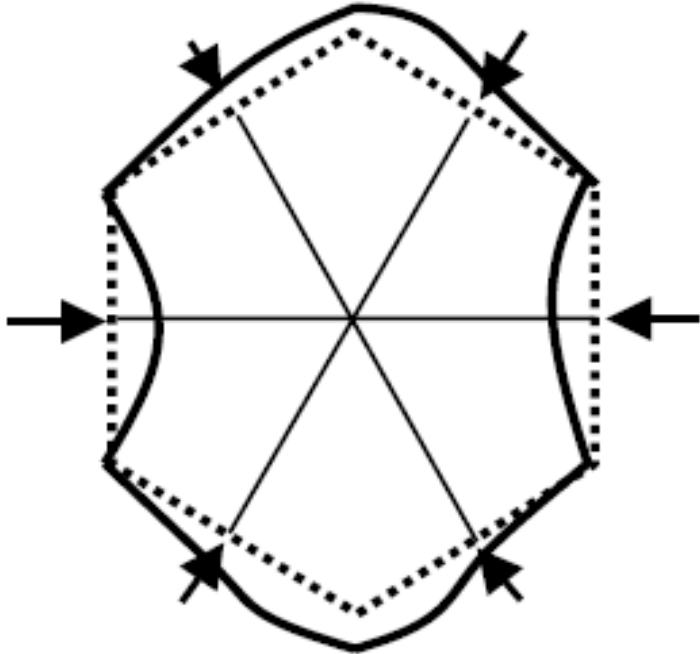
Physical problems to be addressed



The vertical, radial or circumferential deformations (large or small) are induced by dynamic or vibration loads.

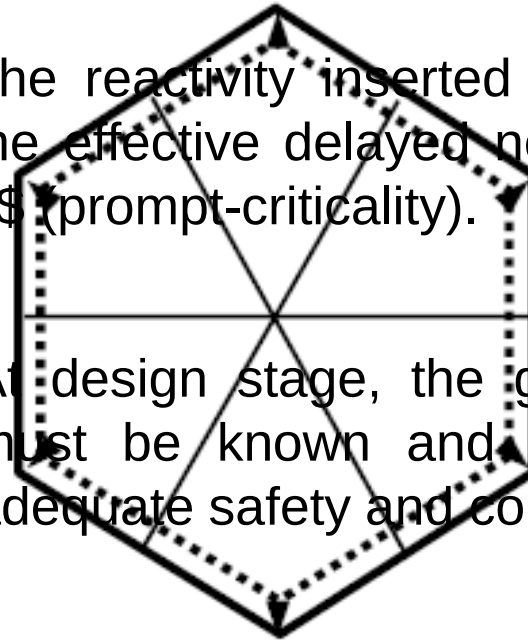
Physical problems to be addressed (Contd)

Since it is not possible to exclude core compaction, no matter the number and robustness of the countermeasures adopted to prevent the initiating causes, it becomes of paramount importance to limit the compaction, through passive, simple and reliable means, so to manage the associated reactivity insertion.



The reactivity inserted should not approach the effective delayed neutron fraction that is β_{eff} (prompt-criticality).

At design stage, the geometrical restraints must be known and controlled to assure adequate safety and core performance.



Scheme of the radially inward deformation of an assembly

Deformation of Pad cross section
due to thermal expansion

Coupling stiffness of

Physical problems to be addressed

Major restraints to consider:

- Reactivity: to enhance the inherent core safety, assemblies have to be supported such to accommodate “dynamic motions” by finite inter-assembly and peripheral gaps.
- Assembly Deformation: high temperature and neutron flux environment produce duct dilation and permanent assembly bowing.
- Assembly Alignment: thermo-mechanical loads can modify the alignment of the assemblies with interfacing control and refuelling system components.
- Load Transmission: the definition of load transmission planes allows to identify interfacing gaps at core and internals component elevations .

Core compaction modeling strategies

Few modelling approach (referred to LMFR) are available in literature:

- 2D models of cores includes a single row of assemblies to analyze and design the LMFR assemblies against seismic loadings.
- Preumont (1987) 2D model considers the fluid coupling created by the thin fluid layers between assemblies
- Martelli model replaces the coupling effect of the fluid with added masses on each assembly.
- Moussallam et al. (2011) model assumes the fluid effect as purely inertial, with no energy dissipation, and small relative displacement between adjacent assemblies: the full Navier-Stokes equations describing the fluid behaviour are reduced to the wave propagation equation associated with a pressure boundary condition at the interfaces with structures .

A lot of work must be done to investigate core compaction on LFR...

Core compaction modeling strategies (Contd)

Deterministic methodology plays an important role in evaluating the inherent capability of plants to withstand severe internal external events.

The SMA methodology considers, often, a higher level of hazard (high intensity/magnitude of the initiating event) to be conservative and determine/associate it the really strength capacity.

The inherent additional capacity of the SSCs may be taken into account as well all significant information concerning material property, geometry (progressive damage of component and structure) and operational status, boundary and initial conditions.

Conservatism is also present since this approach is compounded through the safety analysis and design chain.

Core Compaction analysis

LFR main key issues and proposed strategies and R&D needs.

GENERAL ISSUE	SPECIFIC ISSUE	PROPOSED STRATEGY/NEEDED R&D
Lead technology	Lead purification	Technology for the purification of large quantities of lead to be confirmed.
	Oxygen control	Extend oxygen control technology to pure lead for pool reactors.
Potentially high mechanical loading	Earthquake	Reactor building built with seismic isolators plus short vessel design.
	SGTR accident	Prevention by design of: - steam entrainment into the core; - reactor vessel pressurization; - pressure wave propagation across the primary system.
Main safety functions	Diversified, reliable, redundant DHR and shut down system	Use of both atmospheric air and pool water and of diversified solutions

The primary system design temperature ranges between 400°C and 480°C, while the design pressure is about 1 bar (primary system not pressurized). The operational condition range of the secondary side, entering the RV through the SG tubes, is between 335°C and 450°C at about 18 MPa.

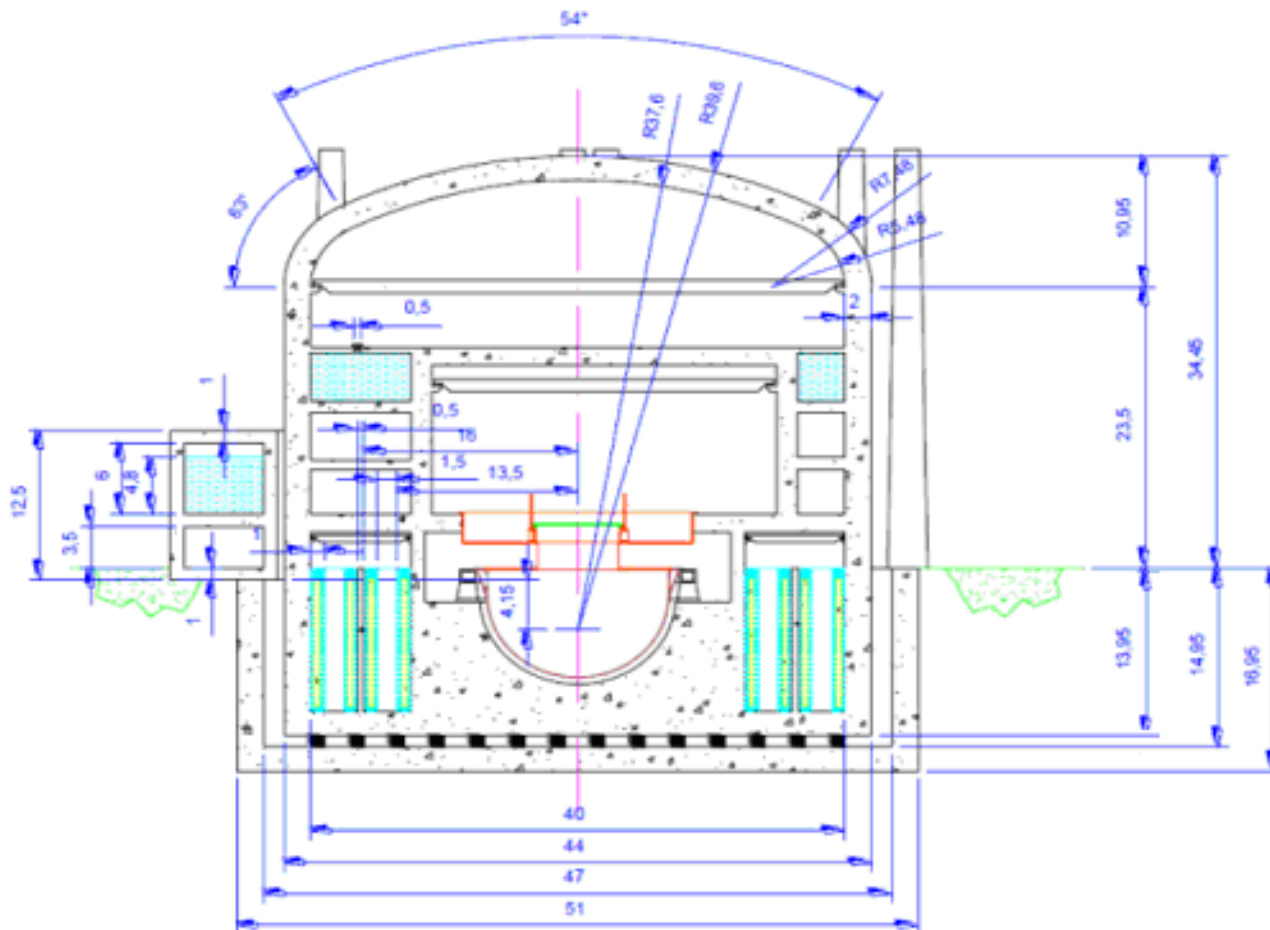
Core Compaction analysis

In studying the core compaction the Advanced Lead-cooled Fast Reactor European Demonstrator - ALFRED, was considered: the reactor building of which was already defined in the ELSY 6th FP.



<http://www.leader-fp7.eu/>

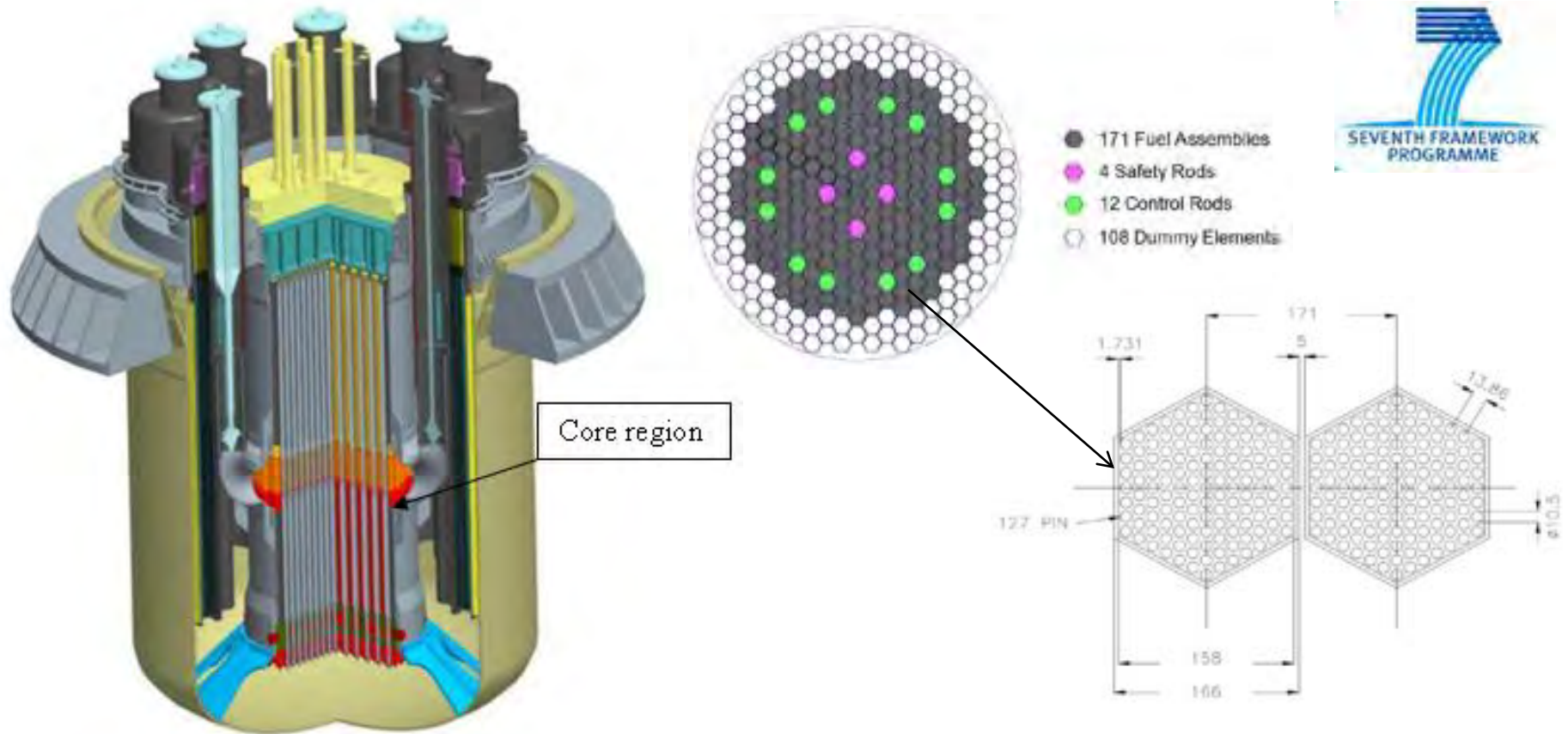
<http://www.elsy-fp6.eu/>



Core Compaction analysis

The major components of the ALFRED reactor are: assemblies, diagrid, inner cylindrical vessel, lateral supports (at two elevations along the ICV) etc. The assemblies are axially positioned and supported by upper and lower core support plates.

<http://www.leader-fp7.eu>

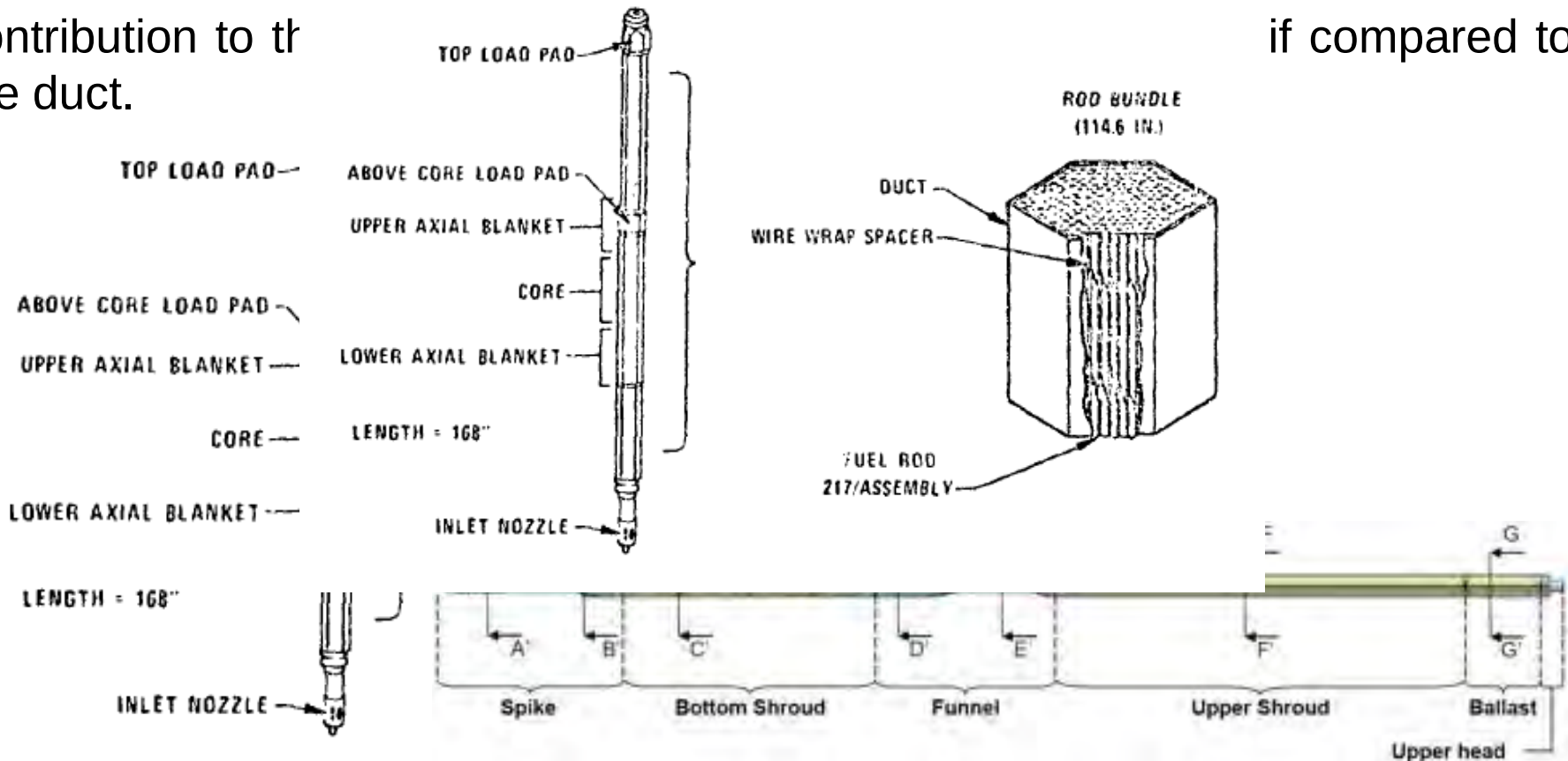


The RV, SGs and SG outlet, and the skirt are made of SA 240 316LN, whereas the SGs support box and the base plate of SA 516 Gr 70 carbon steel.

Core compaction analysis

Fuel rods are of contribution to the duct.

rod and duct: the contribution if compared to



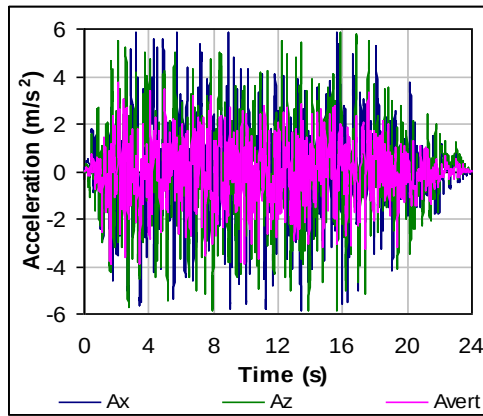
The top load pad (TLP) is located on a transition section between the fuel rod bundle and outlet nozzle. This section is relatively thick and as a result the TLP is essentially rigid when lateral loads are applied, although its characteristic stiffness depends on the nature of the applied/sustained loading (e.g. mechanical, dynamic loads, etc.).

Core compaction analysis

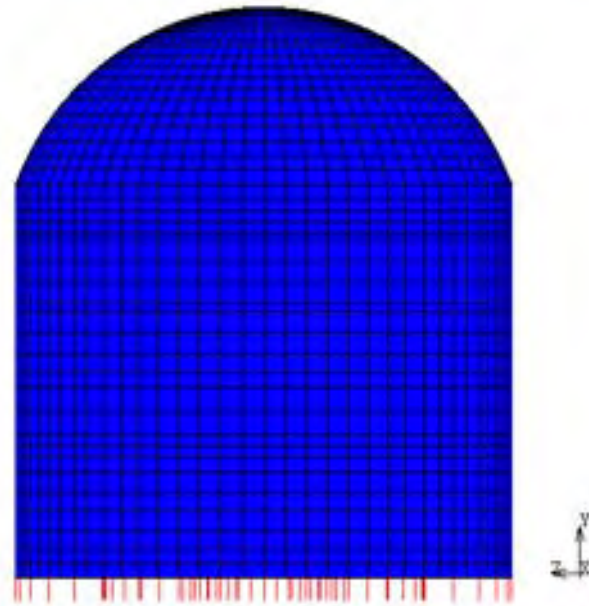
Dynamic loadings to be taken into account :

- **Fluid-induced vibration**, e.g. due to the coolant flow through the assemblies.
- **Shock induced excitation**, typically of short duration, associated to an accidental handling condition, steam generator tube rupture (SGTR) event etc.
- **Internal energy release** represents a beyond design condition; namely, whatever the initiating event (normal or accidental conditions), the nature of the energy release and its forms (pressure wave, kinetic energy of the coolant, etc.), it shall not bring the core to the limit of the prompt-criticality.
- **Seismic excitation** is of major concern because it is unpredictable like its severity. Specific design criteria must be fulfilled, such as the limitation of the maximum allowable displacement of the assemblies, at the foot and head, the maximum allowable acceleration at pins level, etc.

Core compaction modelling



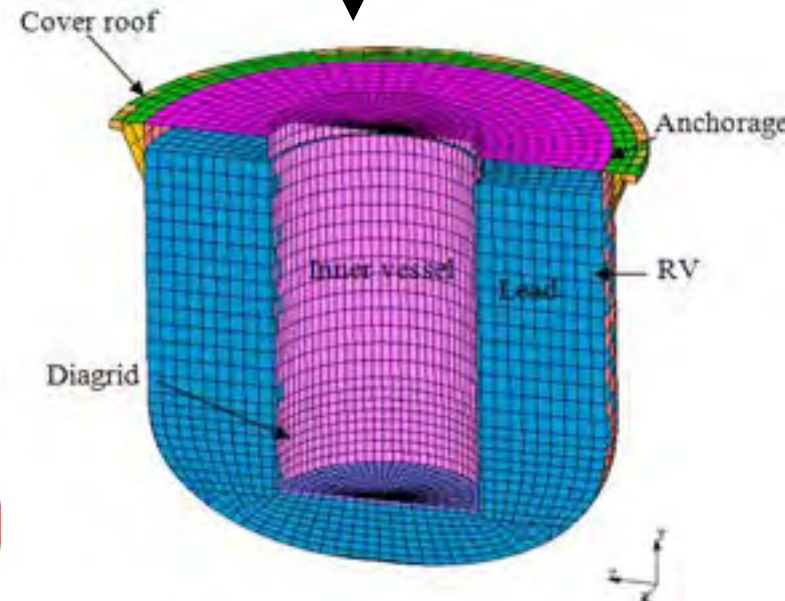
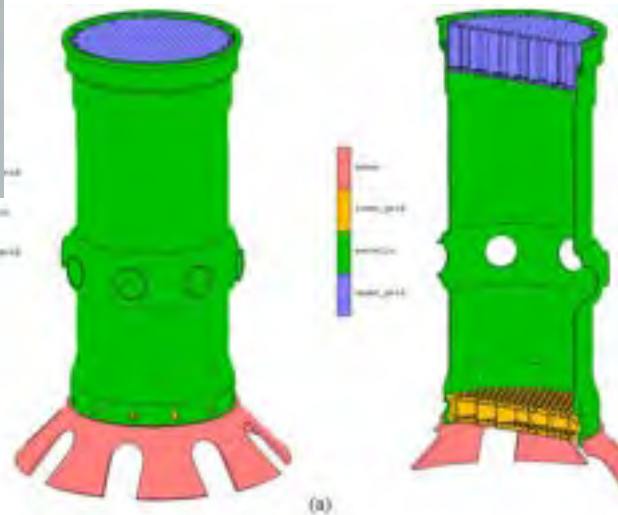
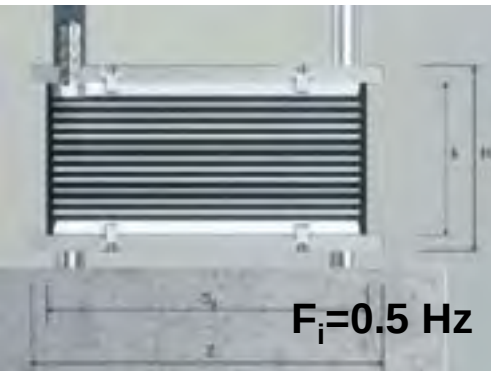
0.3 g PGA



ATHs are calculated (RG 1.60 Rev.1 and 1.92) for 5% critical damping.

$$A_{x,z_out}/A_{x,z_in} = 40-50\%.$$

$$A_{vertout}/A_{vert_in} = 130\%.$$



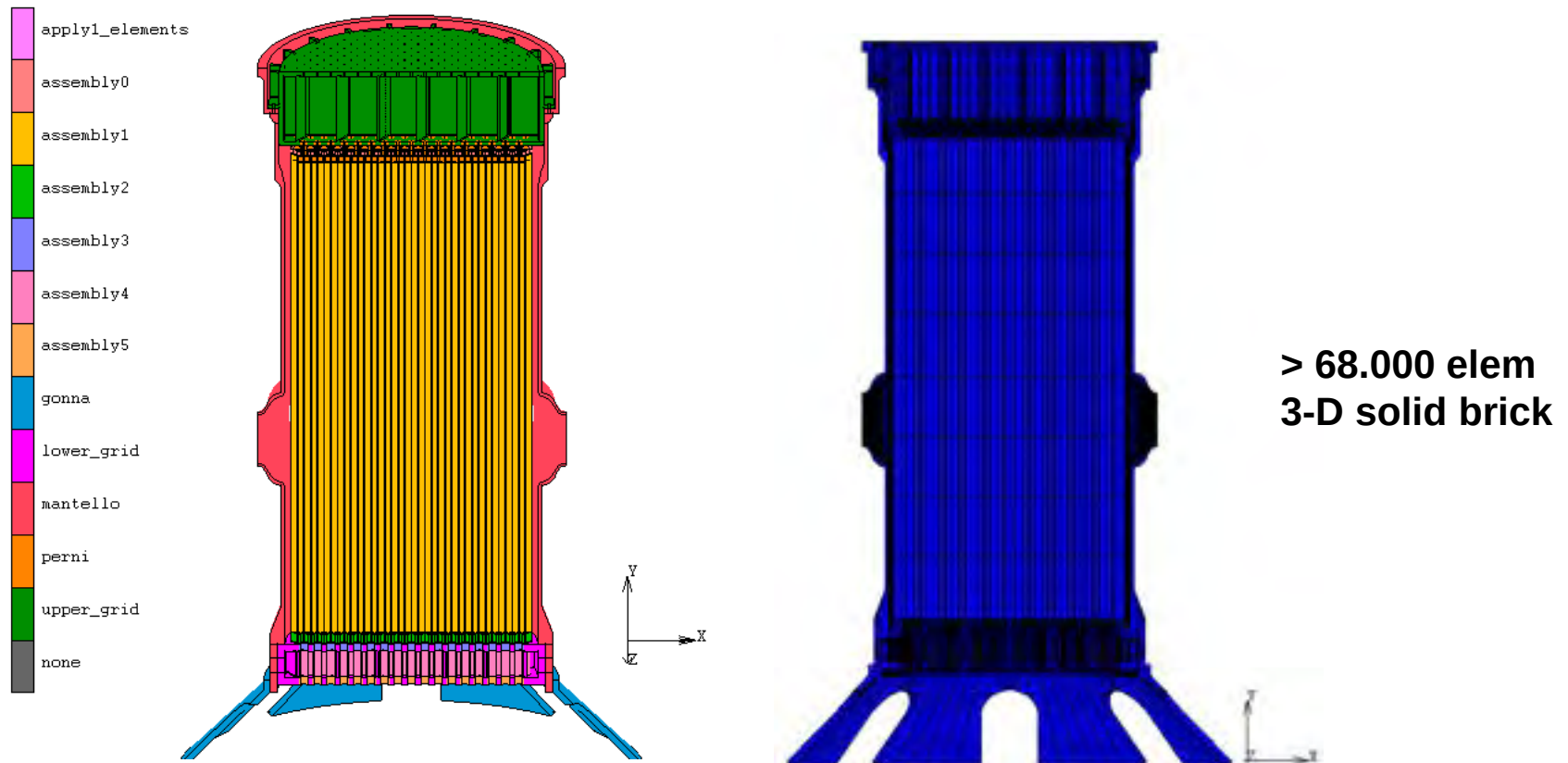
Core compaction modelling

Because of the complexity and lack of information on geometry, not all the RV components are modelled: no piping or primary coolant.

BCs are:

double symmetry condition along the centre line;

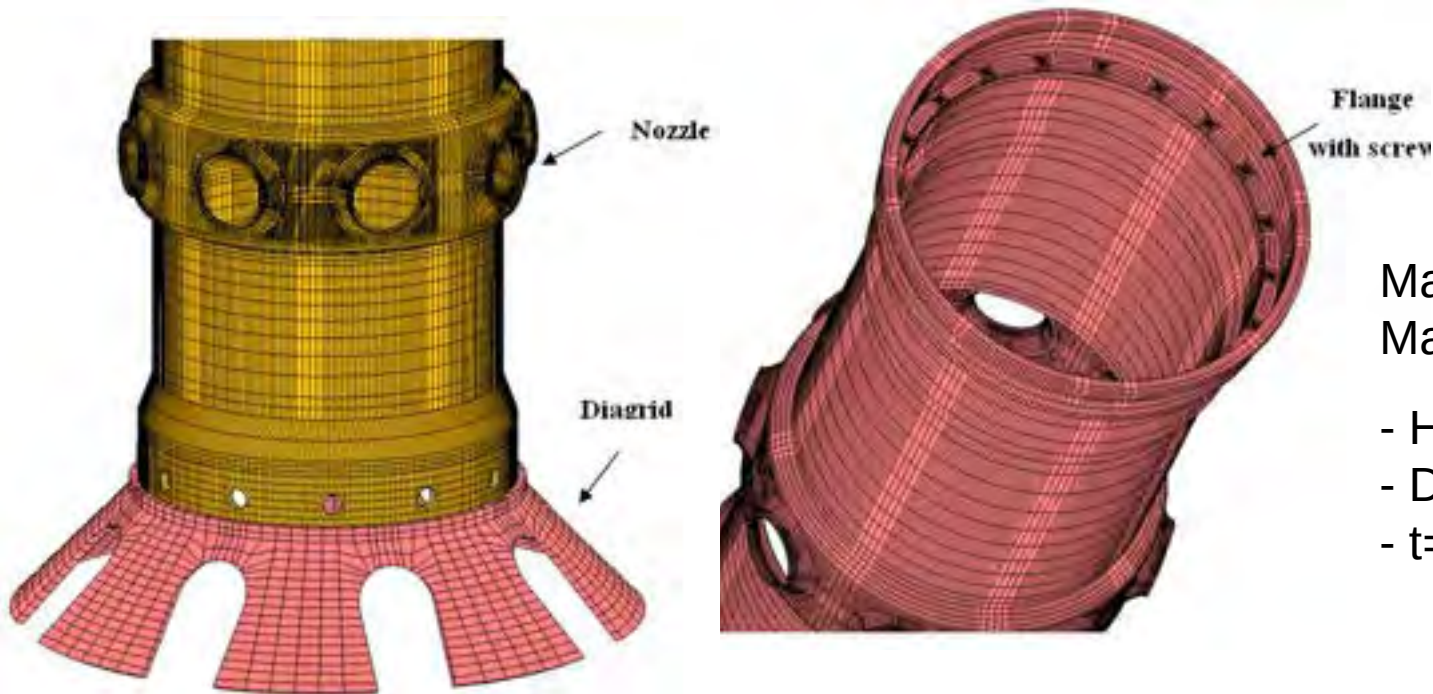
clamp restraints at the diagrid foots and upper part of upper plate and IC shell.



Model of the inner cylindrical vessel with FAs

Core compaction modelling

- The lower part has a diameter slightly greater than the main one to allow the insertion of the lower grid
- In the middle part the diameter and thickness increase due to the presence of outlet nozzles.
- In the upper part is present an inner flange for supporting the upper grid.



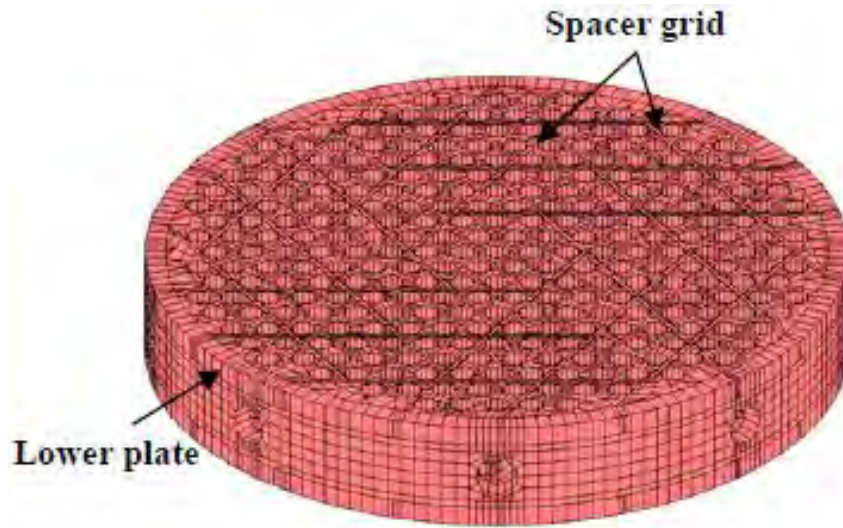
Material: AISI 304;
Main dimension:

- $H=9070$ mm;
- $De=3320$ mm;
- $t=50$ mm.

The sustaining diagrid has openings to allow coolant flows upward.

Core compaction modelling

- The bottom diaphragm was simulated through its two horizontal perforated plates, each one 100 mm thick, connected and stiffened by vertical spokes, and plates holes for housing FAs foots and plates distance guaranteeing verticality.
- This component is enclosed by two identical cylindrical perforated plates, each one 100 mm thick. The distance between the two plates is guaranteed through an internal grid with an hexagonal geometry.



Material: AISI 304;

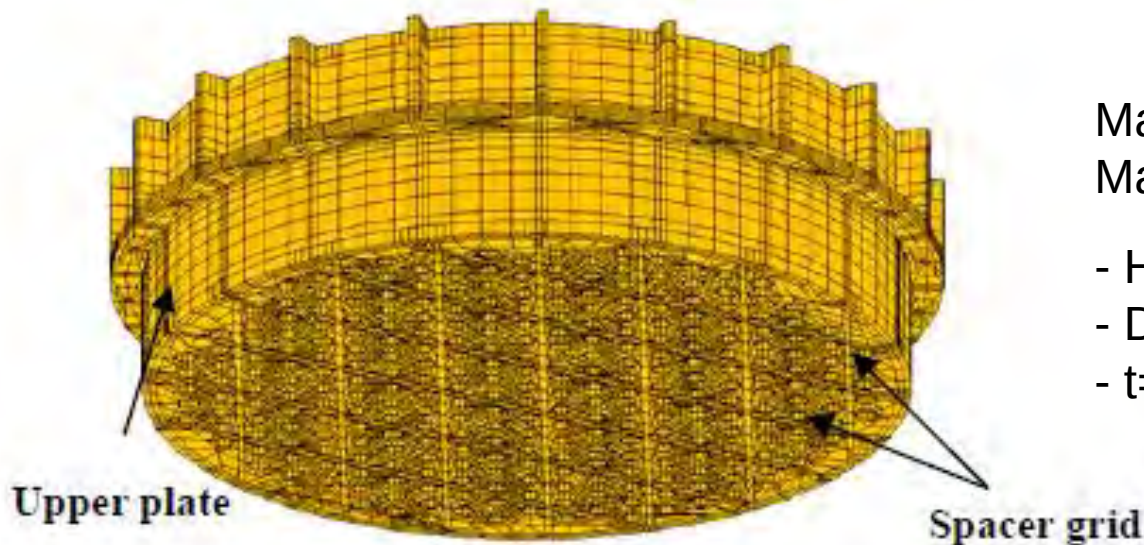
Main dimension:

- $H=550$ mm;
- $D_e=3420$ mm;
- $t=100$ mm.

On the lateral surface are obtained eight holes, four of which used for the insertion of plugs to connect it to the bottom part of the inner vessel.

Core compaction modelling

- The upper grid and inner vessel are linked together via twenty screws;
- The upper grid enclosed at the ends by two perforated cylindrical plates: the diameter of the holes in the upper plate is 20 mm, while the one of the holes in the lower plate is 90 mm.
- An inner grid separates the two plates, its geometrical shape is similar to that one of the lower grid



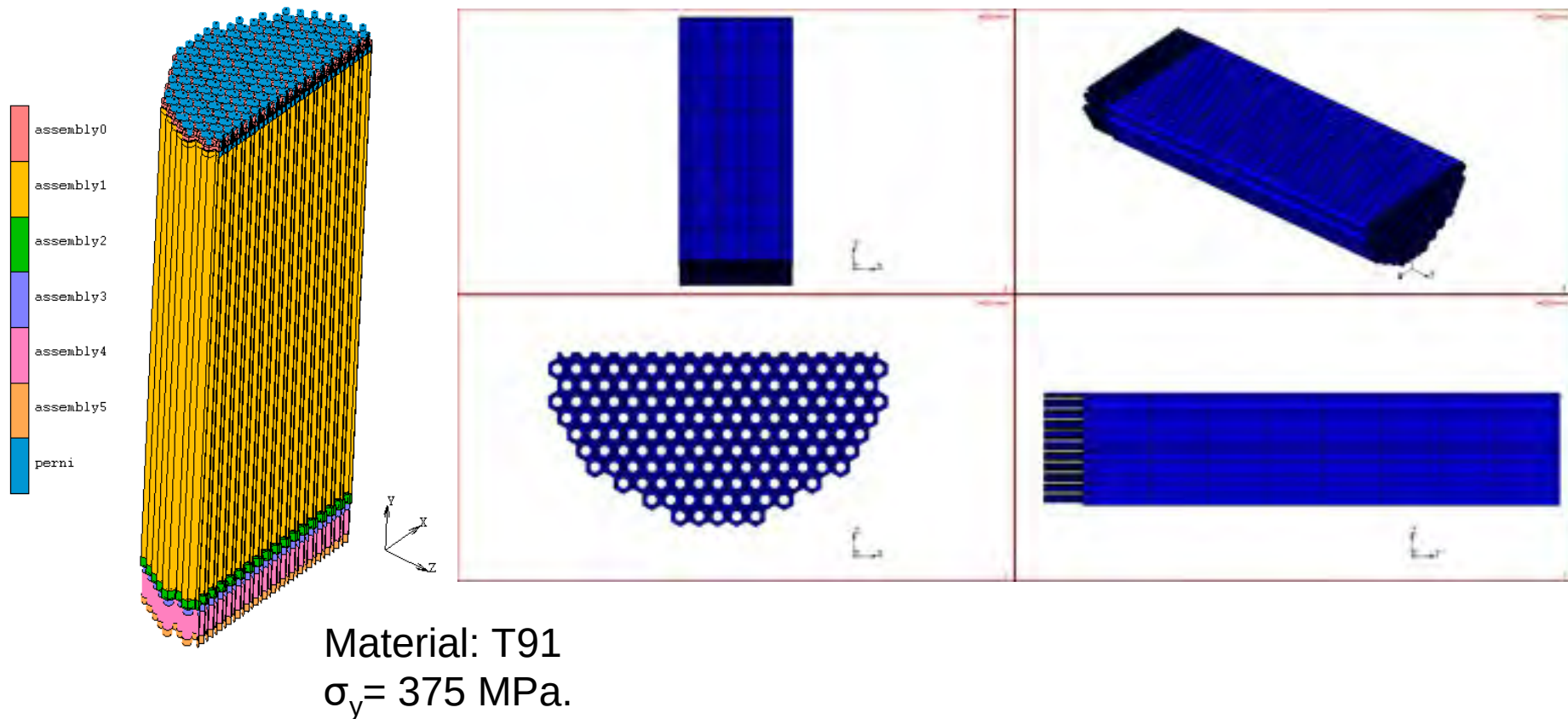
Material: AISI 304;
Main dimension:

- $H=100$ mm;
- $De=3420$ mm
- $t=60$ mm.

Core compaction modelling

Each assembly has an hexagonal shape containing 295 total fuel element. It is 8.15 m long and about 171 mm width.

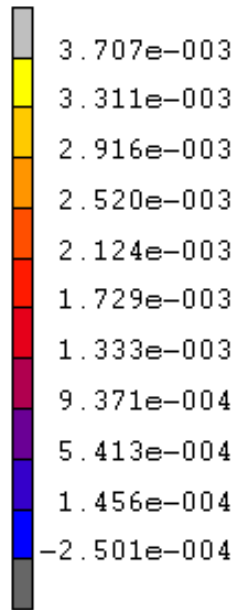
The pitch between two adjacent assembly is 171 mm, while the gap is 5 mm. The spike (bottom part of the assembly) has 0.115 m diameter. It is inserted for about 1 m in the bottom plate allowing lead to flow in the sub-channels.



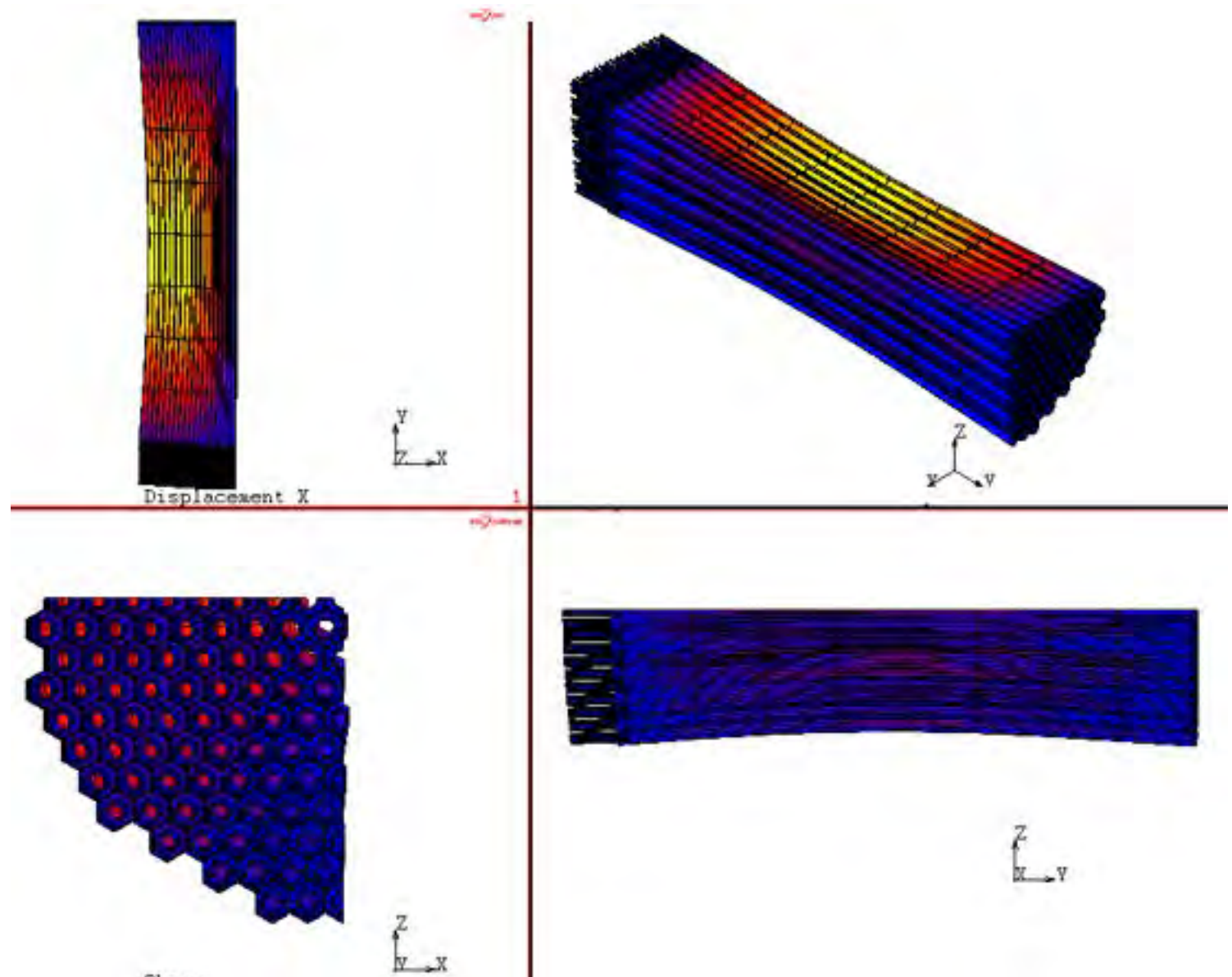
Modelling assumption (Contd)

- The core assemblies were represented by means of a distributed mass over the lower support plate.
- Surface-to-surface contact/interaction is implemented like a single side contact algorithm. The contact detection is based on the touching at the beginning and during the analysis
- Minimum contact distance, defined as the distance value below which two bodies are going in contact, was assumed equal to 10^{-5} m.
- FAs are also restrained to each other's in order to avoid/limit vibrations.
- The ballast, linked to the upper plate, together with the Upper Head is represents through upper restraints.
- FAs spike restraint FAs to the bottom plate
- Clamped restraint between the support skirt and the main vessel and the one between the inner vessel and the reactor cover has been imposed
- No variation of the mechanical properties along the height and radius.

Core compaction results: dynamic behaviour



1st f ~ 23 Hz

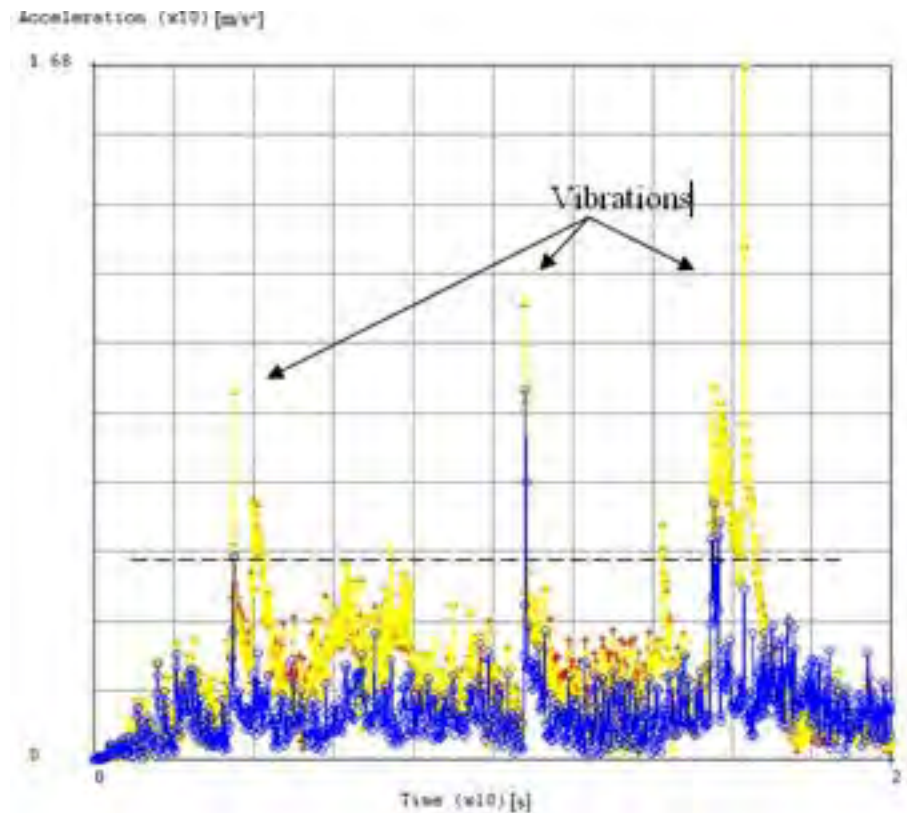
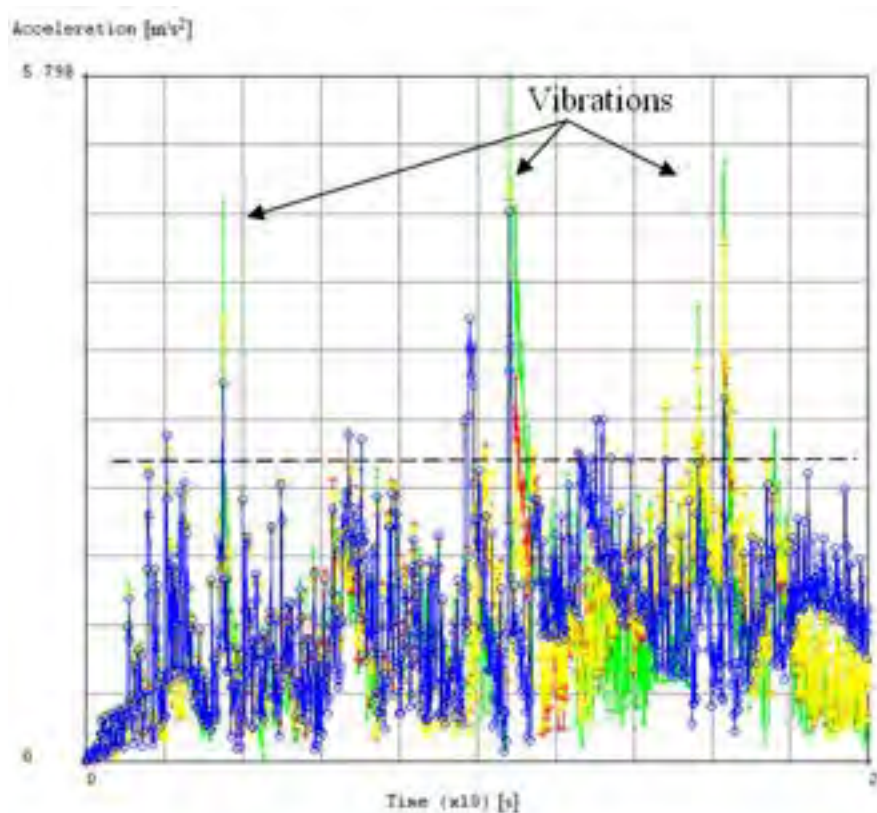


Core compaction results

Contact forces determine a change of the compression rigidity of the structures, and influence the deformation of the element cross-section.

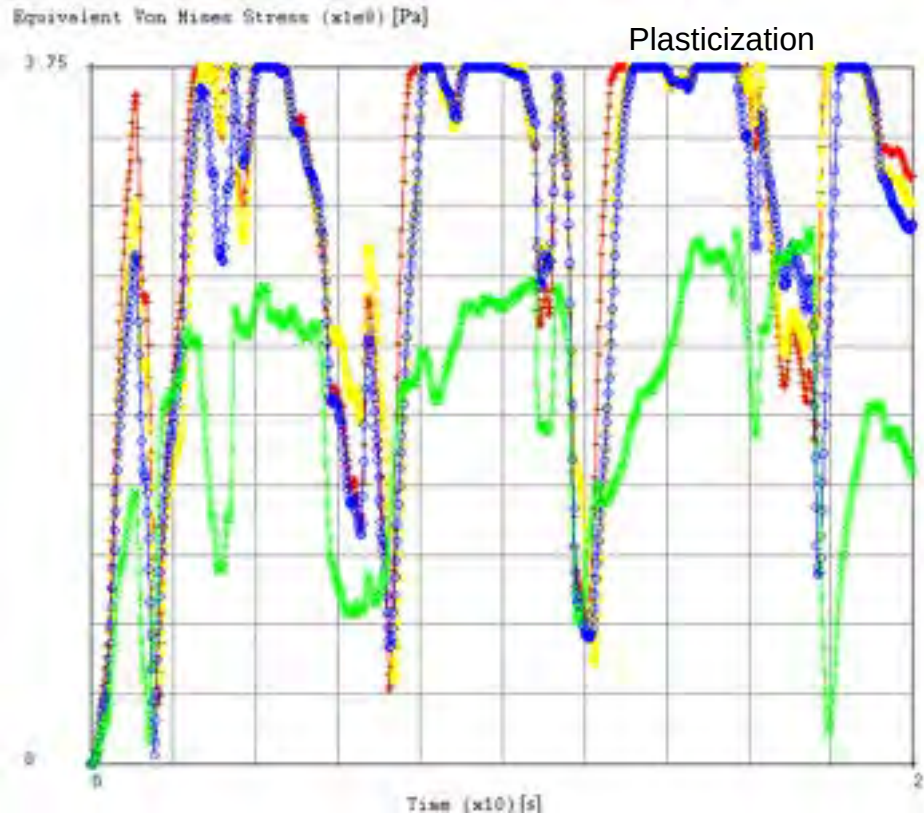
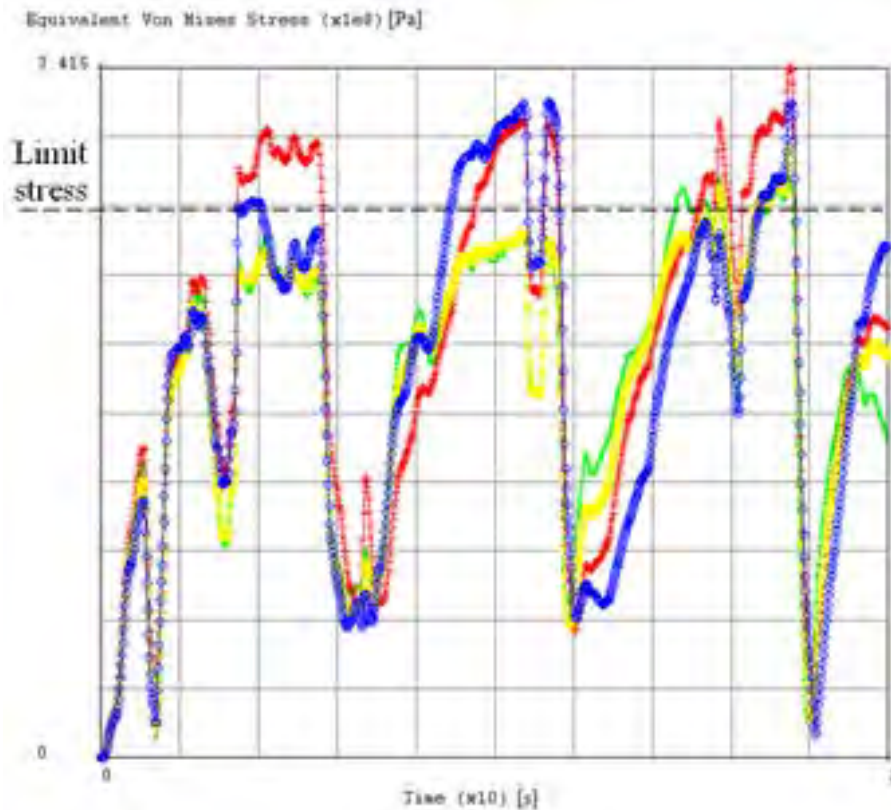
The structure, hit by the seismic motion, amplifies the input acceleration (0.21g and 0.28g at the upper plate and IC restraints) that reaches 7 and 5.7 m/s² respectively at the radial peripheral and central FAs positioned along x axis.

Vibrations (high spikes ($f > 65$ Hz)) are also visible .



Core compaction results

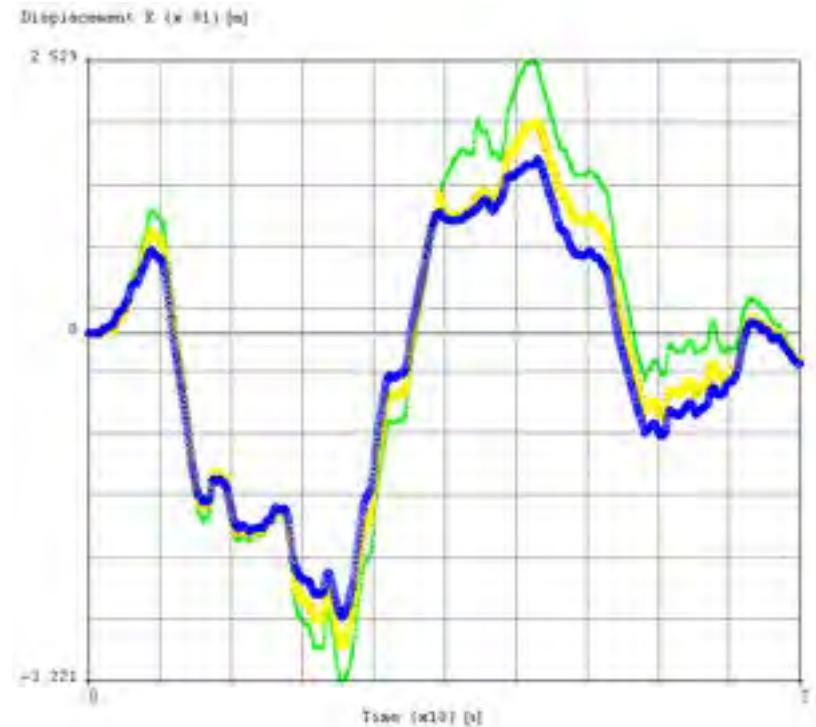
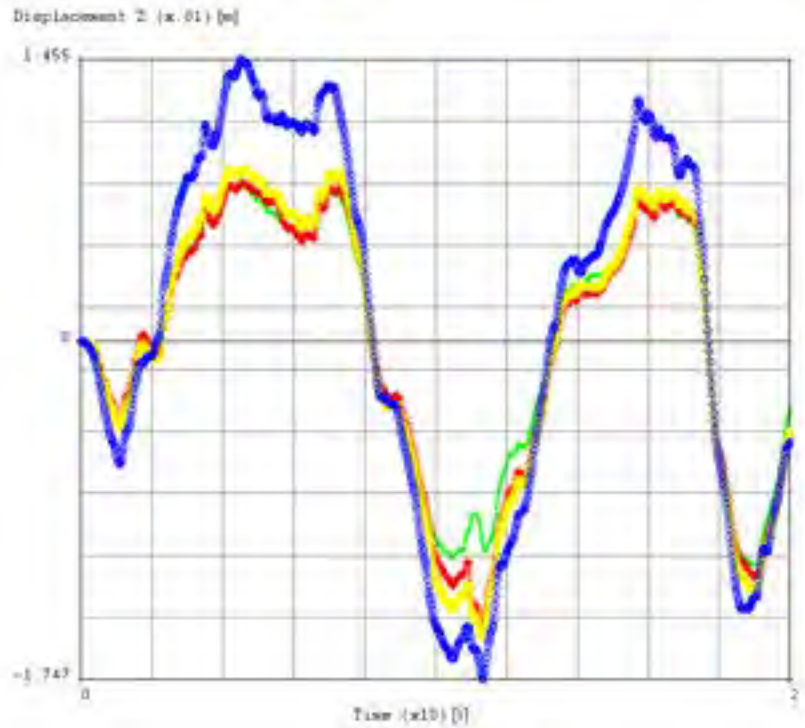
Analysing the Von Mises stress behaviour at the same FAs, it is possible to observe that the stress sometimes overcome the yielding for a prolonged time duration.



A wide plasticisation appears in the upper part of the upper plate, at the nozzle penetration. This latter in particular ovalizes (circumferential buckling).

Core compaction results

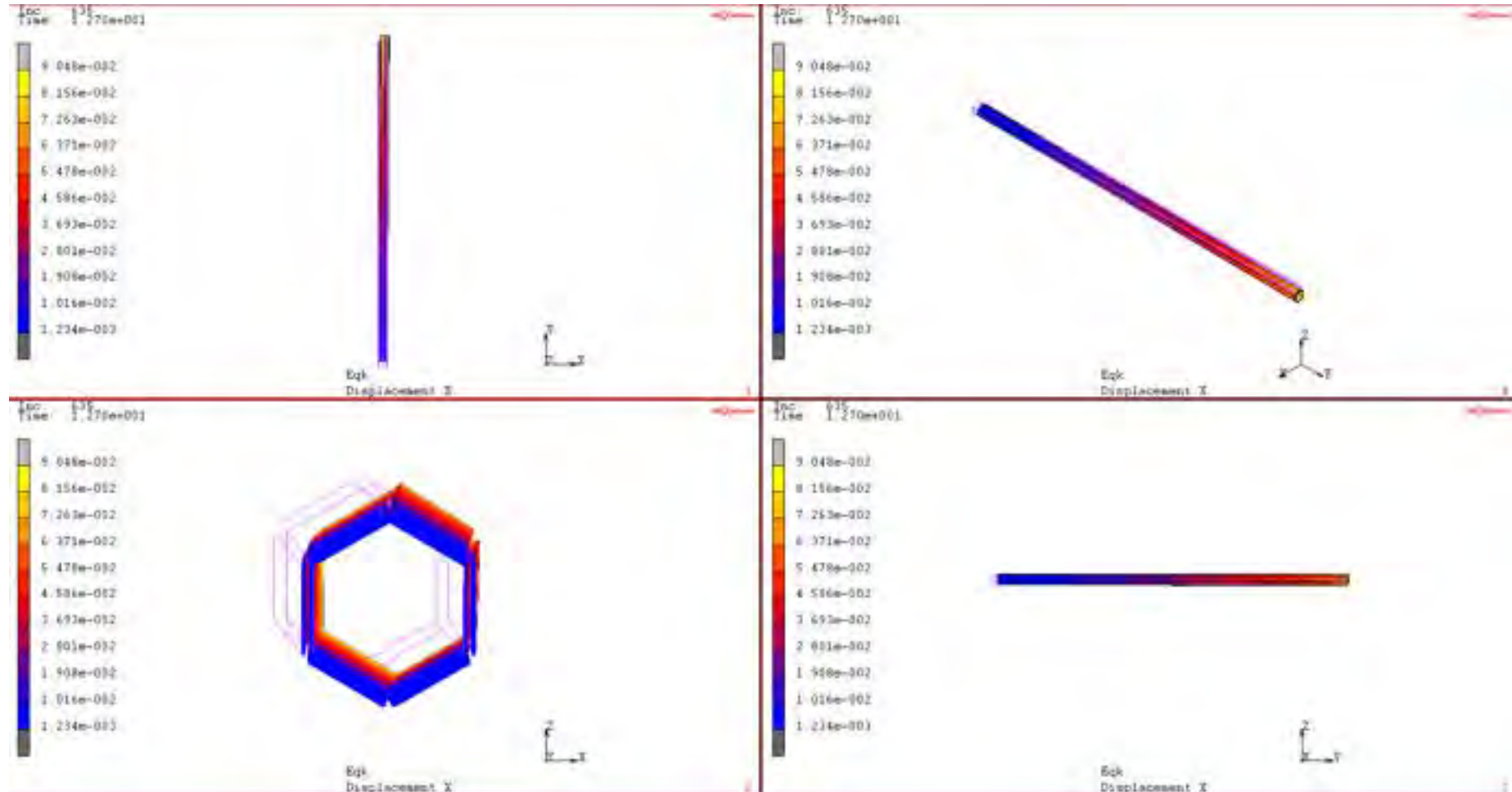
The FAs horizontal displacement is 1÷8 cm; the mean vertical displacement ~ 2.5 cm.



FAs horizontal displacements.

Core compaction results

The deformed shape along the FA elements is characterised by inflexion which determines the inward displacement: the gap between two adjacent FA is 5 mm !!



Compaction is affecting mostly part of FAs (and LOFA could subsequently occur).

Conclusions

- The contact forces determines a change of the compression rigidity of structures, and influences the deformation of the element cross-section;
- The input acceleration amplifies till to reach 7 and 5.7 m/s² respectively at the radial peripheral and central FAs positioned along x axis.
- Vibrations also appear and influence the response of structures (high spikes at $f > 65$ Hz).
- Von Mises stress sometimes overcomes the allowed limit for a prolonged time duration.
- $D_x \approx 2 \div 9$ cm (from the bottom to the upper plate) indicates the presence of the compaction
- Both the lower and upper plates did not suffer a wide plasticization, the opposite occurs instead in the nozzle-piping region

Further insights are needed to better understand the phenomenon also by executing specific experiments (never done on this topic).

Thank you for your attention

List of the publication:

- R. Lo Frano, et al., 2014, Proceedings of the ASME 2014 Small Modular Reactors;
- R. Lo Frano, A. Sanfioenzo, Analysis of the core compaction phenomenon, Proceedings of 23th Int. Conference on Nuclear Engineering, Chiba, Japan May 17-21, 2015.
- R. Lo Frano, G. Forasassi, Preliminary Assessment of the Fluid-structure Interaction Effects in a Gen IV LMR, Proceedings of 9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Malta, 16-18 July 2012.

Reference:

- IAEA, Intercomparison of liquid metal fast reactor seismic analysis codes- Vol. 2: Verification and improvement of reactor core seismic analysis codes using core mock-up experiments, Proc. Research Co-ordination Meeting, Sept. 1994.
- A. Martelli, J. Gauvain, A. Bernard, Non Linear Dynamic and Seismic Analysis of Fast Reactor Cores: 1. Theoretical Model, SMIRT 6, Paris, 1981.
- Y. Shinaora, T. Shimogo, Vibration of Square and Hexagonal Cylinders in a Liquid, J. Pressure Vessel Technology, August, vol. 103, 233-239, 1981.
- A. Preumont, A. Pay, A. Decauwers, The Seismic Analysis of a free standing FBR core, Nuclear Eng. Design, 103, 199-210, 1987.
- M. Morishita, K. Iwata, Seismic Behavior of a free-standing core in a large LMFBR, Nuclear Eng. Design, 140, 309-318, 1993.
- G-H. Koo, J-H Lee, Fluid Effects on the Core Seismic Behavior of a Liquid Metal Reactor, KSME International Journal, 18, 12, 2125-2136, 2004.
- R. Lo Frano, G. Forasassi, Conceptual evaluation of fluid-structure interaction effects coupled to a seismic event in an innovative liquid metal nuclear reactor, Nucl. Eng Design, 239, 11, 2333-2342, 2009.
- N. Moussallam et al., Design of liquid metal fast breeder reactor (LMFBR) core under dynamic loading, Transactions, SMiRT 22, August, 2013.
- P. G. Reinhall et al., Analysis of mechanical bowing phenomena of fuel assemblies in passively safe advanced liquid-metal reactors, Nucl. Tech. 83, 197-204, 1988.
- K. Tsukimori, H. Negishi, Development of 'Pad Element' for detailed core deformation analyses and its verification, Nucl. Eng. Design, 213, 141-156, 2002.



**Accordo di Programma
MSE-ENEA PAR2014-LP2**

WORKSHOP TEMATICO

LFR-GEN IV

STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO

Centro Ricerche ENEA Brasimone, 19-20 Novembre, 2015

Qualifica coatings e materiali strutturali per sistemi LFR

Massimo Angiolini
ENEA C.R. Casaccia
Via Anguillarese, 301 00123 Roma

Introduzione

Lo sviluppo di reattori veloci raffreddati a piombo e piombo bismuto rappresenta una sfida unica per i materiali che sono sottoposti, con diversa entità, a diversi meccanismi di degrado legati a

- ❑ Irraggiamento neutronico
- ❑ Esposizione al metallo liquido
 - Corrosione ($T > 450^\circ$)
 - Infragilimento da metallo liquido (F/M steels)
- ❑ Esposizione ad alte temperature



Le attività sono state dedicate principalmente allo sviluppo di materiali e tecnologie per la realizzazione dei componenti del nocciolo del reattore

- Sviluppo e caratterizzazione di trattamenti superficiali protettivi
- Sviluppo di acciai da creep resistenti al danno da irraggiamento

Sviluppo di Rivestimenti

La soluzione più praticabile per far fronte ai problemi di corrosione da metallo liquido pesante è lo sviluppo di trattamenti superficiali

Questo approccio ha il vantaggio, rispetto allo sviluppo di leghe resistenti alla corrosione, di impiegare materiali strutturali con proprietà note e codificata dalle normative di riferimento

Abbiamo concentrato la nostra attenzione su

- Rivestimenti autopassivanti alumina forming (FeCrAl)
- Rivestimenti ceramici a base allumina

PROPRIETA'

- Resistenza alla corrosione in Pb
- Self-healing
- Buona adesione e compatibilità meccanica con il substrato
- Stabili sotto irraggiamento neutronico (30 DPA / Y)
 - Stabilità dimensionale
 - Stabilità chimica e microstrutturale
 - Conservazione delle proprietà meccaniche
- Affidabilità, durata
- Alto grado di riproducibilità microstrutturale
- Fattibilità con tecnologie già disponibili
- Rapporto costi-efficacia

Sviluppo di Rivestimenti

❖ AlFe	Magnetron sputtering
❖ AlFeCr+Al ₂ O ₃	Cathodic arc deposition (arc – PVD) + Mag. sputtering
❖ AlFeCr	Pack – cementation
❖ FeCrAlY	HVOF (High Velocity Oxy Fuel)
❖ AlFeCrY+ Al ₂ O ₃	Mag. sputtering + Ablazione Laser (PLD)

Prove e Caratterizzazioni

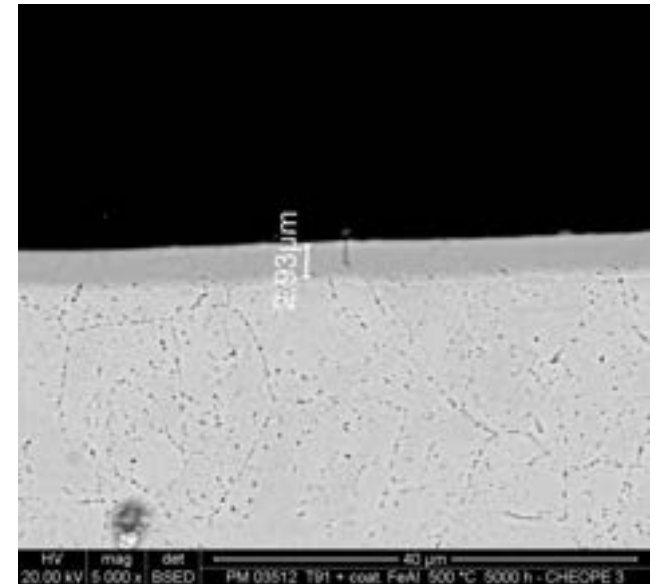
- ❖ Invecchiamento termico (in aria)
- ❖ Invecchiamento tramite cicli termici (in aria)
- ❖ Irraggiamenti con ioni pesanti
- ❖ Prove di corrosione in piombo
- ❖ Prove di Creep in piombo
- ❖ Prove di piega a tre punti/U-bending test
- ❖ Microscopia TEM SEM EDS
- ❖ Micro e nano indentazione

Rivestimenti PVD basati su leghe FeCrAl

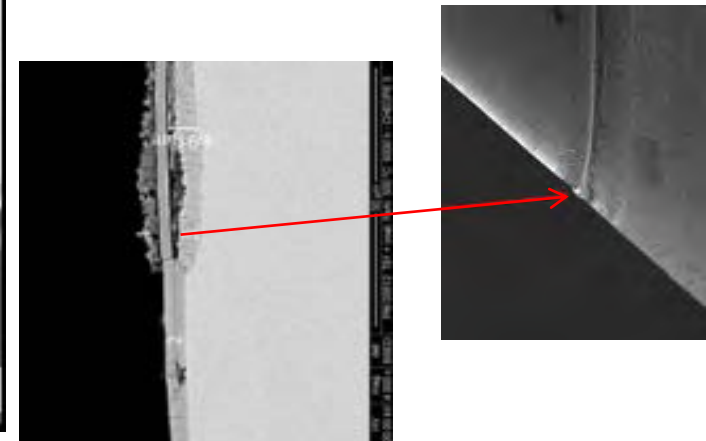
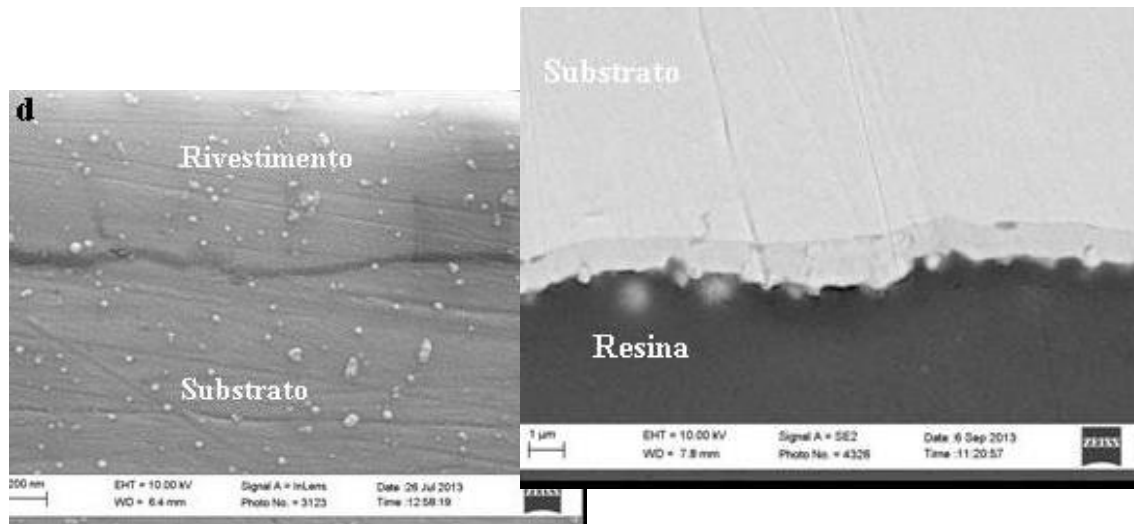
I rivestimenti di leghe a base FeCrAl depositati per PVD sono stati applicati sui substrati : P91, 304, 316L, 441

- ❑ Magnetron sputtering
- ❑ Arc-PVD

- Rivestimenti con buona adesione al substrato in tutti i casi
- Spessore intorno ai 2 μm non uniforme
- Ottime proprietà di resistenza alla corrosione: localmente dei punti di attacco in presenza di difetti



5000 ore di esposizione al piombo liquido @500°C
nell'impianto CHEOPEIII



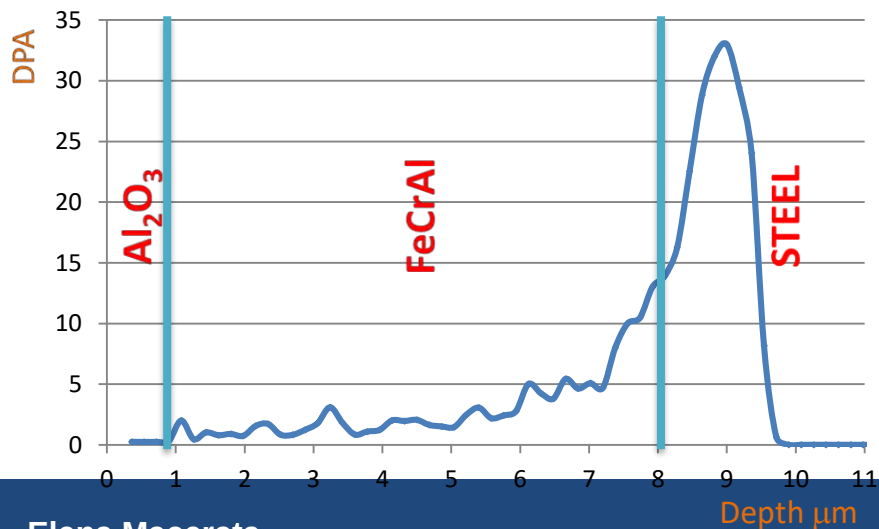
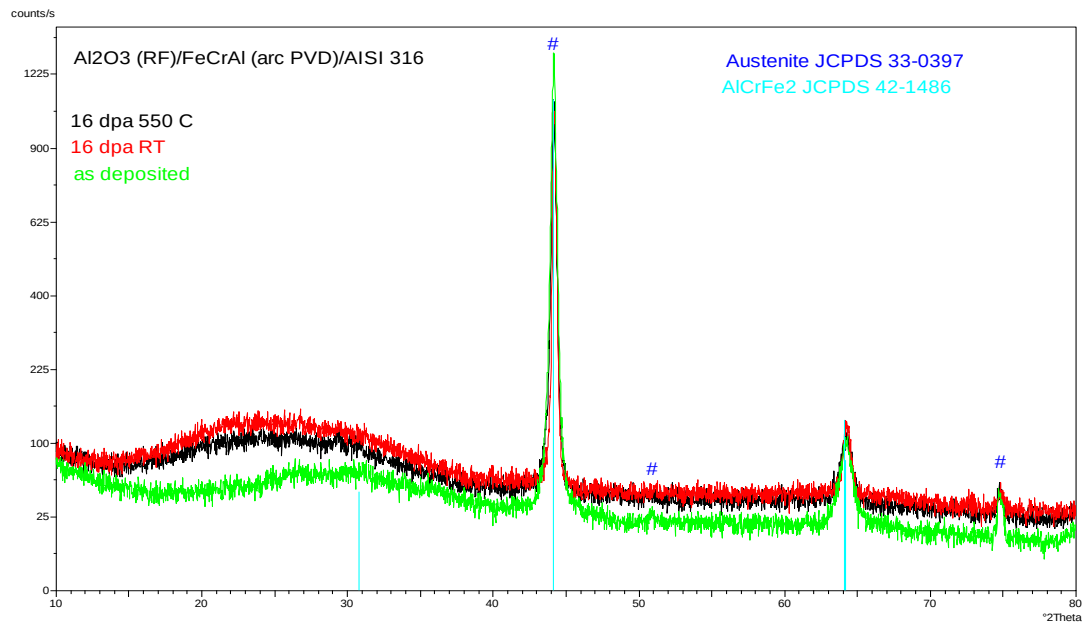
Rivestimenti arc-PVD basati su leghe FeCrAl

Prove di irraggiamento con ioni 58Ni
110 MeV a TA e 550°C
FeCrAl arc-PVD su SS 316L

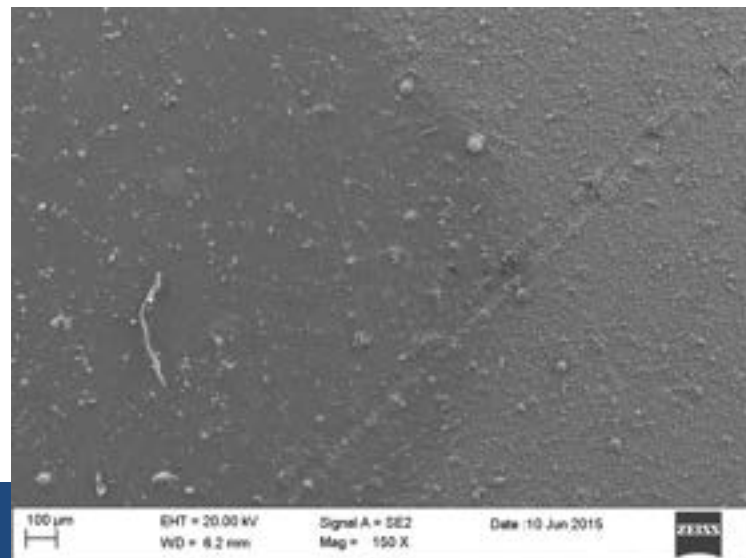
L'esame al microscopio elettronico non mostra segni di delaminazione o cricche

Il campione ha mantenuto adesione al substrato

Stabilità microstrutturale

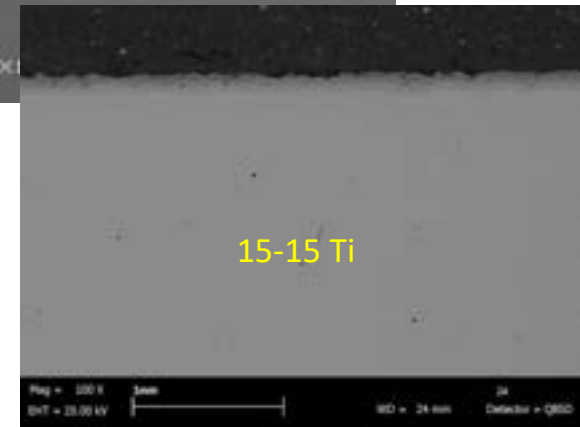
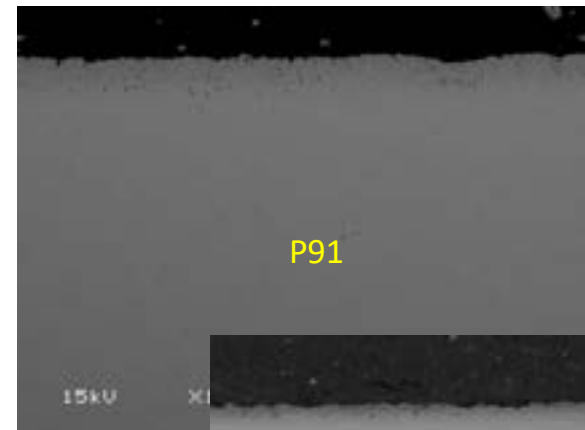


Elena Macerata



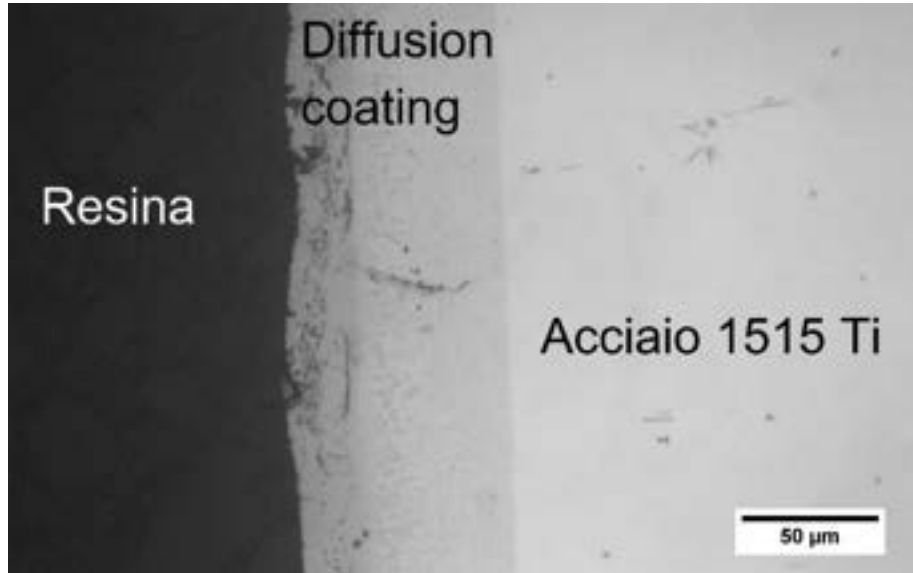
Rivestimenti CVD basati su leghe FeCrAl

- La **pack cementation** è una tecnica di deposizione da fase vapore largamente impiegata nell'industria sin dagli anni 60' per il rivestimento di pale di turbine a gas
- La tecnica è molto versatile e consente di rivestire pezzi con geometrie molto complicate e dimensioni anche notevoli
- La tecnica permette di rivestire anche l'interno di tubi: negli anni 90' la compagnia Alon Surface Technologies Inc, ha sviluppato diversi processi industriali per il rivestimento di tubi lunghi fino a 15 m ed una capacità produttiva di 100.000 metri lineari di tubo all'anno
- Il rivestimento viene ottenuto per deposizione e diffusione della lega sul substrato da rivestire
- **Processo ad alta temperatura** ➡ rischio di alterare la microstruttura e le proprietà meccaniche del substrato

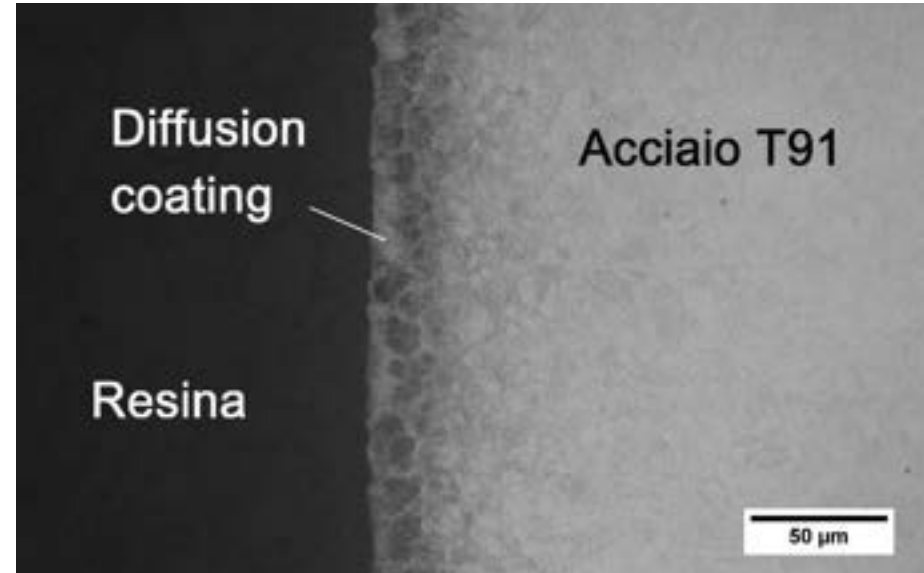


Rivestimenti CVD basati su leghe FeCrAl

Alluminizzazione 15-15 Ti: 45 min@1070°C



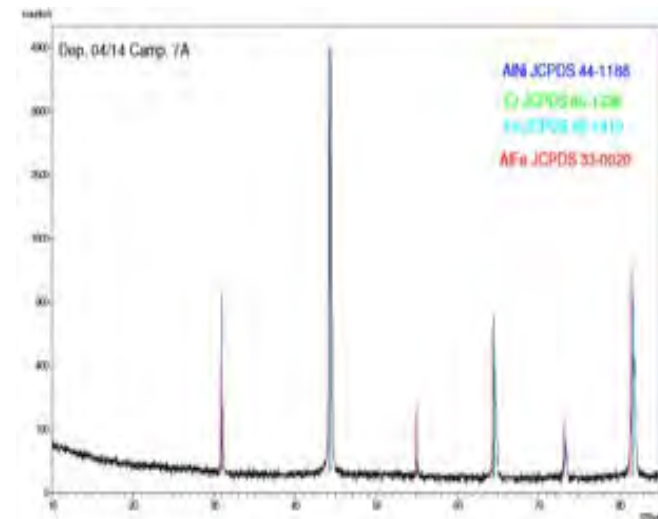
Alluminizzazione 9%Cr: 12hrs@750°C



- Trattamento di diffusion coating compatibile con il ciclo di trattamento termico dell'acciaio
- Evitando la formazione di intermetallici fragili

Ottimizzazione della miscela di alluminizzazione in termini di:

- composizione della master alloy
- percentuale e tipo di sale attivatore



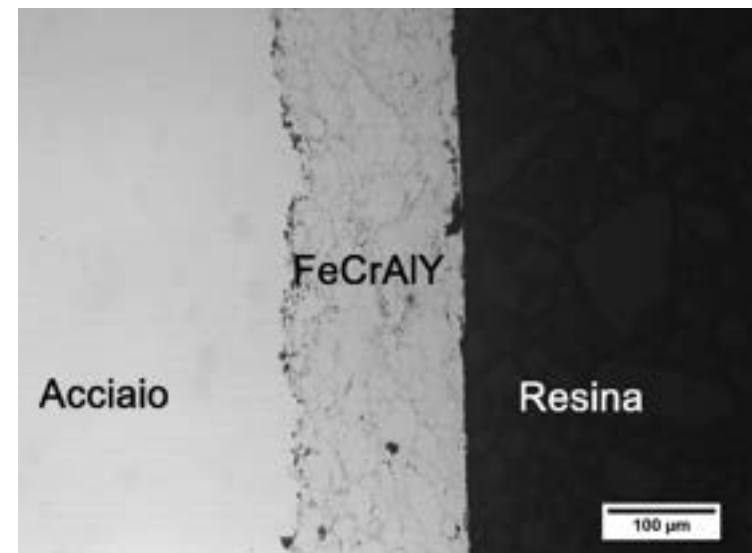
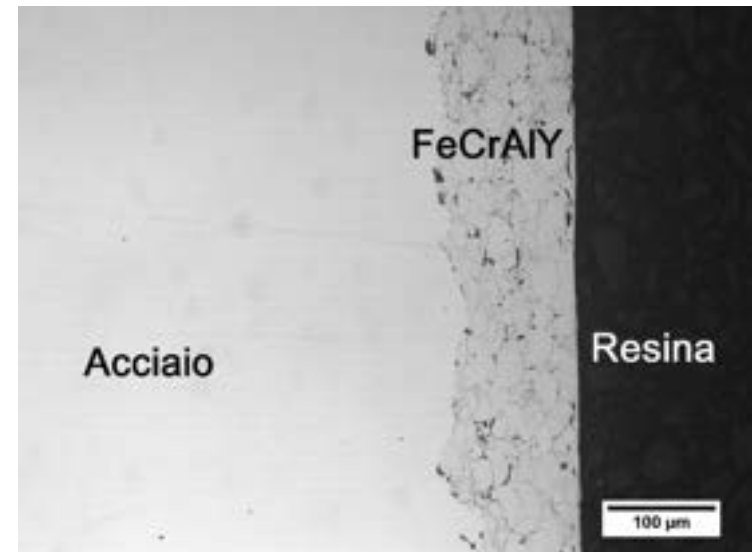
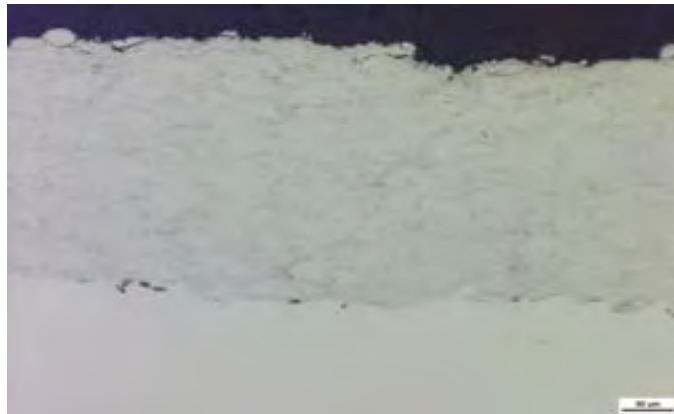
Rivestimenti Thermal Spray (HVOF) di leghe FeCrAlY

Il materiale di rivestimento sotto forma di particelle fuse o semifuse viene spruzzato sulla superficie mediante un flusso di gas ad elevata temperatura e ad alta velocità (>1000 m/s)

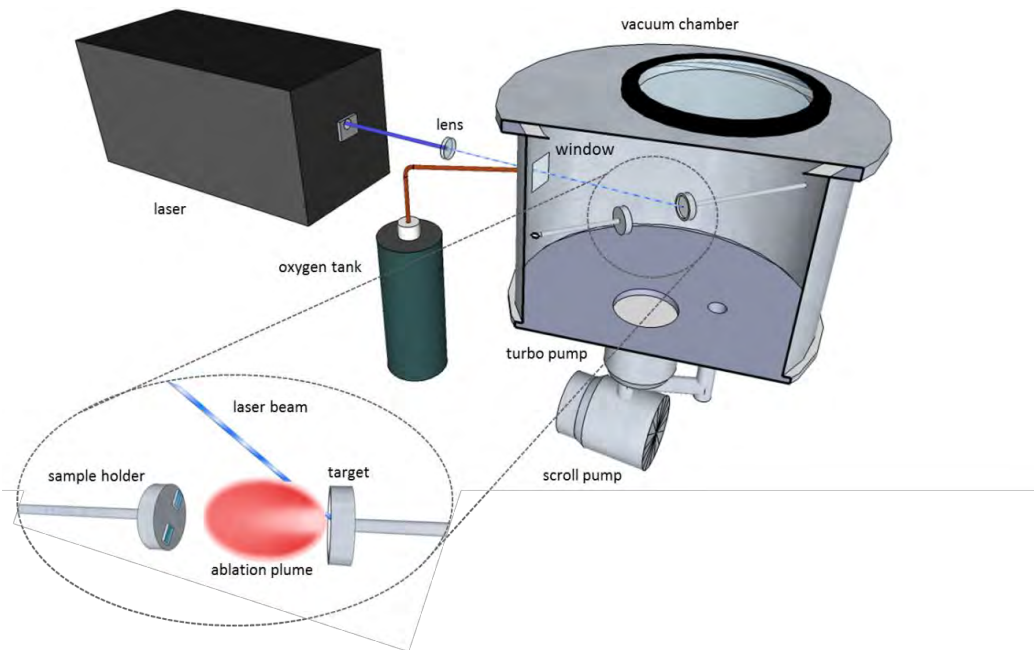
Ottimizzati i parametri di deposizione per la deposizione di rivestimenti FeCrAlY in termini di

- assenza porosità
- controllo delle tensioni residue
- adesione al substrato

E' stata quindi verificata la possibilità di eseguire lavorazioni standard di rettifica per ridurre la rugosità del rivestimento



Rivestimenti Al_2O_3 per Ablazione Laser (PLD)



- ✓ Temperatura di deposizione flessibile
- ✓ Viene conservata la stechiometria del target
- ✓ Rivestimenti con straordinarie proprietà di adesione e compatibilità meccanica col substrato
- ✓ Ottime proprietà di resistenza alla corrosione

Dimostrata la fattibilità di deposizione su tubi



Progettato e realizzato un manipolatore per rivestire campioni cilindrici e dimostrare la possibilità di esportare il procedimento in un contesto produttivo per il rivestimento delle barrette di combustibile

Rivestimenti Al_2O_3 per Ablazione Laser (PLD)

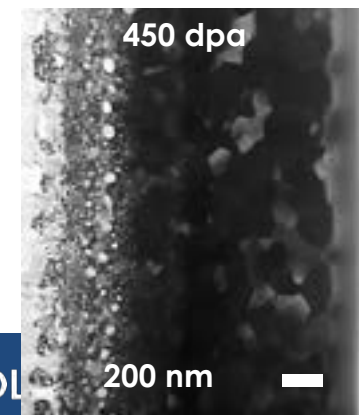
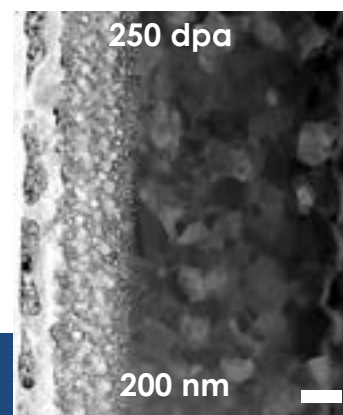
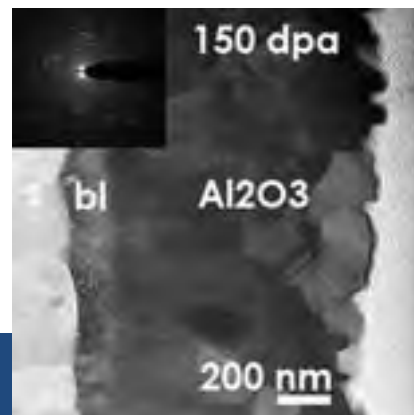
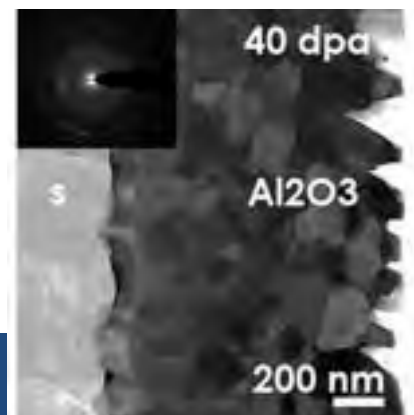
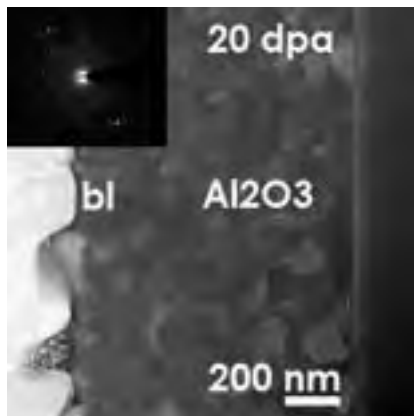
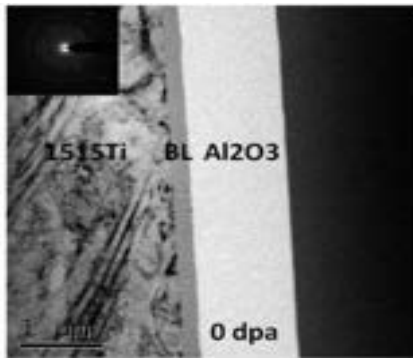
Prove di irraggiamento con ioni pesanti

Cristallizzazione progressiva della fase amorfa

@ 40 DPA il rivestimento è completamente cristallino

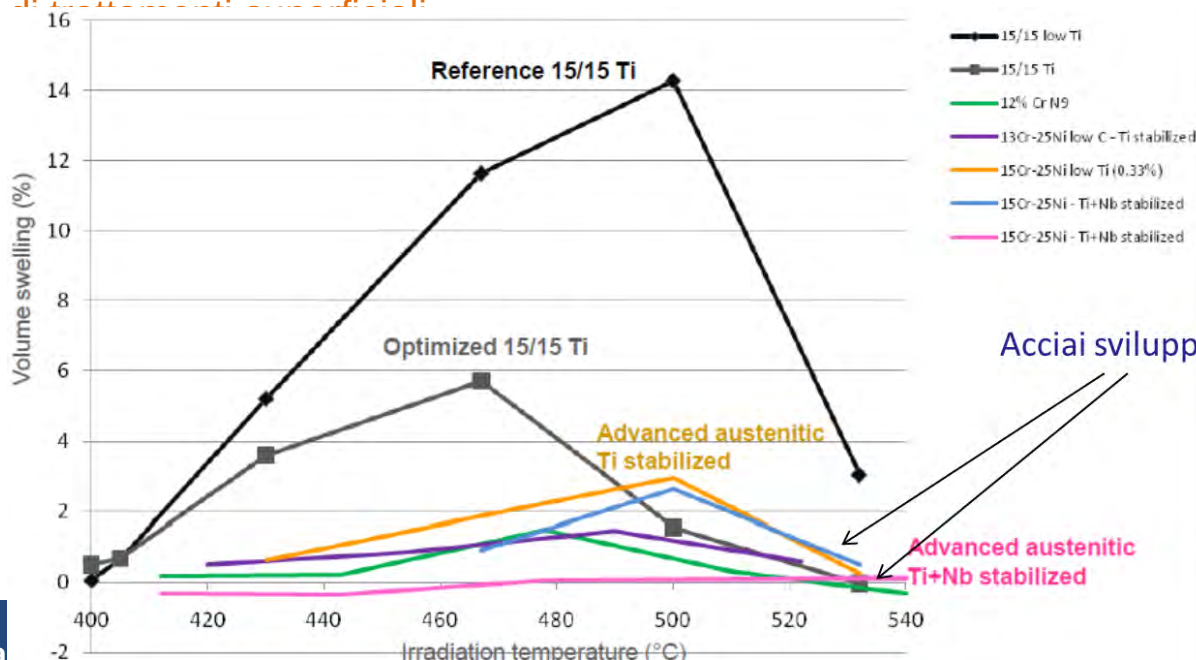
Per dosi più elevate si osserva la crescita dei grani
quindi una stabilizzazione

Nonostante l'irraggiamento fino a dosi DPA molto elevate non si sono osservati segni di delaminazione o cricche ed il rivestimento ha mantenuto l'adesione al substrato



Sviluppo di acciai da creep resistenti al danno da irraggiamento

- Relativamente agli acciai strutturali per applicazioni nucleari, gli acciai doppio stabilizzati (Ti, Nb) hanno dimostrato grande stabilità al rigonfiamento ed ottime proprietà di creep
- Si tratta di leghe austenitiche appartenenti alla famiglia dell'AISI 316, sviluppate da ENEA in collaborazione con il CEA per l'applicazione quale materiale di guaina per i reattori veloci refrigerati al sodio
- I campioni degli acciai sviluppati in ENEA vennero sottoposti ad irraggiamento con neutroni nel reattore Phénix nell'ambito dell'esperimento "Supernova" mostrando una stabilità dimensionale sorprendente per dosi fino ad 89 DPA rispetto alle altre leghe austenitiche sviluppate
- Sono state riprese le attività di R&D ed è stato prodotto un lingotto DS4 (50 kg) dal quale sono stati ricavati dei campioni per l'analisi microstrutturale, prove di trazione e di creep, prove di corrosione e sviluppo



Irraggiamento con ioni pesanti

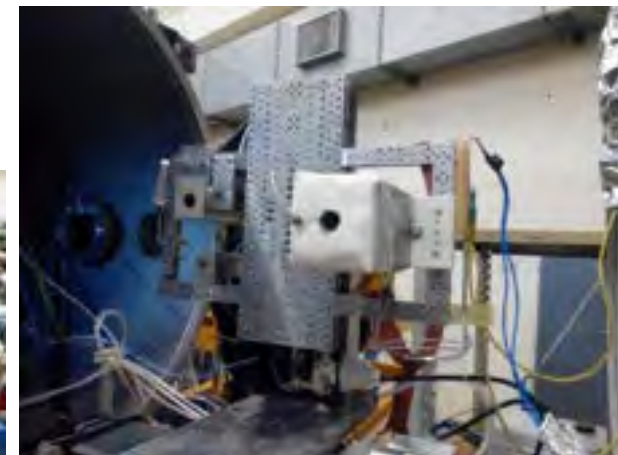
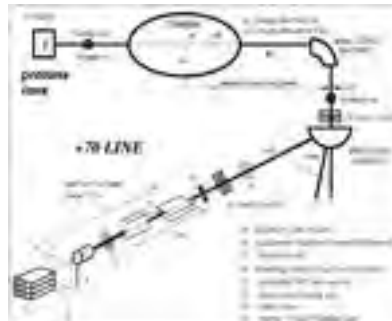
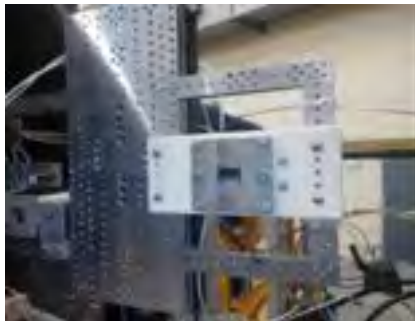
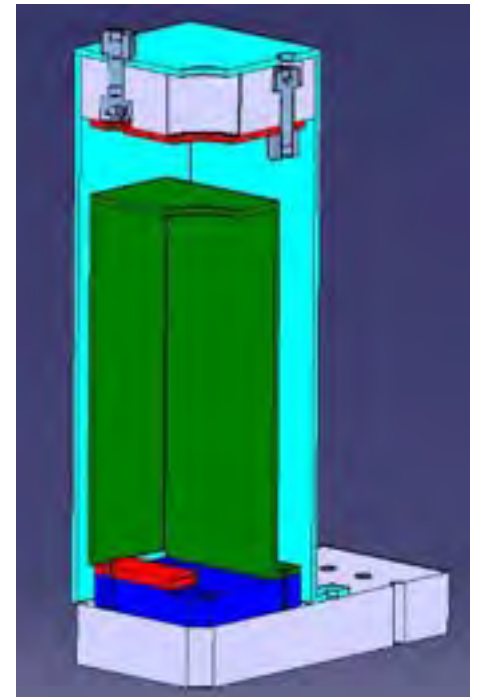
Sono state presentate le seguenti proposte di irraggiamento
Presso I Laboratori Nazionali di Legnaro dell'INFN

ACEIC “Advanced Coatings under Extreme Irradiation Conditions “

LP2-B1 e LP2-B1C “Study of the effect of high fluence irradiation on the swelling and microstructural behavior of anti corrosion coatings for high temperature operation of steels in heavy liquid metals”

Presso la piattaforma di irraggiamento Jannus del CEA due proposte

“Structural and mechanical stability of an advanced Al_2O_3 nanocomposite coating under ion irradiation up to high DPA”

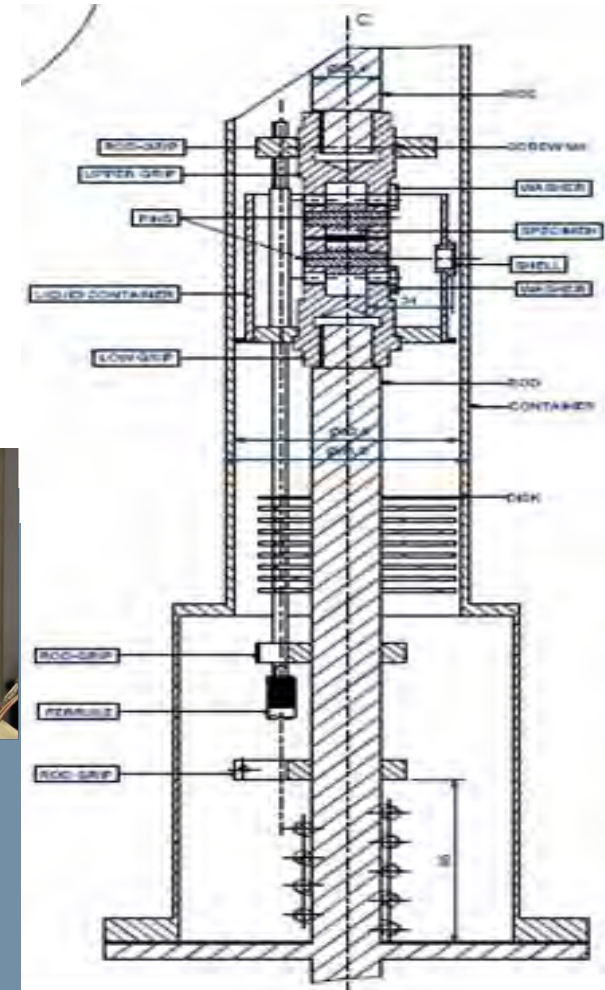
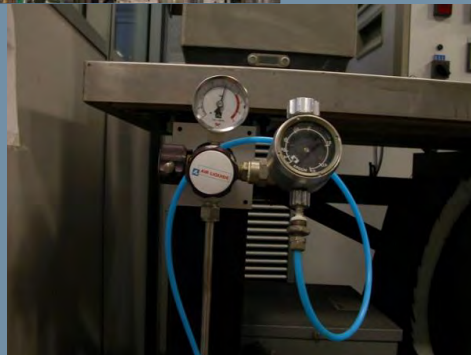
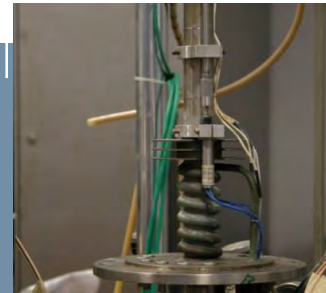
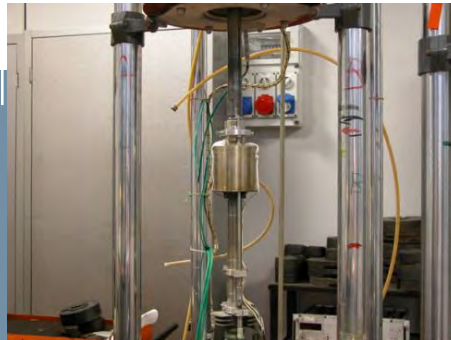
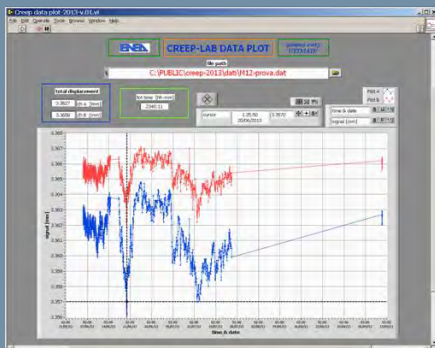


Prove di creep in piombo @CR ENEA Faenza

L'esecuzione delle prove di creep in piombo liquido stagnante ha richiesto l'upgrade delle macchine da creep presenti nel laboratorio per prove termomeccaniche presso il CR ENEA Faenza

- ❖ Realizzazione di linee di gas inerte/riducente per ciascuna macchina per il conditioning del metallo fuso
- ❖ Modifica del sistema di acquisizione delle deformazioni
- ❖ Progettato e realizzato un nuovo sistema di acquisizione (Hardware/Software)

Eseguiti i test preliminare sui materiali base non ricoperti (15 15 Ti)



Overall view of the creep machine

Deliverables

2012 – 2013 Deliverables

- Sviluppo di sistemi multilayer per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo
- Sviluppo di layer per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo mediante tecniche di ablazione laser
- Report sulla caratterizzazione di coating realizzati mediante ablazione laser mediante prove di irraggiamento con ioni pesanti
- Rapporto sulla installazione e collaudo di una macchina per Detonation Spray
- Report sulla caratterizzazione di materiali strutturali ricoperti per applicazioni nucleari
- Implementazione del laboratorio della chimica del piombo

2013 – 2014 Deliverables

- Sviluppo di ricoperture CVD a base Al-Fe per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo
- Studio del comportamento di rivestimenti sottoposti a ciclaggio termico
- Sviluppo di Ricoperture per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo mediante tecniche di ablazione laser
- Report sulla caratterizzazione di materiali strutturali ricoperti per applicazioni nucleari: definizione dei criteri di fallimento dei rivestimenti per deplezione dell'elemento passivante
- Report sulla caratterizzazione delle proprietà meccaniche di ricoperture per applicazioni nucleari
- Report sulla caratterizzazione di rivestimenti mediante prove di irraggiamento con ioni pesanti
- Modellazione dei fenomeni di corrosione/dissoluzione da metallo liquido pesante
- Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante
- Double Stabilized Stainless Steel Procurement
- Concettualizzazione di un impianto per il monitoraggio del rateo di corrosione su materiali strutturali operanti in piombo

2014-2015 Deliverables

- Sviluppo di ricoperture a base FeCrAl per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo
- Sviluppo di ricoperture per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo mediante tecniche di ablazione laser
- Report sulla caratterizzazione di materiali strutturali ricoperti per applicazioni nucleari
- Report sulla caratterizzazione di rivestimenti mediante prove di irraggiamento con ioni pesanti
- Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante
- Characterization of mechanical properties and Corrosion behavior in lead of DS4 steel

F. García Ferré, E. Bertarelli, A. Chiodoni, D. Carnelli, D. Gastaldi, P. Vena, M.G. Beghi and F. Di Fonzo, *The mechanical properties of a nanocrystalline Al₂O₃/α-Al₂O₃ composite coating measured by nanoindentation and Brillouin spectroscopy*, Acta Mater. 61 (2013) 2662-2670

F. García Ferré, M. Ormellese, F. Di Fonzo, M.G. Beghi, *Advanced Al₂O₃ coatings for high temperature operation of steels in heavy liquid metals: a preliminary study*, Corr. Sci. 77 (2013) 375-378

Presentazioni a conferenze:

- * EMRS, Strasbourg, 2013
- * HLM coolants in nuclear technology, Obninsk 2013
- * MRS, San Francisco, 2013
- * IAEA 46th Meeting of the Technical Working Group on Fast Reactors, Vienna 2013
- * CAARI, San Antonio, 2014
- * IAEA 47th Meeting of the Technical Working Group on Fast Reactors Vienna 2014
- * EUROCORR, Pisa, 2014
- * TMS, Orlando, 2015
- * EERA JPNM Meeting Madrid 2015
- * IAEA 48th Meeting of the Technical Working Group on Fast Reactors Obninsk 2015

Le attività sono state svolte in collaborazione con



CIRTEN

Consorzio Interuniversitario per la Ricerca Tecnologica Nucleare



UNIVERSITA' degli STUDI di ROMA
TOR VERGATA



ISTITUTO ITALIANO DI TECNOLOGIA
CENTER FOR NANOSCIENCE AND TECHNOLOGY

Sviluppo di ricoperture a base FeCrAl per pack cementation

- messa a punto di un protocollo da esportare su scala industriale per il rivestimento di simulacri e manufatti,
- messa a punto di lavorazioni pre e post deposizione per l'ottenimento di particolari proprietà superficiali e tolleranze.

Sviluppo di ricoperture mediante tecniche di ablazione laser.

- rivestimento di campioni cilindrici per effettuare prove di creep su tubi pressurizzati,
- Prove di corrosione in piombo liquido stagnante ad alta temperatura (800°C)

Prove di corrosione in Pb statico a diversi tempi di esposizione e concentrazione di ossigeno

Caratterizzazione delle proprietà meccaniche, di corrosione in piombo e di swelling dell'acciaio DS4

- proprietà a trazione ed analisi microstrutturale della lega,
- caratterizzazione a creep in aria del materiale,
- prove di irraggiamento con ioni pesanti.

Caratterizzazione degli strati ossidati in metallo liquido pesante con tecniche TEM, SEM, spettroscopia RAMAN, Diffrazione di raggi x e ICP-MS

Modelling termodinamico del sistema Fe-Cr-Pb-O

Sommario

E' stata data una breve rassegna delle attività sui materiali per applicazioni Gen IV del triennio 2012-15, che hanno riguardato

- Lo sviluppo di rivestimenti protettivi ad alte prestazioni

- Lo sviluppo di leghe per applicazioni ad alta temperatura resistenti all'irraggiamento

- Lo studio teorico e sperimentale dei processi di corrosione ed infragilimento da metallo liquido pesante

Le attività sono state portate avanti in collaborazione con università italiane (CIRTEN) ed i partner industriali IIT e CSM

Le tematiche affrontate hanno ricadute immediate in campo nucleare ma hanno valenza ed applicazioni in altri contesti, come la fusione nucleare e più in generale nell'impiantistica

Sono state acquisite attrezzature ed impianti che oltre ad essere funzionali allo svolgimento e futura prosecuzione delle attività in progetto, hanno potenziato le capacità dell'ENEA nel settore della metallurgia avanzata e dei nuovi materiali

Le ricerche, collaborazioni e sinergie attivate nel contesto dell'accordo di programma hanno portato alla presentazione/partecipazione a quattro proposte di progetto in ambito EERA NM che vede coinvolti centri di ricerca e gruppi industriali della Comunità Europea

Sviluppo di ricoperture a base di FeCrAl per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo

Alessandra Bellucci

WORKSHOP TEMATICO

LFR-GEN IV STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO
Centro Ricerche ENEA Brasimone 19-20 Novembre, 2015



I contenuti

- **Breve introduzione ai criteri di selezione dei rivestimenti**
- **I rivestimenti sviluppati:**
 - i principi dei processi di deposizione
 - i settori industriali di applicazione
 - l'attività sperimentale:
 - l'ottimizzazione dei parametri di processo
 - la produzione di provini per l'attività di caratterizzazione (Università di Tor Vergata)
 - la produzione di provini per le campagne di *testing* ENEA

I requisiti per i materiali operanti in piombo

- durability under irradiation;
- prevention of dissolution attack;
- tolerable oxidation rate during and after oxide scale formation;
- long-term stability under normal and temporarily abnormal conditions;
- self-healing ability;
- long-term mechanical stability;
- tolerable influence on the mechanical properties of the structural material;
- feasibility on an industrial level

G. Muller, G. Schumacher, A. heinzel, A. Jianu, A. Weisenburger *"Corrosion protection in lead and lead-bismuth eutectic at elevated temperatures"* in LBE Handbook, NEA No.7268 OECD (2015) 617 - 646

Al_2O_3 former

I materiali contenuti Al presentano eccellente resistenza a corrosione in bagni di Pb grazie alla formazione di un **film protettivo di Al_2O_3**

- **(5-15) wt% di Al superficiale:** formazione film α - Al_2O_3
- presenza di Cr: accelerazione trasformazione di θ – in α – Al_2O_3

E. Yamaki, M. Takahashi *Journal of Nuclear Science and Technology* vol. 48, No. 5, (2011) 797 - 804

A.K. Rivai, M. Takahashi *Journal of Nuclear Materials* 398 (2010) 146 - 152

E. Yamaki - Irisawa, S. Numata, M. Takahashi *Progress in Nuclear Energy*, vol. 53, 7 (2011) 1066 - 1072

A. Weisenburger, A. Heinzl, G. Muller, H. Muscher, A. Rousanov *Journal of Nuclear Materials* 376 (2008) 274 - 281

G. Muller et al. *Journal of Nuclear Materials* 335 (2004) 163 - 168

Y. Kurata, M. Futakawa, S. Saito *Journal of Nuclear Materials* 335 (2004) 501 - 507

A. Heinzl, M. Kondo, M. Takahashi *Journal of Nuclear Materials* 350 (2006) 264 - 270

M. Kondo, M. Takahashi *Journal of Nuclear Materials* 356 (2006) 203 - 212

P. Hosemann, H.T. Thau, A.I. Johnson, S.A. Maloy, N. Li *Journal of Nuclear Materials* 373 (2008) 246 - 253

Le soluzioni

- 1) Rivestimenti *multilayer* **FeCrAl + Al₂O₃** (PVD – Physical Vapour Deposition)
- 2) Rivestimenti **FeCrAlY** (HVOF – High Velocity Oxy Fuel)
- 3) Rivestimenti **alluminuri** (pack cementation)

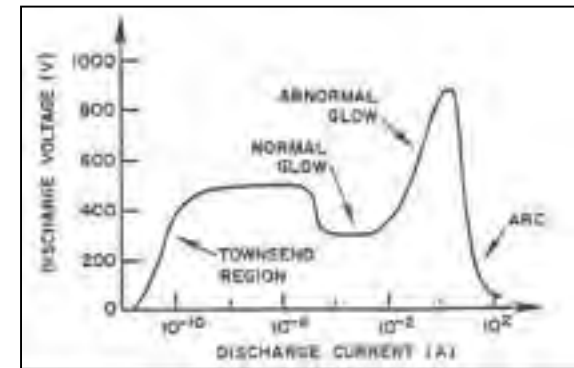
- I substrati:

- acciai austenitici:
15 – 15 Ti
AISI316
- acciai ferritici/martensitici:
T91

1) Il processo PVD arco

- **Generazione di vapori** dalla sorgente attraverso la **formazione di un arco**:

- catodo = sorgente
- anodo = camera di deposizione



regime di arco:

bassa tensione/elevata corrente

- **Confinamento** della scarica in una piccola area (decine di mm²): **spot catodico**
- **Movimento rapido** - (1-100) m/s - **dello spot catodico** (differenza di resistività):
erosione uniforme della sorgente

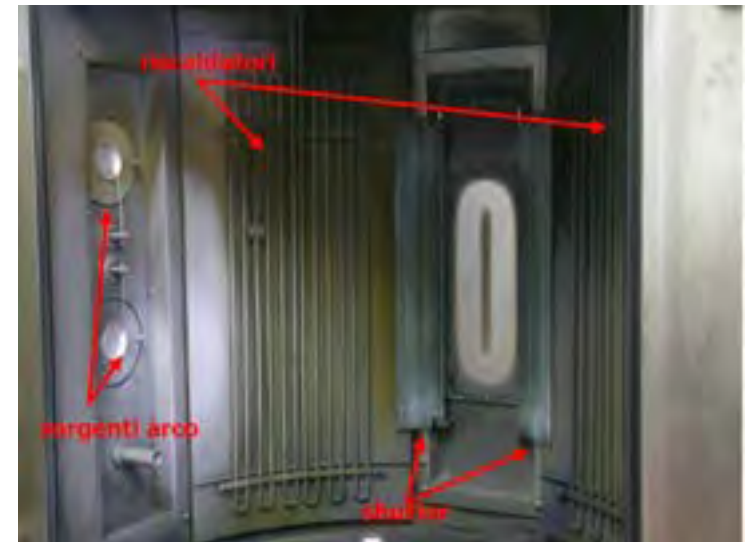


1) Settori di applicazione dei rivestimenti PVD

- **industria ottica:** vetri e specchi architettonici, rivestimenti assorbenti e riflettenti, vetri selettivi;
- **industria elettronica:** conduttori, contatti, isolatori, celle solari;
- **industria meccanica:** film lubrificanti, rivestimenti anti-usura, anti-erosione ed anti-frizione, barriere di diffusione, rivestimenti duri per utensili;
- **componenti di precisione:** utensili, attrezzature, sensori, attuatori;
- **industria chimica:** rivestimenti anti-corrosione e catalitici, componenti batterie;
- **industria elettronica e delle telecomunicazioni;**
- **medicina e implantologia:** rivestimenti biocompatibili per protesi e scheletri dentali, per protesi ortopediche e per strumenti e utensili chirurgici;
- **industria aeronautica e spaziale;**
- **industria materie plastiche:** viti estrusione, ugelli iniezione, stampi trasformazione materie plastiche;
- **componenti decorative:** orologi, occhiali, bigiotteria....;

1) L'impianto PVD del CSM

- **Due tecnologie di deposizione PVD:**
 - » arco catodico (4 sorgenti)
 - » RF *magnetron sputtering*
- **Riscaldatori:**
 - » 2 resistori (15 kW, 10^3 V)
 - » Tmax: 450 °C
- **Portasubstrati:**
 - » movimentazione planetaria
 - » carico massimo: 600 kg
- **Dimensioni:**
 - » camera: (1000X1150)cm
 - » $l_{\max}$ componenti: (40-60)cm



1) La campagna FeCrAl

SIGLA	SORGENTI	FeAl/Cr	CORRENTE PROCESSO/Ah	ADHESION LAYER	BIAS/V
FeAl - 1	FeAl	\	100	Al	150
FeAl - 2	FeAl	\	100	Al	50
FeAl - 3	FeAl	\	100	Cr	50
FeAl - 4	FeAl	\	100	Cr	150
FeAl - 5	FeAl	\	300	Cr	100
FeAl - 6	FeAl	\	100	Cr	125
FeAl - 7	FeAl	\	100	Cr	100
FeAl - 8	FeAl	\	200	Cr	100
FeCrAl - 1	FeCrAl	\	100	Al	150
FeCrAl - 2	FeCrAl	\	94	Al	50
FeCrAl - 3	FeAl+Cr	0,9	100	Cr	50
FeCrAl - 4	FeAl + Cr	0,8	100	Cr	50
FeCrAl - 5	FeAl + Cr	0,7	100	Cr	50
FeCrAl - 6	FeAl + Cr	0,8	100	Cr	100
FeCrAl - 7	FeAl + Cr	0,8	200	Cr	100
FeCrAl - 8	FeAl + Cr	0,8	300	Cr	100

analisi EDS rivestimento

FeCrAl - 2

Al K	4,8
Cr K	20,5
Fe K	74,8

FeCrAl - 3

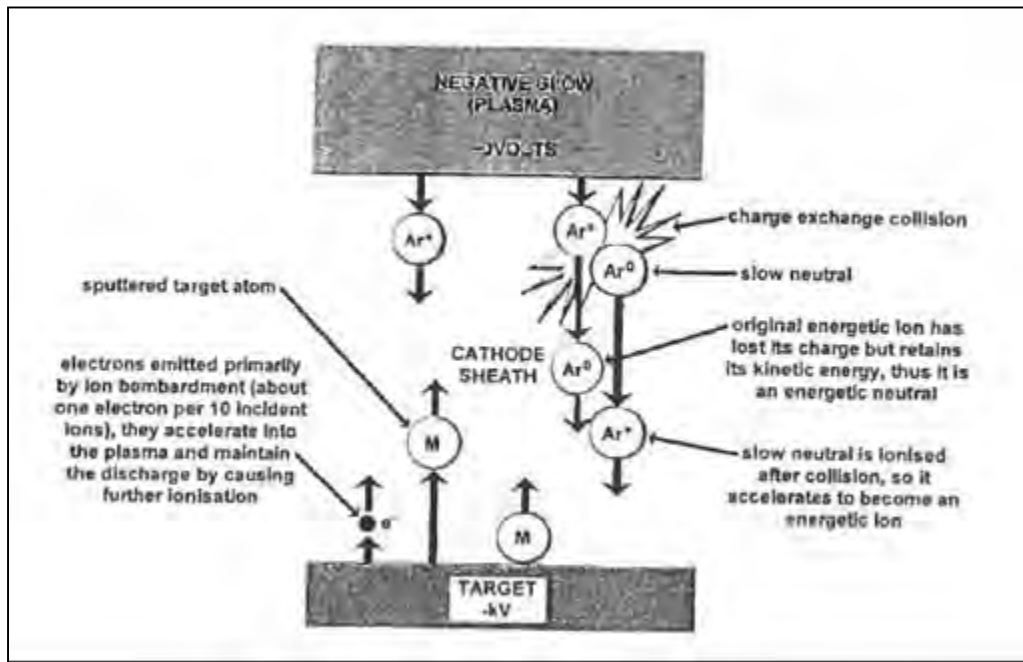
Al K	10,4
Cr K	24,1
Fe K	65,6

FeCrAl - 4

Al K	8,6
Cr K	29,0
Fe K	62,4

1) PVD RF sputtering

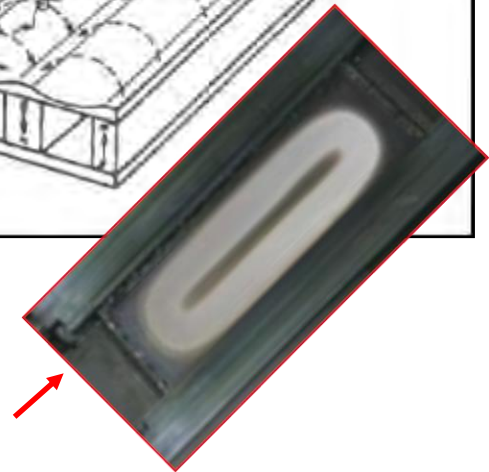
- **Generazione di vapori** dalla sorgente attraverso l'accensione di una **scarica a bagliore**:
 - catodo = sorgente (target)
 - anodo = camera di deposizione
- **Regime di scarica**: tensioni elevate (1-2 kV)



SCHEMA DI EROSIONE TARGET MAGNETRON



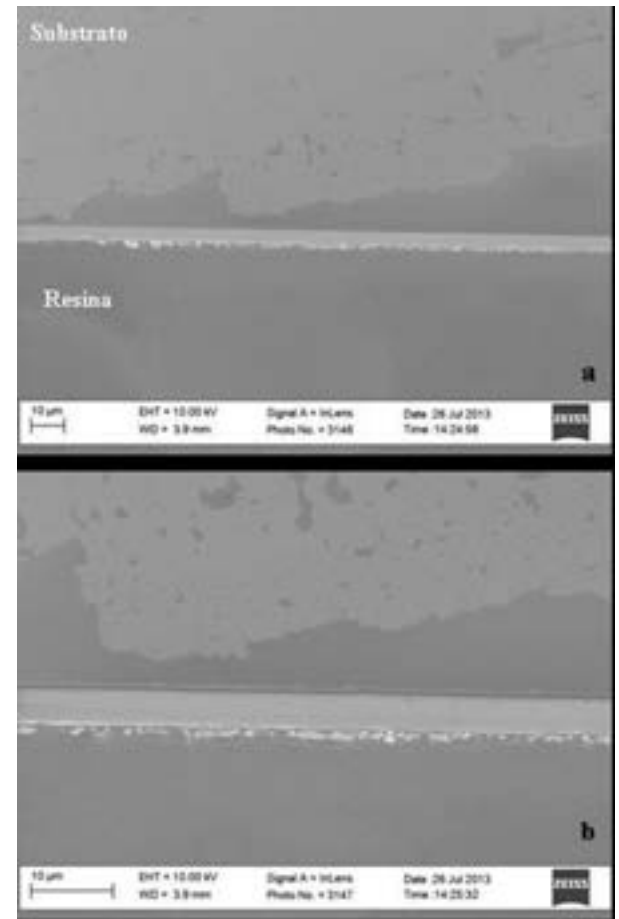
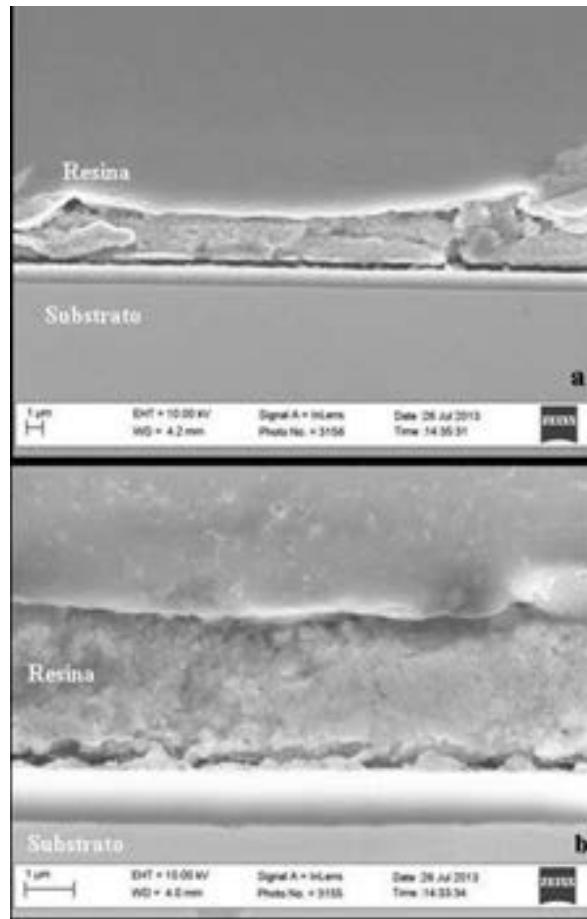
IMMAGINE EROSIONE TARGET MAGNETRON



1) La campagna Al_2O_3

modulabilità spessore:

- 0,5 micron
- 1 micron
- 4 micron
- 6 micron

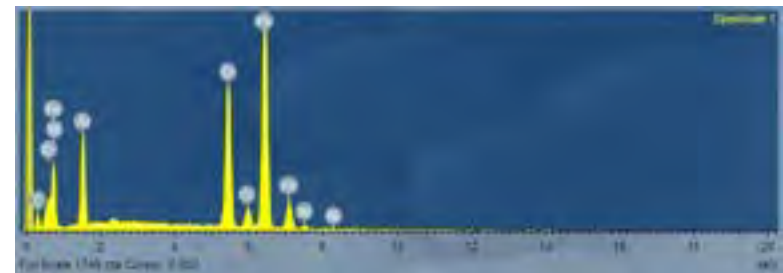
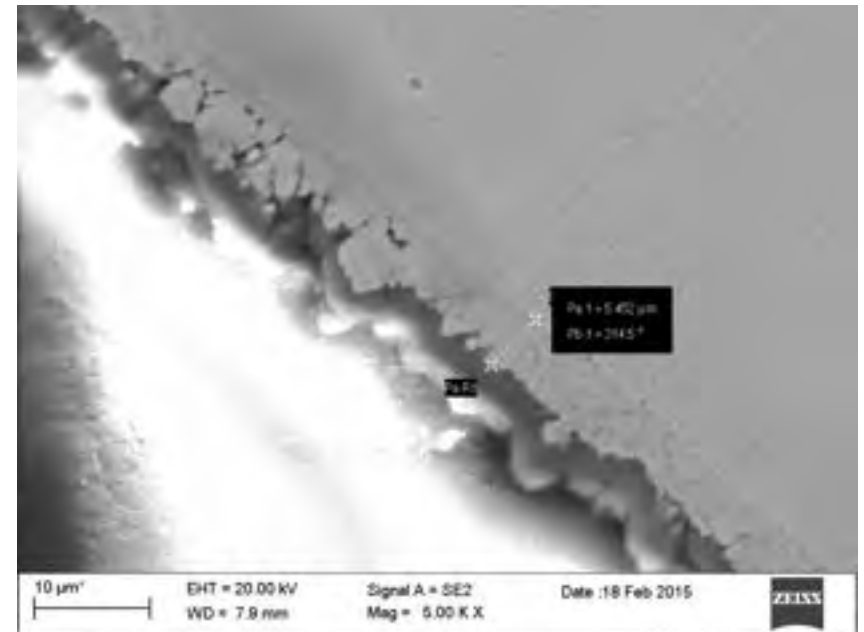
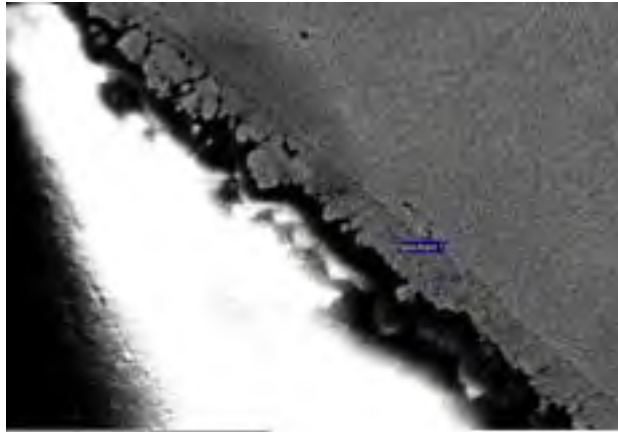


1) II multilayer

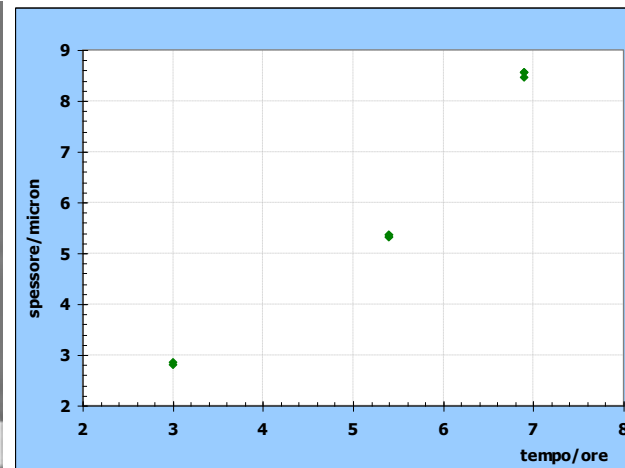
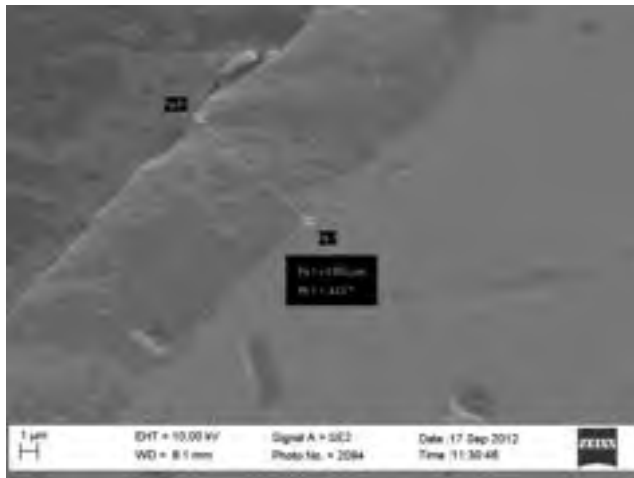
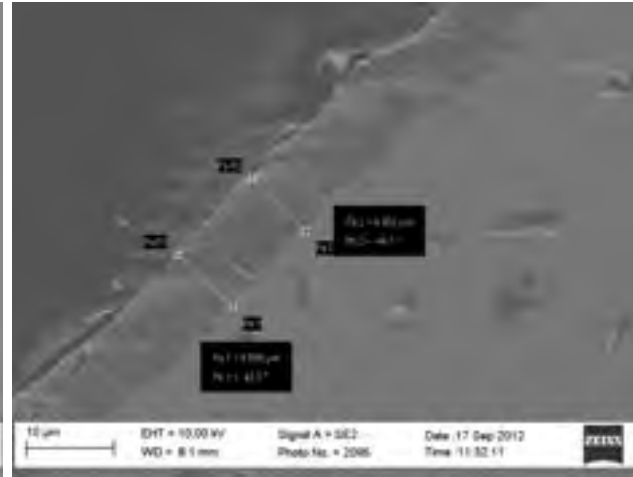
TOP LAYER: magnetron RF sputtering Al_2O_3

INTERLAYER: arc PVD FeAl + Cr

ADHESION LAYER: arc PVD Cr



1) PVD – la campagna TiN

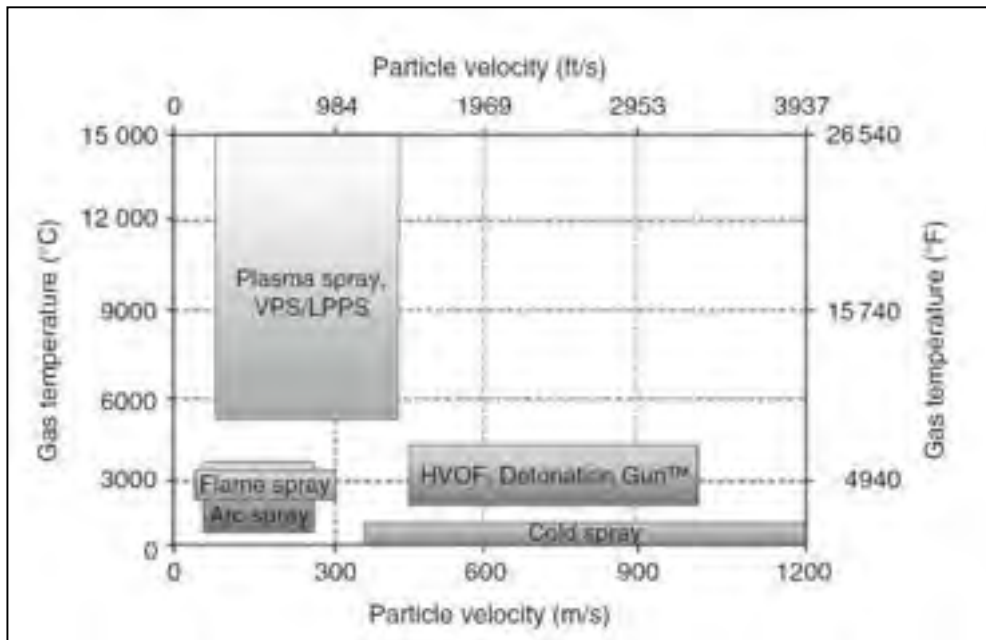


controllo incremento spessore TiN

2) Il processo HVOF

I processi di termospruzzatura consistono tutti di tre passaggi principali:

- creare materiale di appropriata composizione in forma di polvere, filo o barretta
- impartire sufficiente energia cinetica o termica
- proiettare le particelle verso il substrato da rivestire



In un processo HVOF la velocità di impatto delle particelle è dell'ordine di 1000 m/s, mentre in un processo Plasma Spray è circa 100 m/s

2) Il processo HVOF

- Il principale vantaggio del processo HVOF è il ridotto tempo di permanenza della polvere nella fiamma e l'elevatissima velocità di impatto delle particelle con produzione di rivestimenti molto densi
- La forza di legame dei rivestimenti può raggiungere valori dell'ordine di 90 MPa con porosità inferiori a 1%.
- Spessori tipici dei rivestimenti HVOF sono 100 – 400 micron.

2) Settori di applicazione dei rivestimenti HVOF

- I rivestimenti termospruzzati sono utilizzati per la protezione delle superfici, principalmente contro la corrosione ad alta temperatura e l'usura.
- Si trovano applicati in diversi settori industriali, quali aeronautico, navale, meccanico, siderurgico, energia, cartario.
- I rivestimenti HVOF vengono impiegati come protezione termica per rivestire componenti di turbine a gas per applicazioni civili, militari, marine ed industriali; essi vengono depositati sulle parti "calde" della turbina quali liner, ugelli e palettature dei primi stadi.

2) L'impianto HVOF del CSM

I processi di deposizione sono stati eseguiti utilizzando l'impianto HVOF presente presso CSM, un sistema **JP5000 Tafa System**.



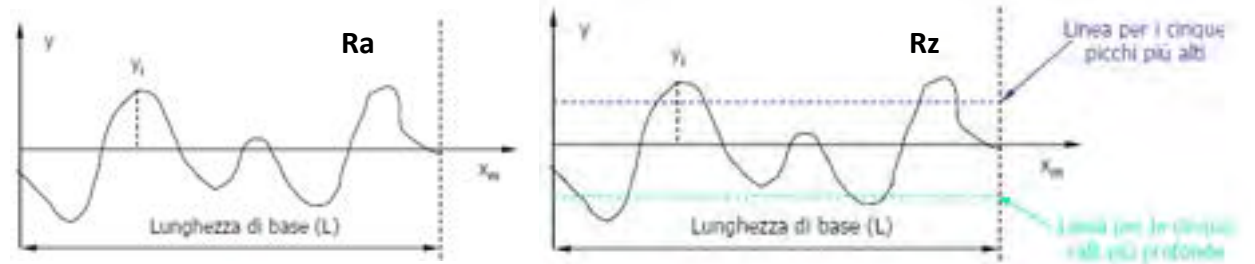
2) La campagna FeCrAlY

- La deposizione HVOF di polvere FeCrAlY (Amdry 9700 Fe₂₄Cr₈Al_{0.5}Y) è un processo consolidato. Nell'attività di messa a punto dei processi di deposizione dei rivestimenti ci si è quindi focalizzati su:
 - controllo delle tensioni residue del rivestimento
 - lavorazioni post deposizione di rettifica superficiale del rivestimento

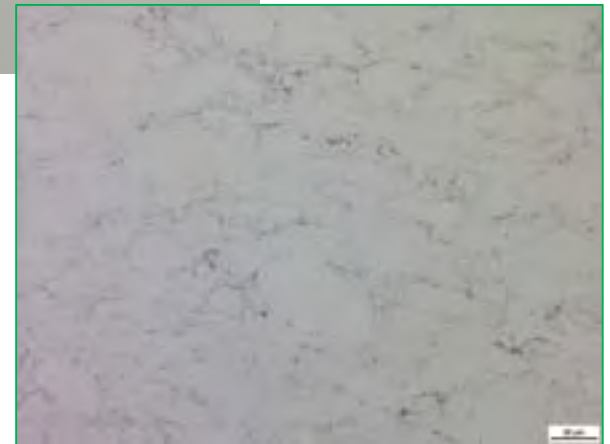
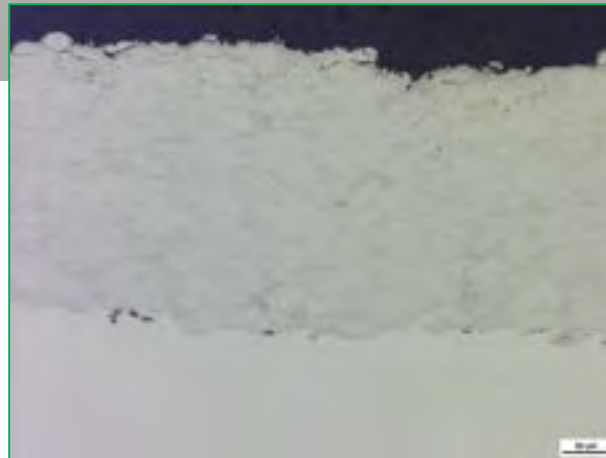
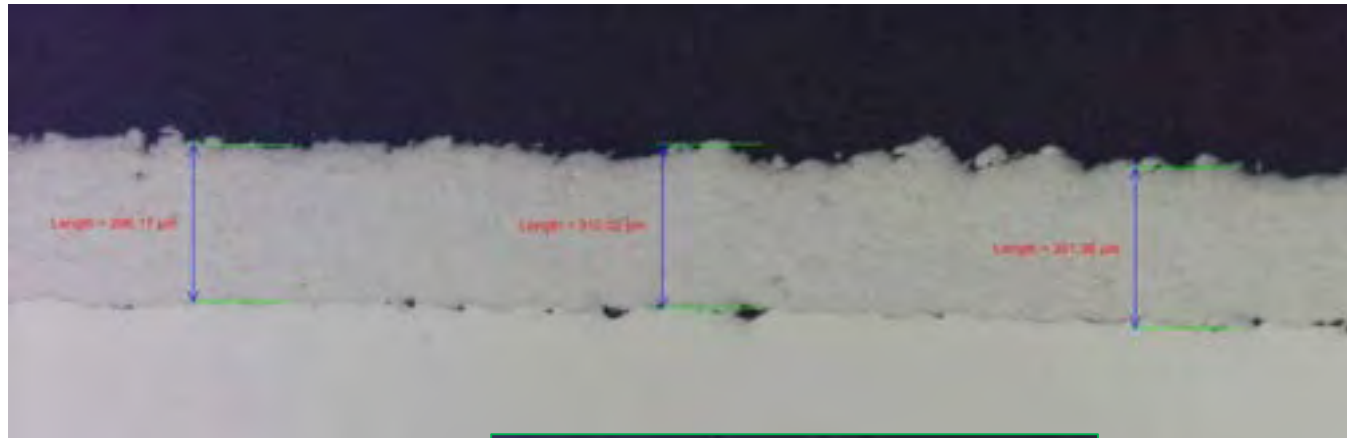
A causa del contributo predominante del peening stress, in genere i rivestimenti HVOF presentano stress compressivo: più alte velocità delle particelle producono rivestimenti con maggior stress residuo compressivo, ma minore porosità e frazione di ossidazione.

pressione in camera combustione	
psi	bar
93	6,4
82	5,6
71	4,9

	Ra	Rz
tal quale	5,84	32,52
dopo rettifica	0,2	1,26



2) Il rivestimento FeCrAlY HVOF



3) I processi di diffusion coating

- Varie sono le metodologie disponibili con un comune processo base:

1. **generazione di vapori** contenenti l'elemento formatore della scaglia protettiva
2. **trasporto dei vapori alla superficie** del componente da trattare
3. **reazione con il substrato e diffusione**

M: Metallic source

AX: activator

Inert filler: Al_2O_3 , SiO_2

Temperature: 750-1200°C

Ar, Ar-10% H_2

Substrate



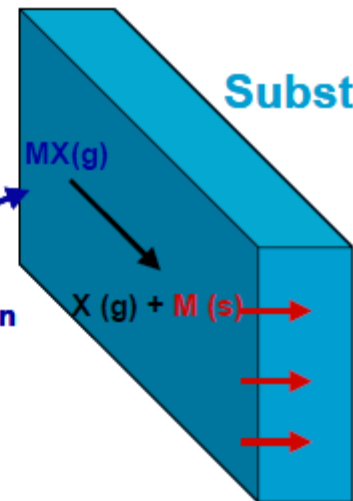
Gas state diffusion

M: Al, Si, Cr or Ti

X: F, Cl, Br or I

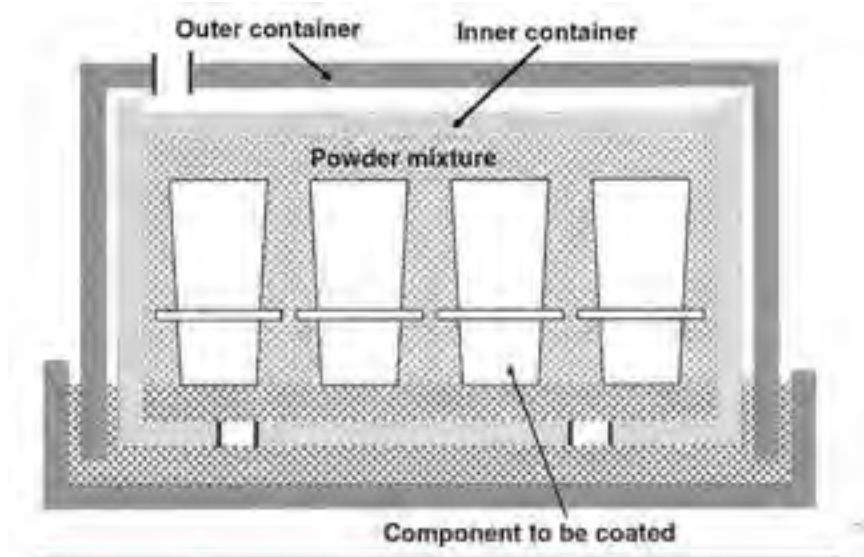
A: Na, or NH_4

Solid state diffusion



3) Il processo pack cementation

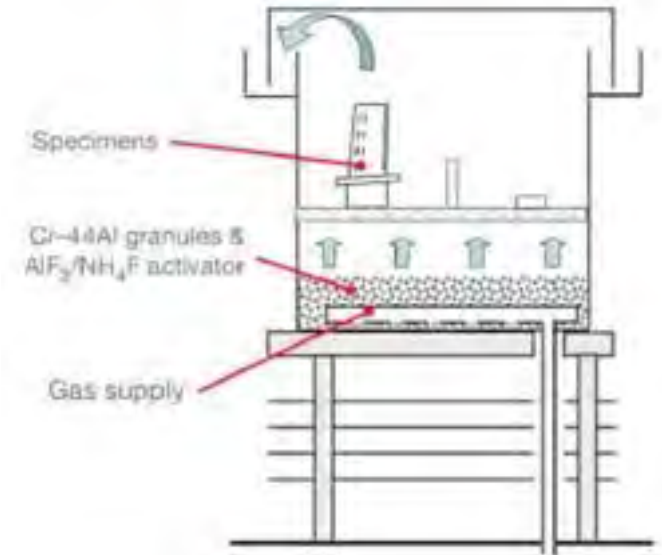
- Nel processo di **pack cementation** i componenti sono immersi in una miscela di polveri:
 - gli elementi da depositare (**sorgente**)
 - un sale alogenuro(**attivatore**)
 - un diluente inerte (**filler**)
- Quando la miscela viene riscaldata, l'attivatore reagisce per produrre un atmosfera di alogenuri dell'elemento della sorgente che diffonde e trasferisce l'elemento della sorgente alla superficie da rivestire. Il *filler* crea nel *pack* porosità interconnesse per il trasporto dei gas e ne impedisce la sinterizzazione.
- Il riscaldamento avviene in flusso di gas inerte



3) Il processo pack cementation

Nella variante ***above the pack*** i componenti da rivestire sono posti sopra il *pack*:

- non è necessario l'*unpacking* dei componenti
- si evita l'intrappolamento di polveri nei rivestimenti



Nella variante ***vapor phase aluminizing***, le polveri di sorgenti di Al sono sostituite da *pellets*:

- riduzione del lavoro di gestione dei rifiuti di processo
- Nella tecnica ***slurry***, la miscela di polveri viene sostituita da una *slurry*.

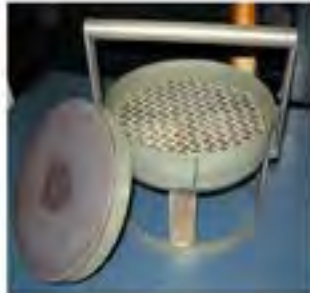
3) Settori di applicazione dei rivestimenti alluminuri

- Si stima che sul primo stadio delle palette delle turbine a gas, più dell'80% dei componenti rivestiti sia trattata con il processo di *pack cementation* .
- Il trattamento di componenti di grandi dimensioni è stato oggetto di diversi studi, portando allo sviluppo di alcuni brevetti ed alla dimostrazione che questo processo permetta il rivestimento anche della superficie interna di un tubo.
- Negli anni ottanta la compagnia statunitense Alon sviluppò un processo noto con il marchio di Alonizing™ basato sul processo di alluminizzazione per *pack cementation*. Lo scopo era proteggere i componenti delle fornaci per il trattamento di cracking dell'etilene dalla carburazione e dalla formazione di coke. Con gli impianti Alon si afferma di poter rivestire con Al, Cr e/o Si tubi lunghi 15 metri su scala industriale. Gli impianti della DAL Diffusion Alloys (UK) vengono dichiarati capaci di trattare tubi lunghi 18,5 metri.
- I trattamenti di alluminizzazione forniscono protezione da diversi fenomeni di degrado, incrementando la resistenza ad ossidazione, a sulfurazione, a carburazione.

3) L'impianto pack cementation CSM



in regime di flusso:
pressione atmosferica
vuoto
pressione intermedia
in regime pulsato



L'impianto CSM



Un impianto industriale

3) Le campagne di alluminizzazione

- **La microstruttura del rivestimento che si forma dipende dal substrato:** lo sviluppo di rivestimenti alluminuri sui due substrati **T91** e **15 – 15 Ti** ha richiesto **due campagne di ottimizzazione dei parametri di processo**.
- Per entrambe le tipologie di acciai è stato scelto di sviluppare rivestimenti alluminuri **bassa attività, favorendo cioè la formazione di fasi meno ricche in Al e quindi meno fragili**. Nella selezione dei componenti della pack è stato quindi scelto di utilizzare leghe base Al piuttosto che Al puro. In particolare sono state utilizzate le leghe **Al – Co** e **Al – Cr**, entrambi prodotti commerciali reperibili sul mercato.
- Quale sale attivatore è stato selezionato il **NH₄Cl**, cioè un attivatore che decompone evitando così la formazione di particelle solide che possano rimanere intrappolate nel rivestimento compromettendone la qualità. Esso inoltre non presenta tossicità, a differenza del rispettivo fluoruro.

Alluminizzazione bassa attività dell'acciaio T91

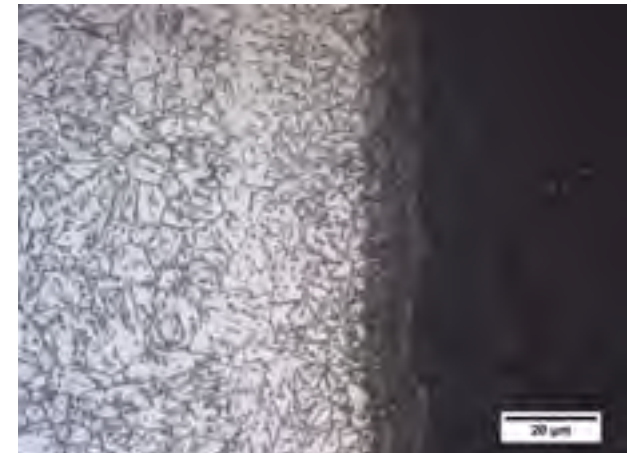
- Il trattamento termico dell'acciaio T91 consiste di:
 - una fase di austenitizzazione (**1040 – 1080**) °C seguita da un rapido raffreddamento in aria per la trasformazione martensitica.
 - una successiva fase di rinvenimento (**730 – 800**) °C è poi richiesta per trasformare parte della martensite in ferrite e permettere ai carburi di precipitare omogeneamente all'interno della matrice martensitica. Questo trattamento riduce la durezza del materiale, ne aumenta la tenacia a frattura e lo rende più facilmente lavorabile.

- 24/15: Al/Co; 12hrs@750°C
- 28/15: Al/Co; 12hrs@780°C
- 29/15: Al/Cr; 12hrs@780°C

trattamento 24/15	
provino	incremento peso (%)
3	18,7
4	17,0

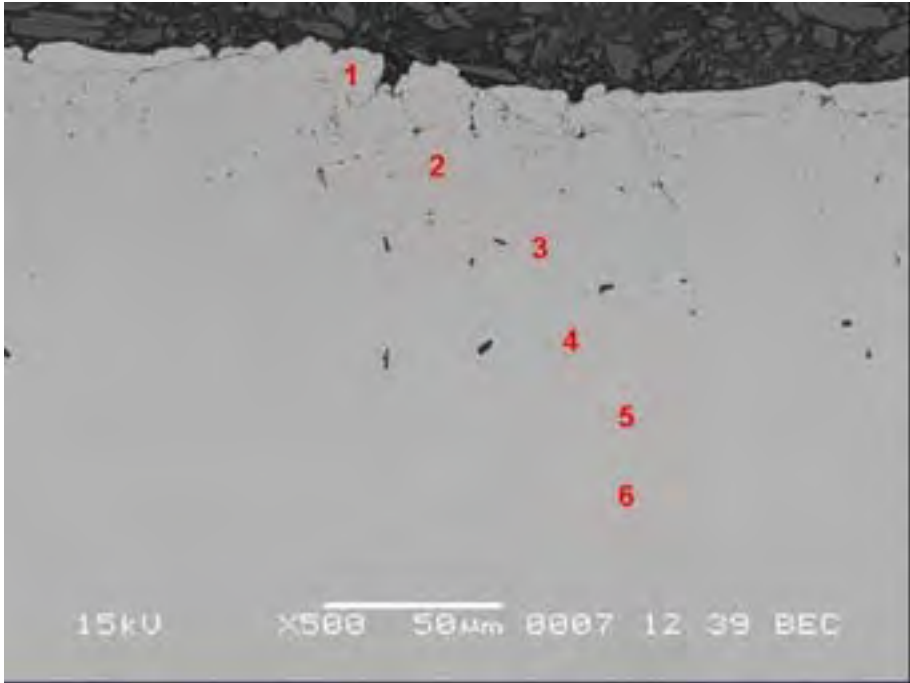
trattamento 28/15	
provino	incremento peso (%)
11	19,0
12	21,7

trattamento 29/15	
provino	incremento peso (%)
13	47,1
14	38,3



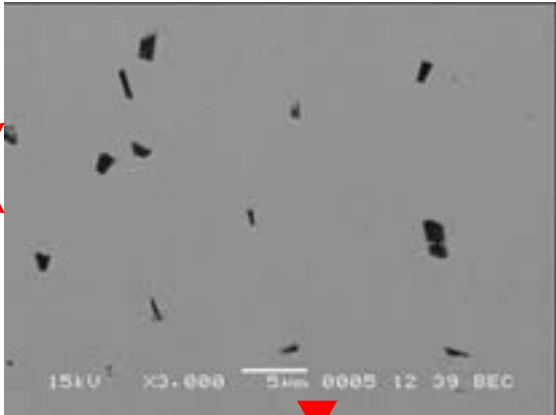
MO sezione campione 29/15

Il profilo di composizione: l'analisi EDS puntuale



	N	O	Al	Mo	Cr	Fe	Si
spectrum 1	0	1,6	11,8	0,7	7	78,7	0,1
spectrum 2	0	1,5	9,1	0,6	8,3	80,3	0,1
spectrum 3	0	1,5	6	0,7	8,7	82,9	0,2
spectrum 4	0	1,5	2,5	1,2	9,8	84,7	0,4
spectrum 5	0	1,6	1	0,6	9,6	86,8	0,3
spectrum 6	0	1,3	0,1	0,8	9,3	88,1	0,4

analisi SEM sezione campione Grade 91 alluminizzato



DETAGLIO
INNER LAYER

PRECIPITATI

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (3-Sigma)
N -K	0.048	2.98	28.4	14.3	+/- 2.6
O -K	0.003	2.77	1.7	1.0	+/- 0.8
Al-K	0.375	1.37	53.3	51.6	+/- 0.8
Mo-L	0.005	1.42	0.2	0.7	+/- 0.4
Cr-K	0.037	1.04	2.1	3.8	+/- 0.4
Fe-K	0.260	1.10	14.3	28.6	+/- 1.8
Si-K	0.000	1.74	0.0	0.0	+/- 0.0
Total			100.0	100.0	

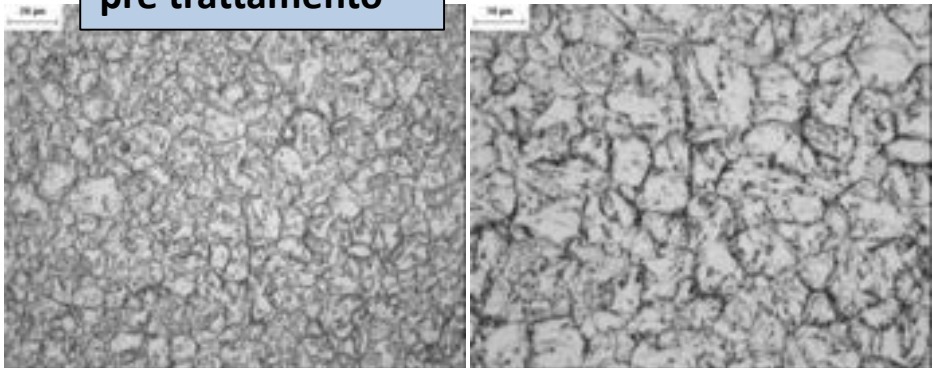
MATRICE

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (3-Sigma)
N -K	0.000	1.97	0.0	0.0	+/- 0.0
O -K	0.009	1.54	4.3	1.4	+/- 0.3
Al-K	0.061	1.79	19.7	11.0	+/- 0.3
Mo-L	0.003	1.28	0.2	0.4	+/- 0.4
Cr-K	0.080	0.87	6.4	6.9	+/- 0.4
Fe-K	0.784	1.02	69.4	80.3	+/- 2.4
Total			100.0	100.0	

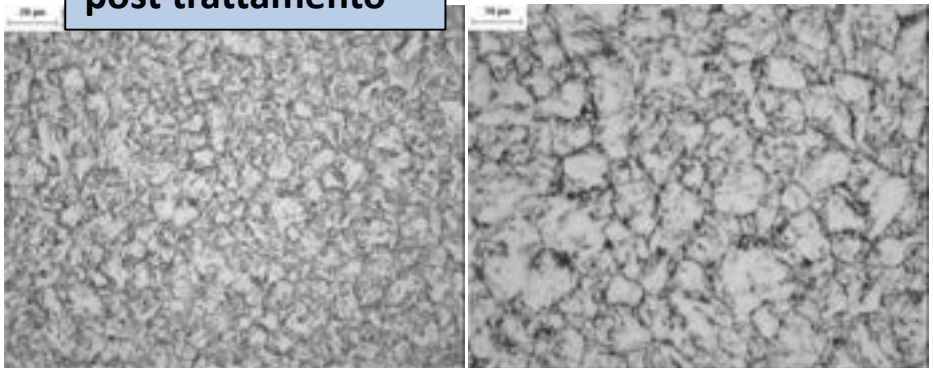
La microstruttura

campione Grade 91 alluminizzato

pre trattamento



post trattamento



Analysis Statistics	ASTM Grain Size: "G"	ASTM Grain Size: "G"	ASTM Grain Size
Minimum	10.6	Field 1	11.0
Maximum	11.4	Field 2	10.9
Mean	11.0	Field 3	11.0
Std. Dev.	0.3	Field 4	11.2
		Field 5	11.4
Field Statistics		Field 6	11.2
Total Line Length	4520.6	Field 7	10.7
Number of Intercepts	645	Field 8	11.2
Mean Intercept Length	7.0	Field 9	10.8
Total Number of Lines	40	Field 10	10.7
Confidence Interval	0.5	Accum.	11.0
Relative Accuracy	0.7		

Analysis Statistics	ASTM Grain Size: "G"	ASTM Grain Size: "G"	ASTM Grain Size
Minimum	10.7	Field 1	11.2
Maximum	11.5	Field 2	11.2
Mean	11.0	Field 3	11.0
Std. Dev.	0.2	Field 4	10.8
		Field 5	11.0
Field Statistics		Field 6	10.7
Total Line Length	4520.6	Field 7	10.9
Number of Intercepts	666	Field 8	10.8
Mean Intercept Length	6.8	Field 9	11.0
Total Number of Lines	40	Field 10	11.8
Confidence Interval	0.4	Accum.	11.05
Relative Accuracy	0.0		

HV10kg	pre trattamento	post trattamento
	215	219
	219	220
	216	219

Alluminizzazione bassa attività dell'acciaio 15 – 15 Ti

Nella messa a punto dei parametri del processo di alluminizzazione per l'acciaio 15 – 15 Ti si è fatto riferimento ai parametri del ciclo di produzione:

- **annealing treatment:** 15h (time in furnace) a 1230°C
- **post hot rolling:** when the sheet temperature has been above 1065°C for 45-50 minutes, the sheets are taken out of the furnace and water quenched

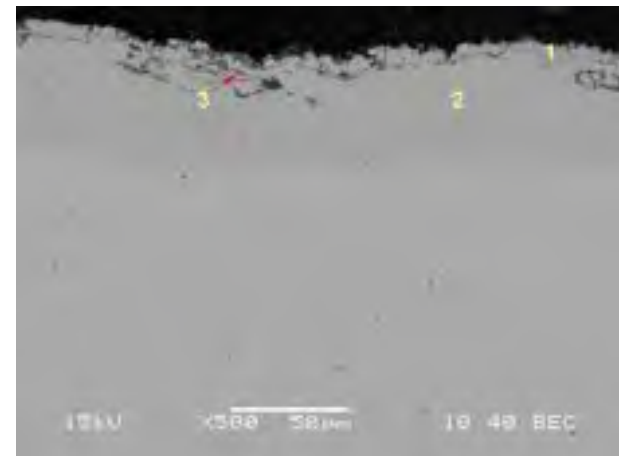
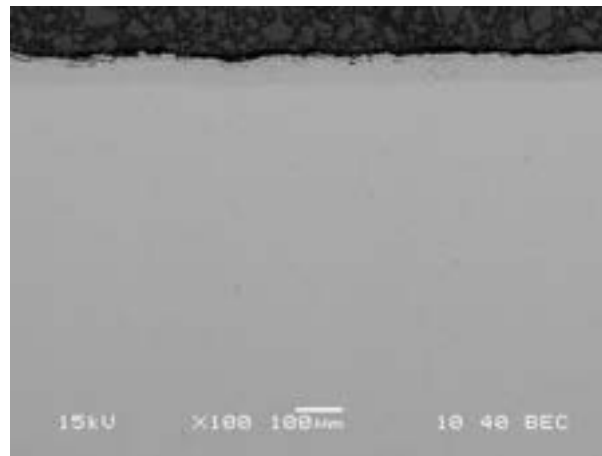
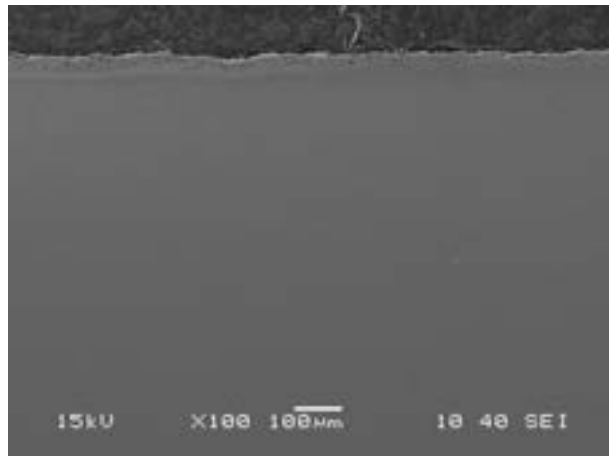
- 26/15: Al/Co; 45min@1065°C
- 27/15: Al/Cr; 45min@1065°C

trattamento 26/15	
provino	incremento peso (%)
7	554,0
8	564,1

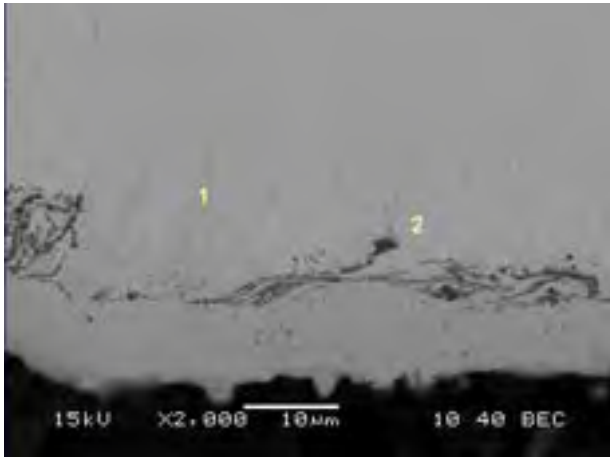
trattamento 27/15	
provino	incremento peso (%)
9	460,7
10	447,9

Alluminizzazione bassa attività dell'acciaio 15 – 15 Ti

- Riscaldamento@1065°C + immersione in acqua

[illegible]

Alluminizzazione bassa attività dell'acciaio 15 – 15 Ti



Rif. 1

Element	k-ratio (calc.)	ZAF	Atom %
Al-K	0.098	1.90	32.3
Ti-K	0.003	1.00	0.3
Cr-K	0.071	0.95	6.1
Fe-K	0.368	0.99	30.5
Ni-K	0.354	1.04	29.5
Si-K	0.002	1.69	0.5
Mo-L	0.004	1.37	0.3
O -K	0.001	1.79	0.7
Total			100.0

Rif. 2

Element	k-ratio (calc.)	ZAF	Atom %	Element	k-ratio (calc.)	ZAF	Atom %
Al-K	0.035	1.85	12.1	Al-K	0.035	1.85	12.1
Ti-K	0.003	0.97	0.4	Ti-K	0.003	0.97	0.4
Cr-K	0.174	0.91	15.5	Cr-K	0.174	0.91	15.5
Fe-K	0.652	1.02	60.5	Fe-K	0.652	1.02	60.5
Ni-K	0.069	1.05	6.3	Ni-K	0.069	1.05	6.3
Si-K	0.005	1.53	1.4	Si-K	0.005	1.53	1.4
Mo-L	0.015	1.28	1.0	Mo-L	0.015	1.28	1.0
O -K	0.006	1.60	2.8	O -K	0.006	1.60	2.8
Total			100.0	Total			100.0

Conclusioni

- Nell'ambito del triennio PAR2011- 2014, CSM ha sviluppato rivestimenti per la protezione di materiali strutturali operanti in sistemi nucleari refrigerati a piombo valutando e comparando diverse tecnologie di deposizione appartenenti alle tre famiglie:

- Physical Vapour Deposition (PVD)
 - HVOF
 - pack cementation

Sulla base dei risultati conseguiti, le soluzioni protettive FeCrAlY da processo HVOF e alluminizzazione da processo pack cementation appaiono maggiormente promettenti.

- E' necessario sviluppare attività propedeutiche allo sviluppo di metodologie di scale up delle soluzioni sviluppate, quali ad esempio:
 - trattamenti termici post deposizione
 - lavorazioni meccaniche post deposizione
 - operazioni di giunzione post deposizione
 - messa a punto dei parametri di deposizione e/o di mascherature per il rivestimenti di simulacri



García Ferré and F. Di Fonzo

Acknowledgements



Alexander Mairov
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MILANO 1863

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Pasquale Vena
Marco G. beghi



Yves Serruys
Patrick Trocellier
Lucile Beck



Cédric Baumier
Odile Kaitasov

Coatings: a great challenge

Materials degradation modes

- Fatigue
- Low T radiation hardening & embrittlement
- Radiation-induced and -modified solute segregation and phase stability
- High temperature He embrittlement
- **Corrosion**
- **Creep (thermal & irradiation)**
- **Void swelling**

Requirements for coatings

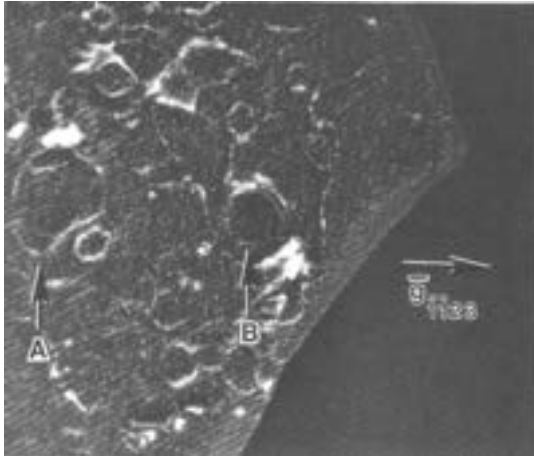
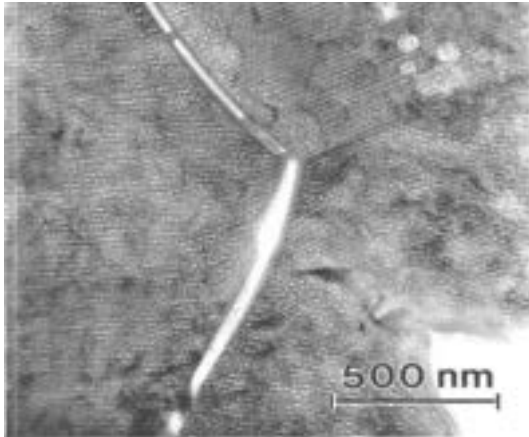
- High thermal conductivity
- Strong interfacial bonding
- Match of mechanical properties with steels
- Wear resistance
- Chemical stability
- Toughness
- **Radiation tolerance**



J.L. Straalsund – Westinghouse Hanford

Radiation damage in sapphire

neutrons

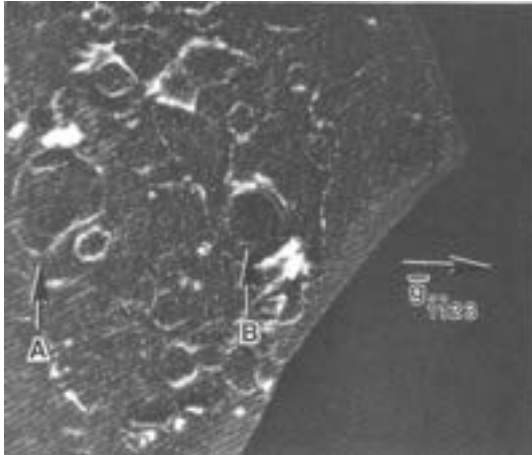
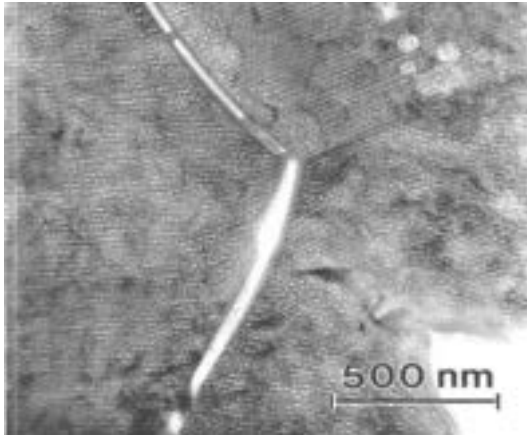


R.A. Youngman et al – J Mater Res - 1991

- voids and dislocation loops
- anisotropic void swelling along c-axis
- intergranular micro-cracking

Radiation damage in sapphire

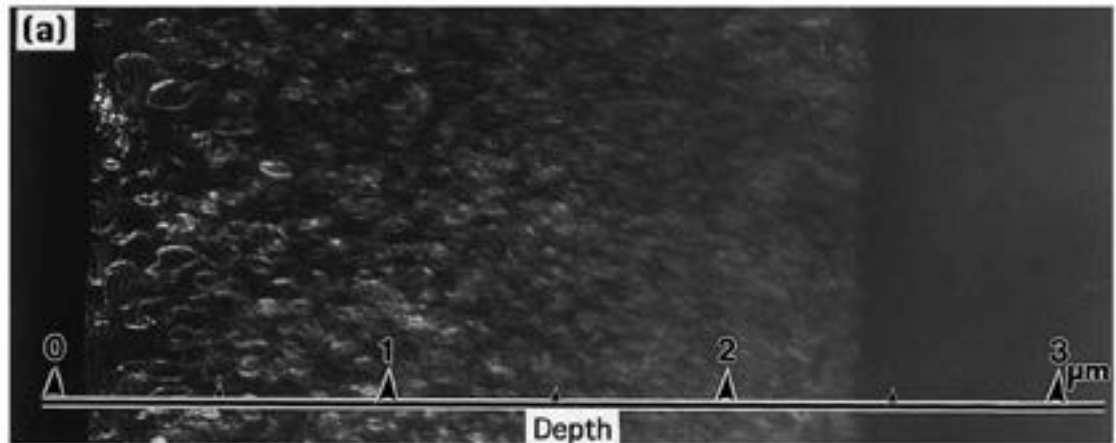
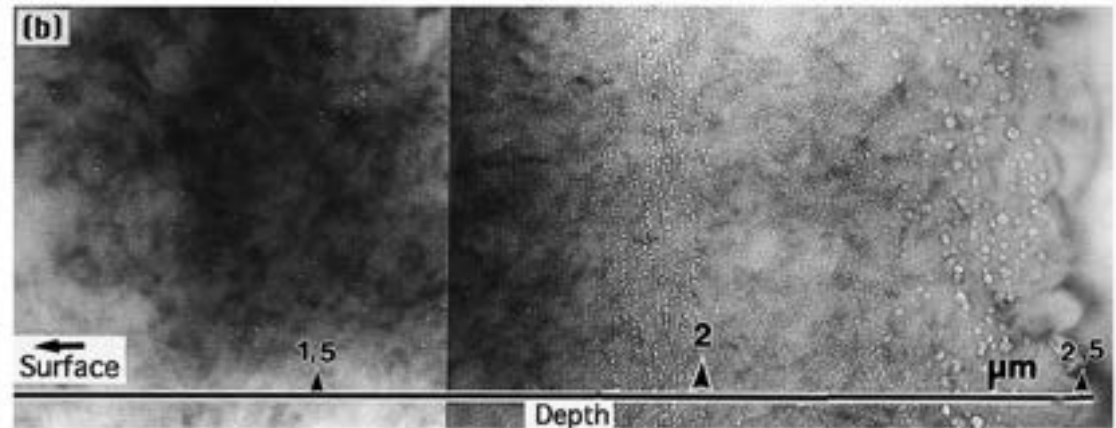
neutrons



R.A. Youngman et al – J Mater Res - 1991

- voids and dislocation loops
- anisotropic void swelling along c-axis
- intergranular micro-cracking

ions



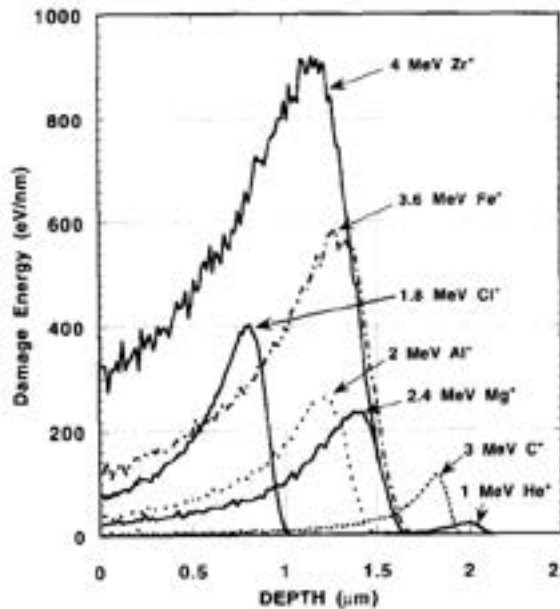
Y. Katano et al. – J Nucl Mater - 1998

- equivalent microstructural features

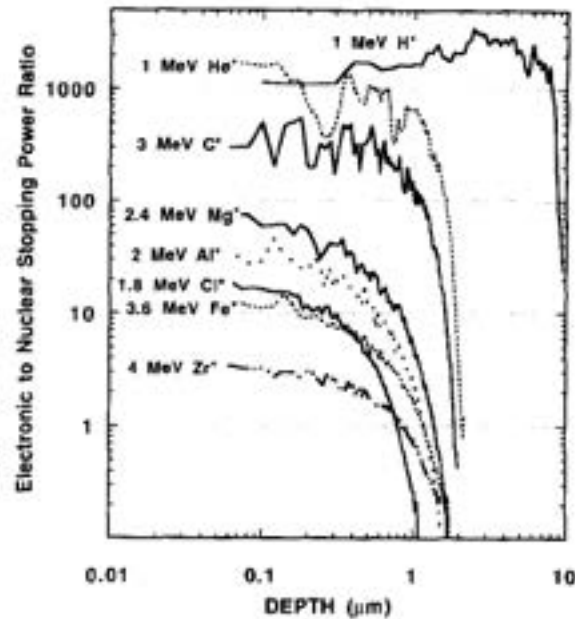
Ion irradiation of sapphire

What is the effect of irradiation spectrum and type of ions?

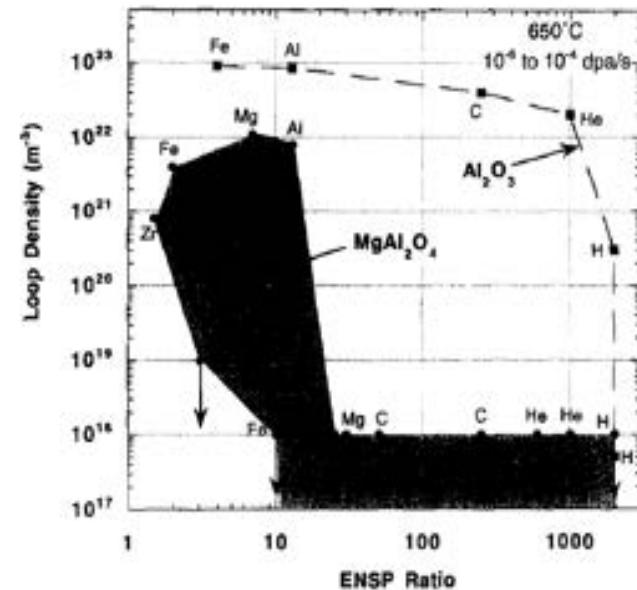
Zinkle - Journal of Nuclear Materials - 1995



Depth-dependent damage energy density in crystalline Al₂O₃



Electronic to Nuclear Stopping Power ratio in crystalline Al₂O₃

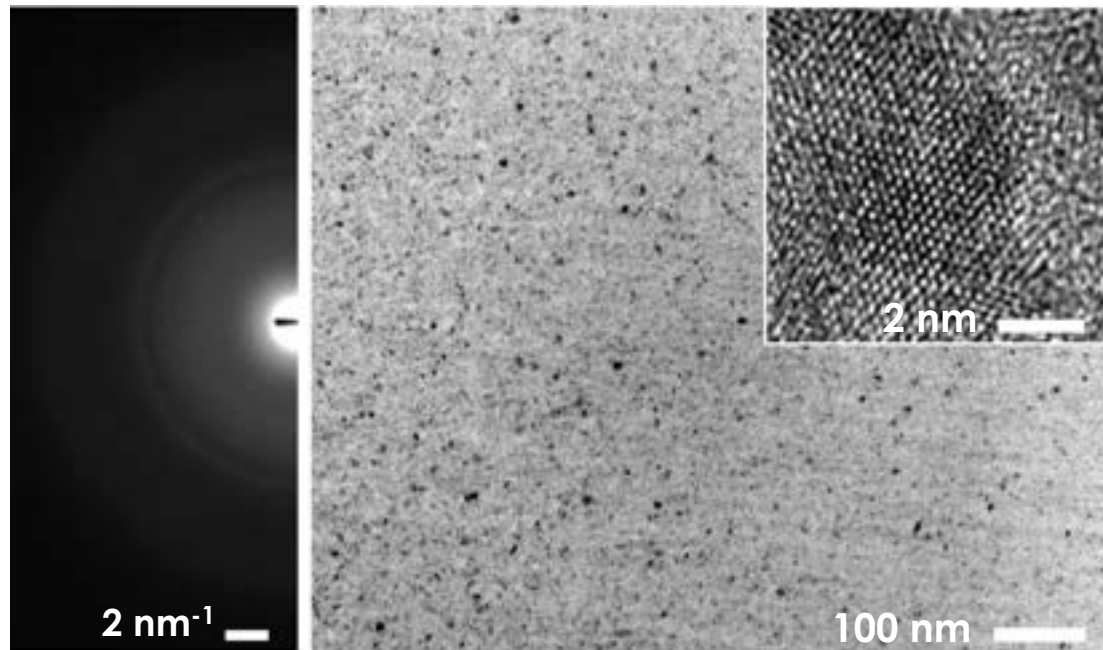


Effect of ENSP on dislocation loop density

A high ionizing component suppresses dislocation loop formation and enhances loop growth

**For sapphire in LFRs:
ENSP ≈ 4 (PKAs + γ radiation)**

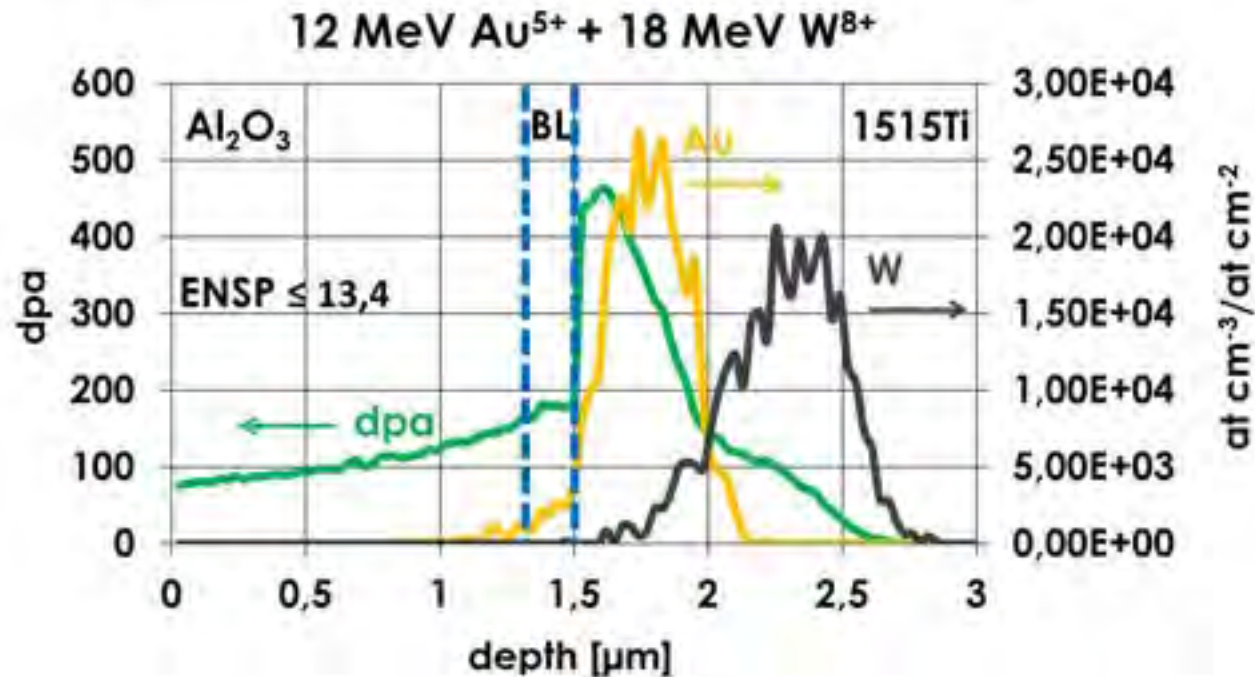
homogeneous dispersion of randomly oriented crystalline Al_2O_3 nanodomains in amorphous Al_2O_3 matrix



Amorphous matrix as a lubricant

Heavy ion irradiation of Al_2O_3 coatings

Au and W ions up to 20, 40 and 150 dpa (end-of-life damage) @600°C



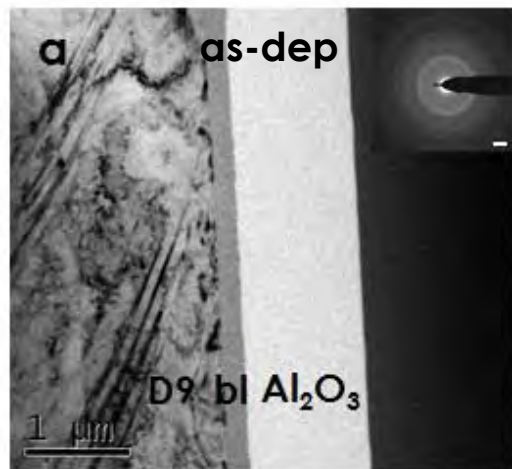
Main criteria

- Minimum coating thickness for nanoindentation: 1 μm
- Implantation beyond coating $\rightarrow$ negligible chemical effects
- Low ENSP ratio to simulate effect of neutrons
- Low enough absolute electronic stopping power to avoid single swift ion track formation (7 keV/nm vs $\approx 9,5$ keV/nm threshold @RT)
- Different doses, corresponding to up to **20, 40 and 150 dpa** at the interface between Al_2O_3 and BL
- dpa calculated using SRIM (Kinchin-Pease)



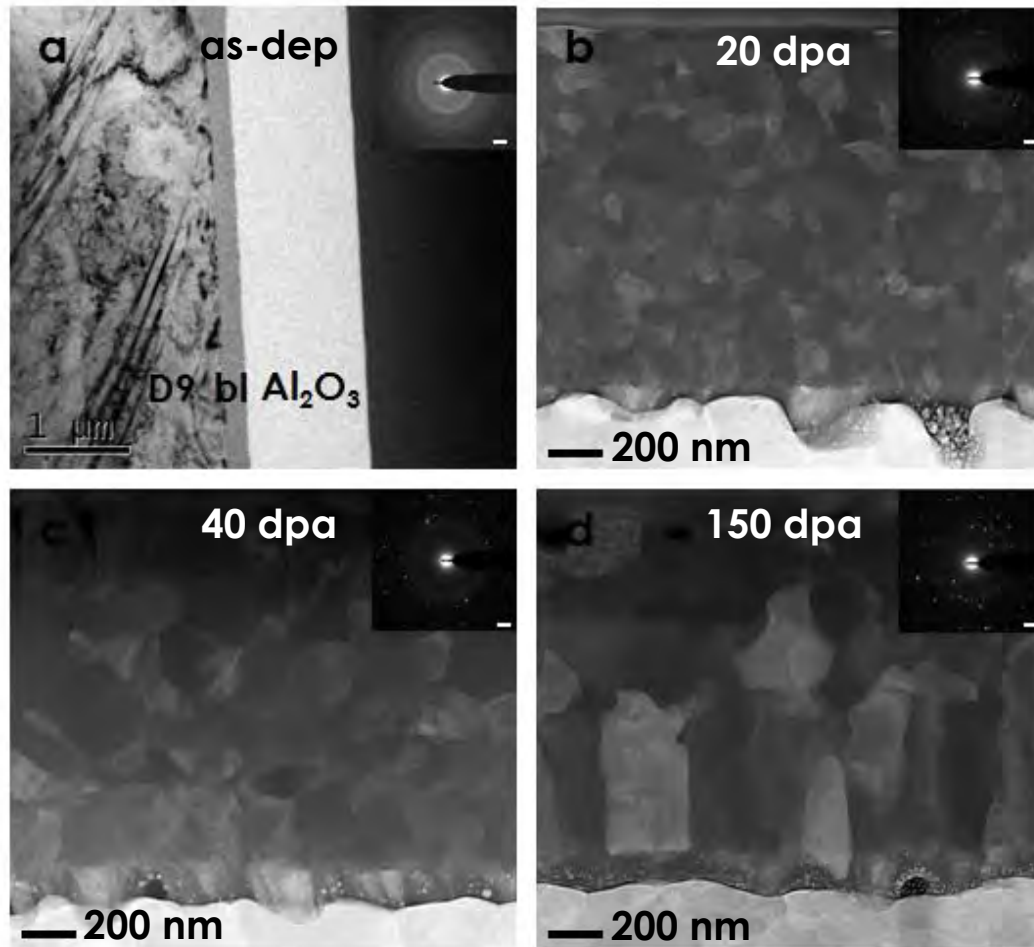
Sample holder

Structural features and mechanical properties

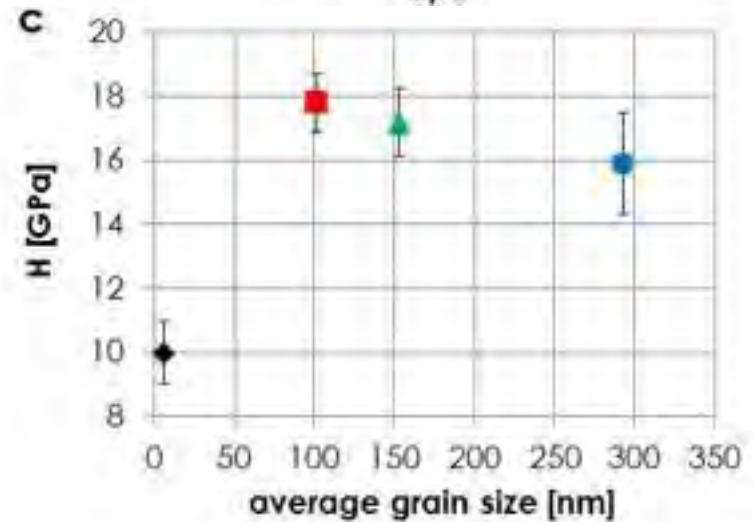
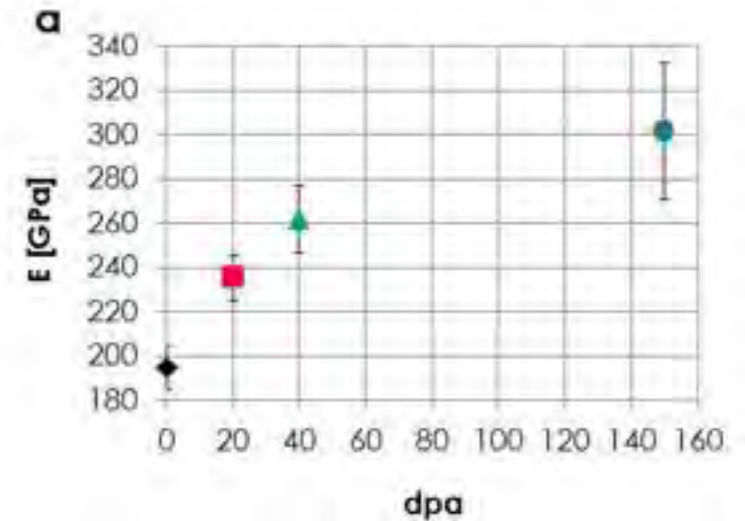


radiation-induced nanocrystallization & coarsening

Structural features and mechanical properties

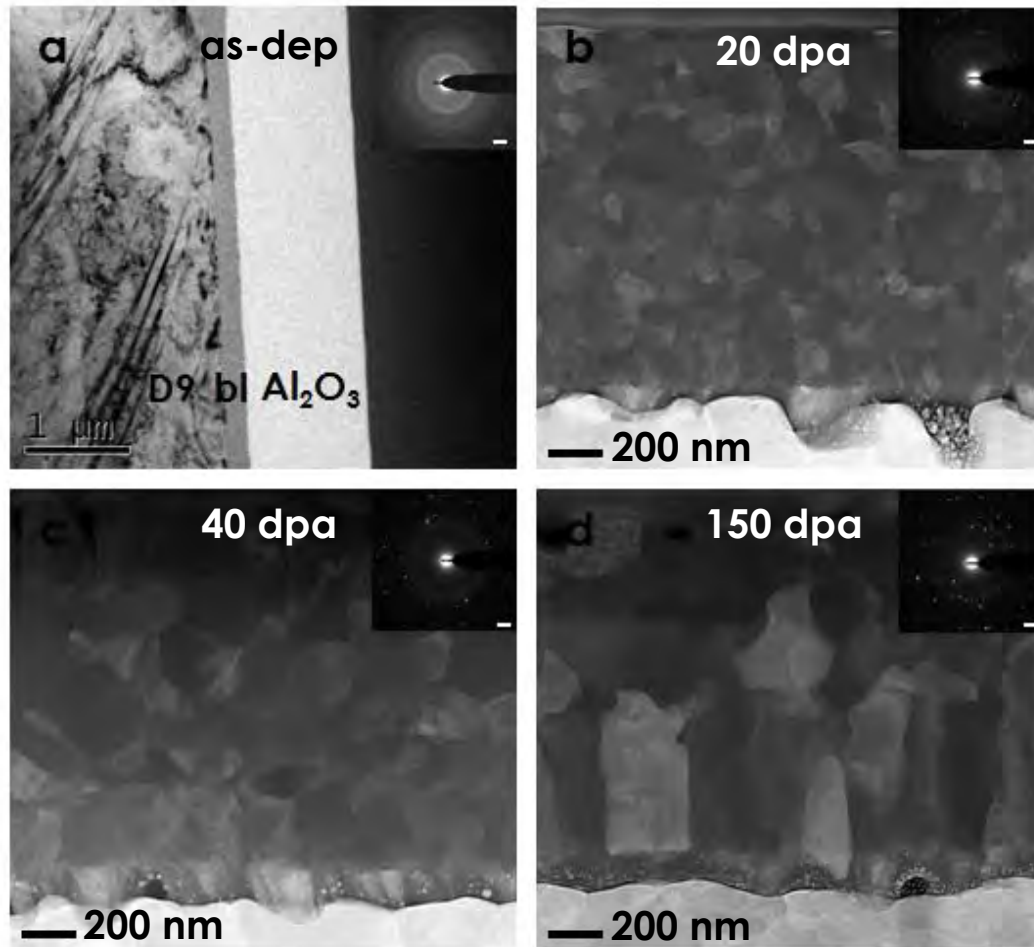


radiation-induced nanocrystallization & coarsening



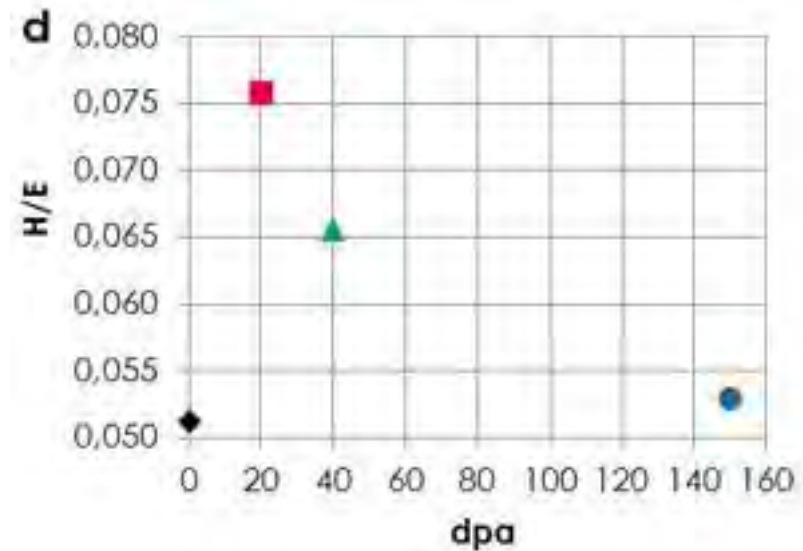
Hall-Petch hardening

Fracture toughness



radiation-induced nanocrystallization & coarsening

Hardness to elastic modulus ratio H/E relates to fracture toughness

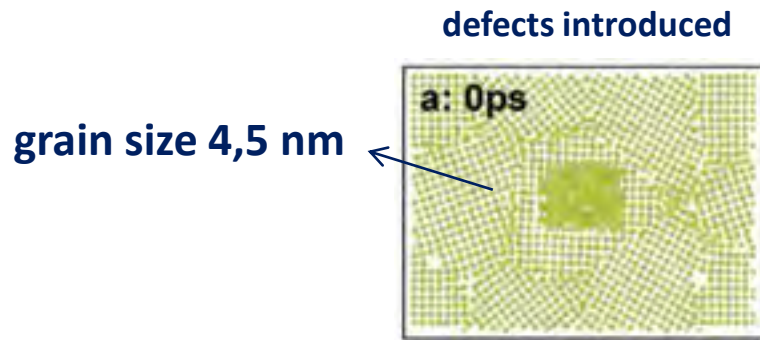


Improvement of fracture toughness in-service

Nanocrystallization mechanism

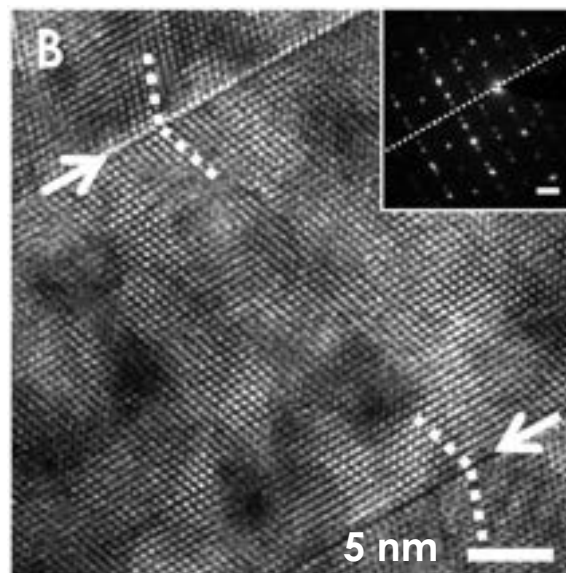
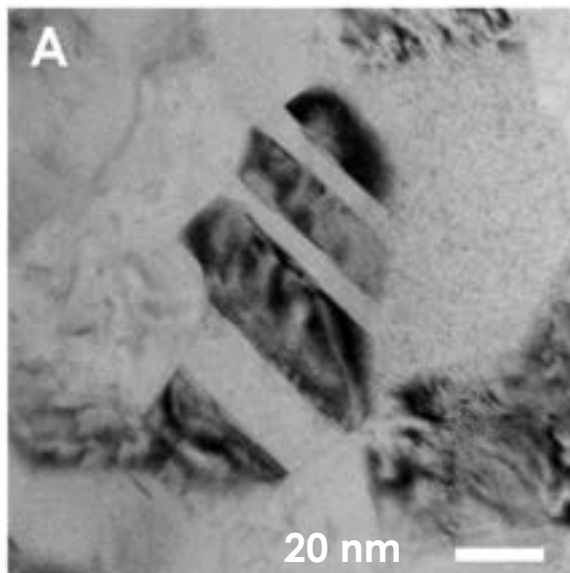
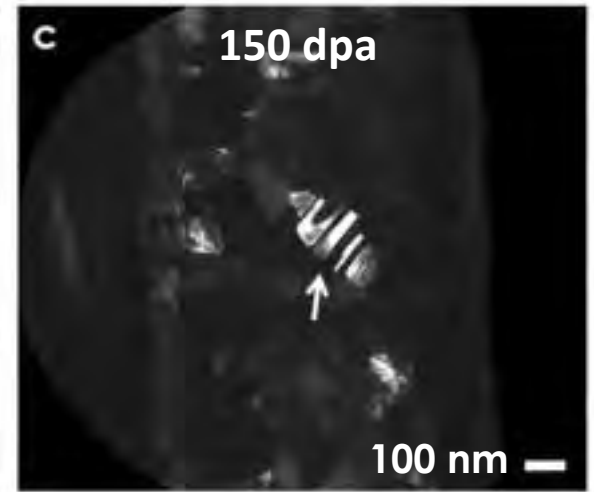
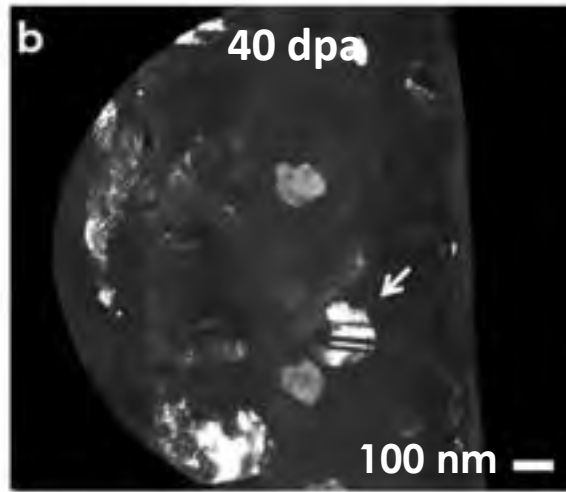
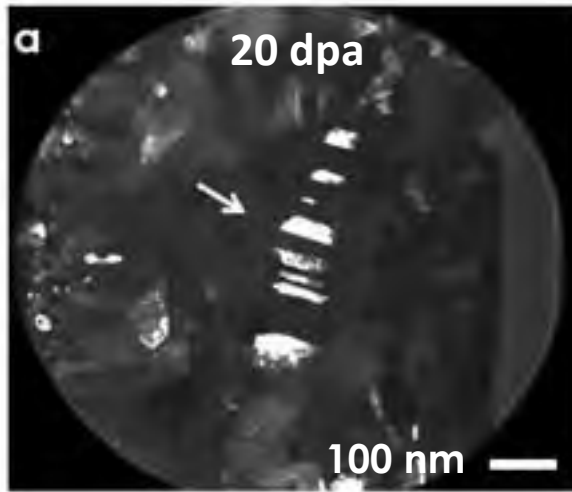
Molecular dynamics simulation: disorder-driven grain growth mechanism

Y. Zhang et al. – PCCP – 2014



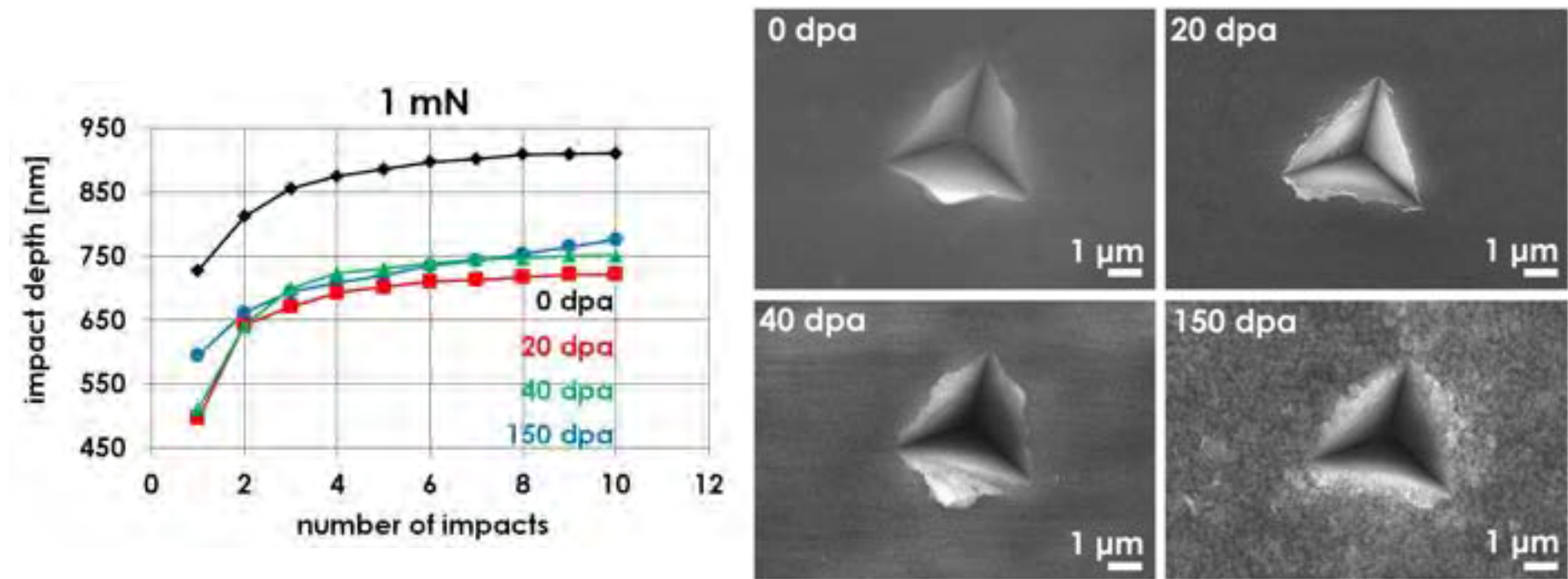
Coarsening slows down as grain size increases

Twinning



**Deformation twins found for
all radiation damage levels**

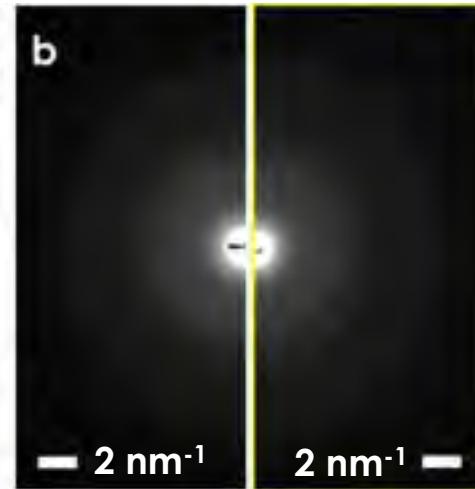
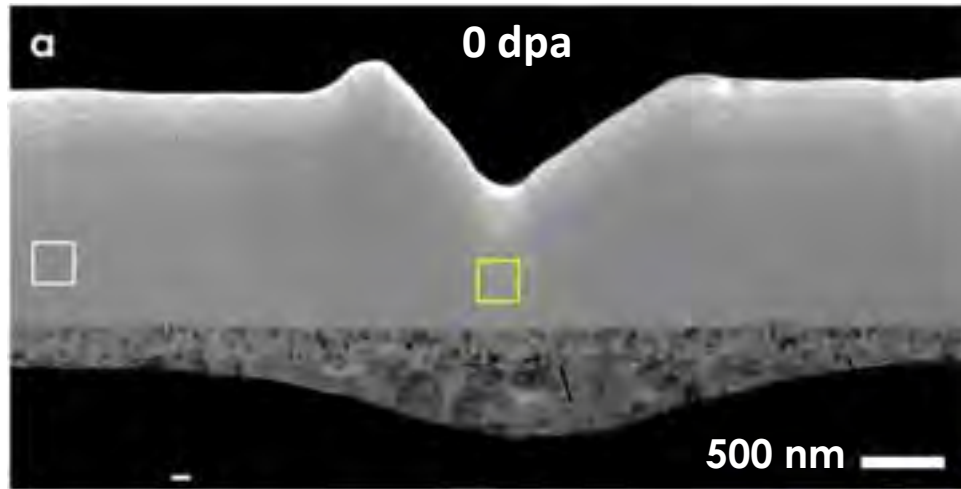
cube-corner diamond stylus «blasted» 10 times against sample's surface in the same point



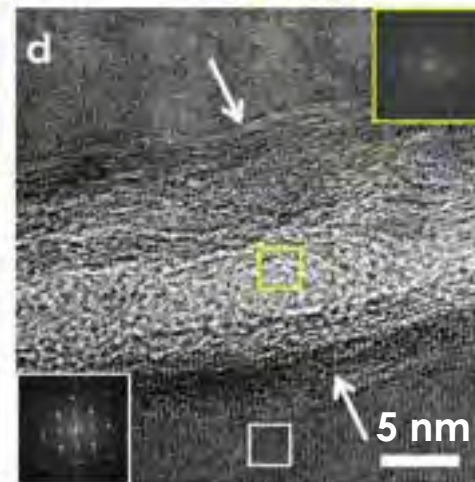
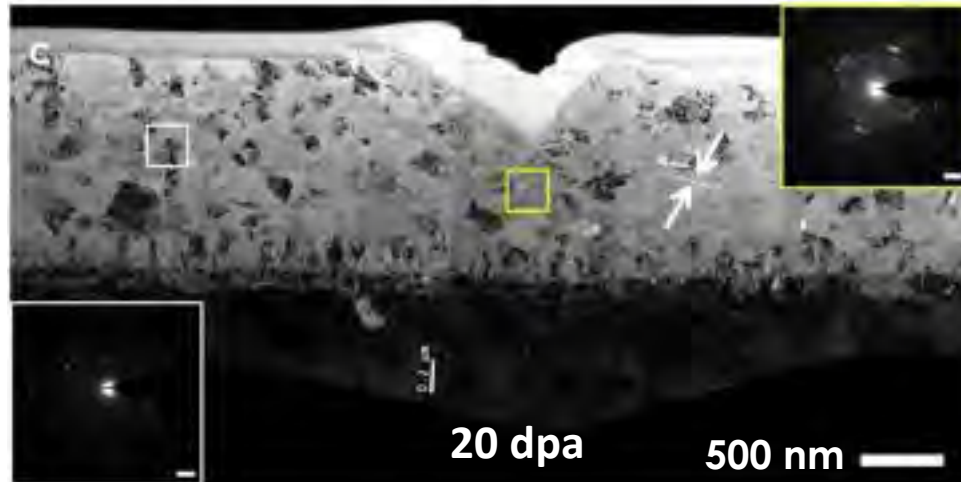
Impact energy dissipated more efficiently in the irradiated samples

Mechanisms of impact energy dissipation

Nanoimpact testing (1mN – 10 impacts)



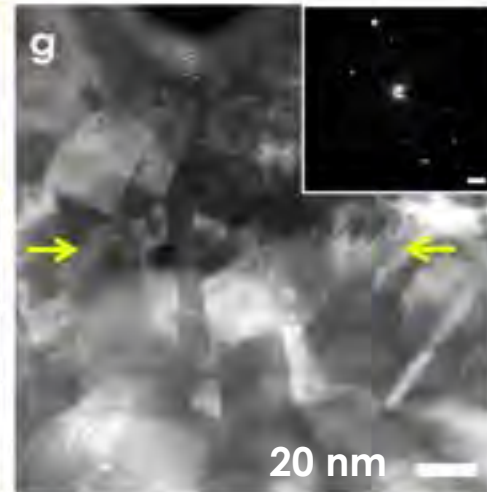
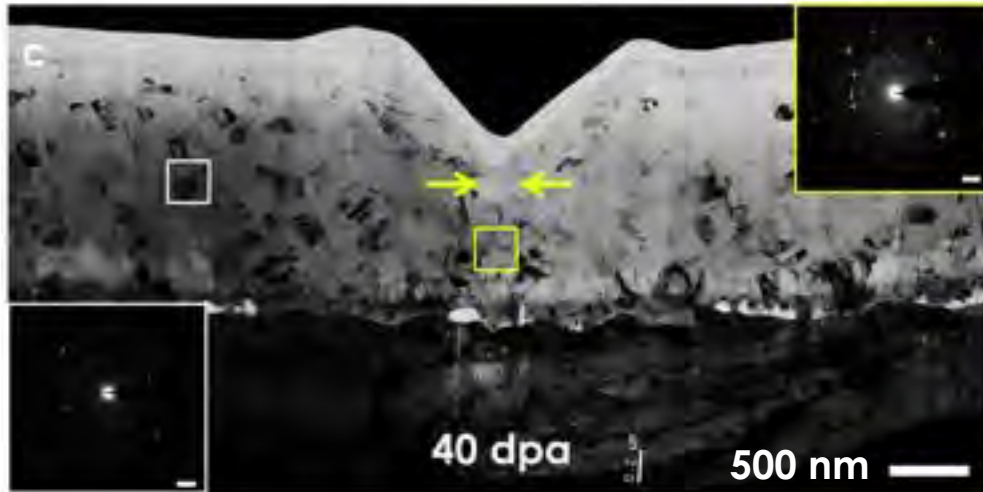
plastic flow
through shear
bands



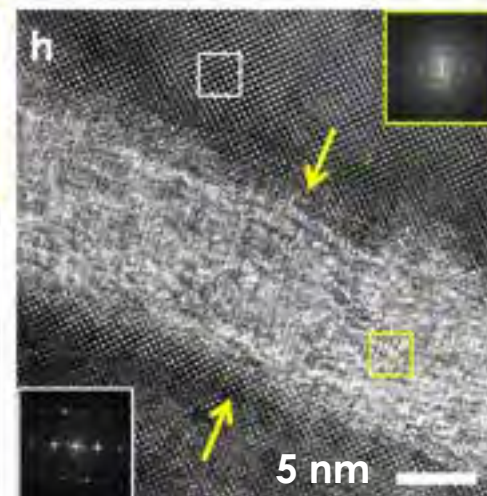
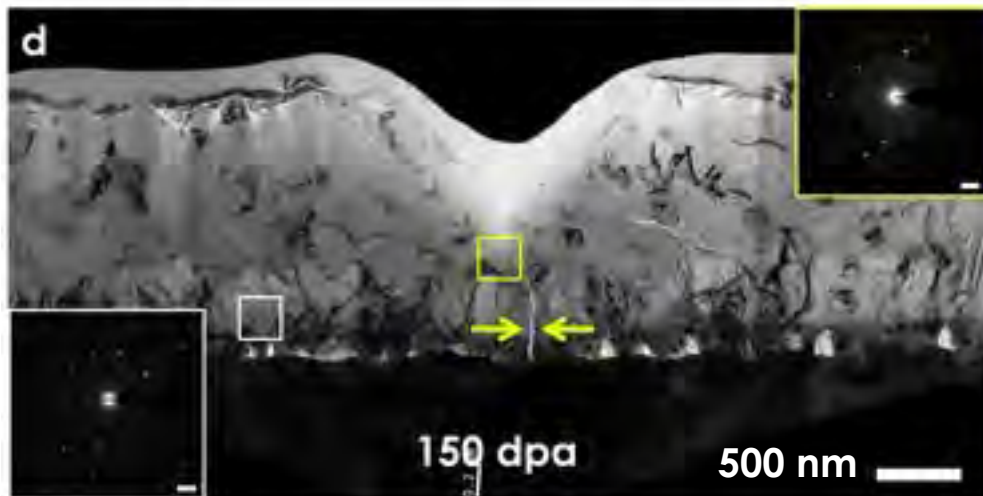
local shear
amorphization

Mechanisms of impact energy dissipation

Nanoimpact testing (1mN – 10 impacts)



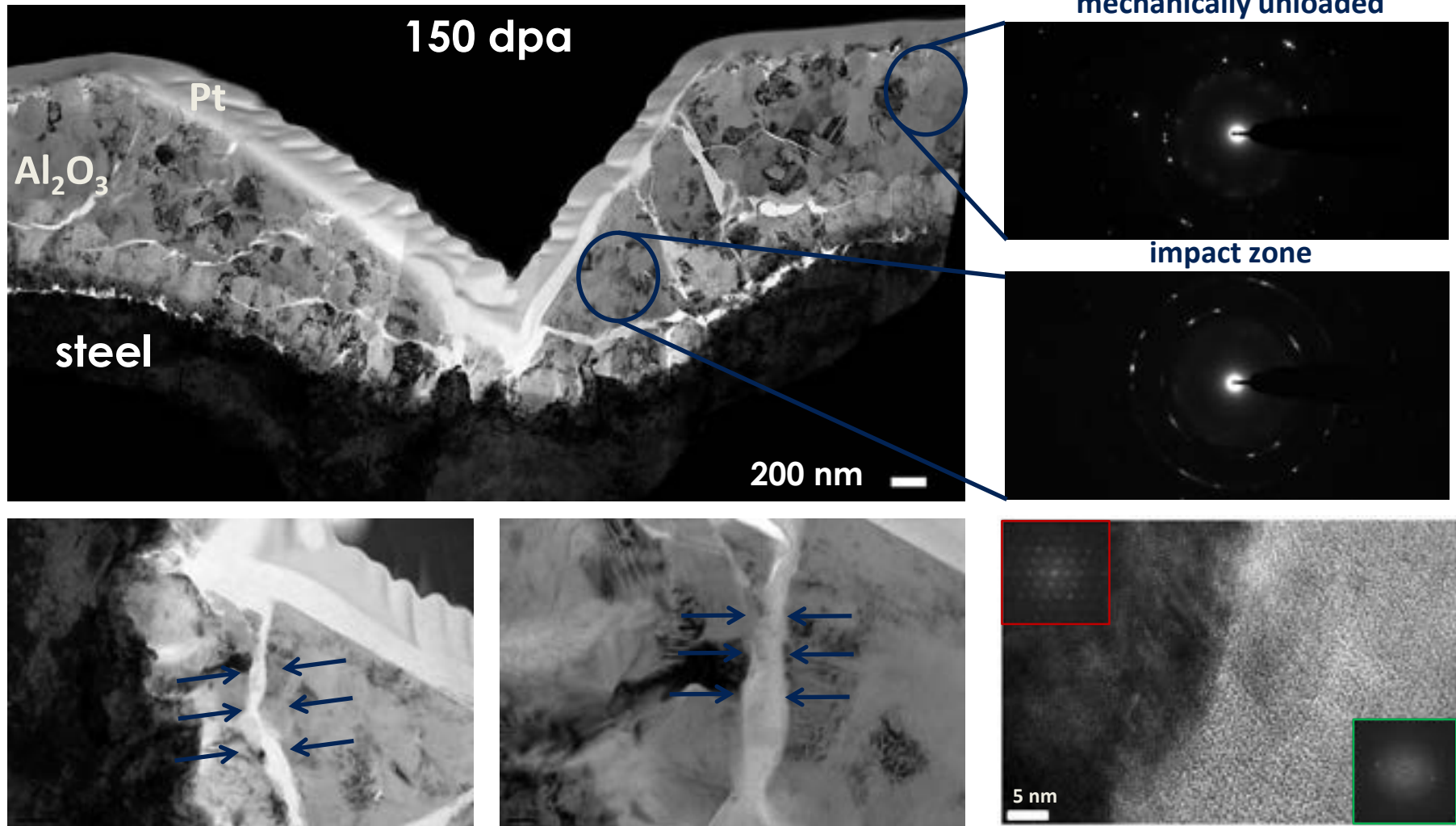
twinning



local shear
amorphization

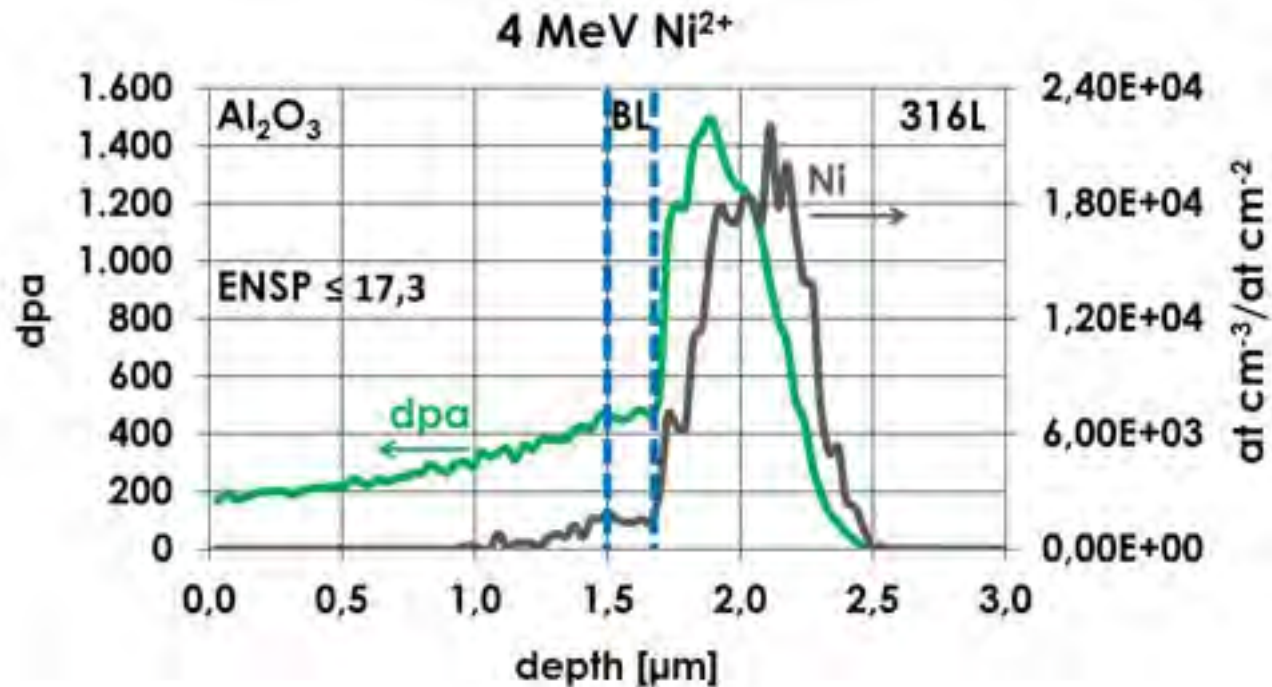
Mechanisms of impact energy dissipation

Nanoimpact testing (10 mN – 10 impacts)



Heavy ion irradiation of Al_2O_3 coatings

Ni ions up to 250 and 450 dpa (beyond end-of-life dose) @ 600°C



Main criteria

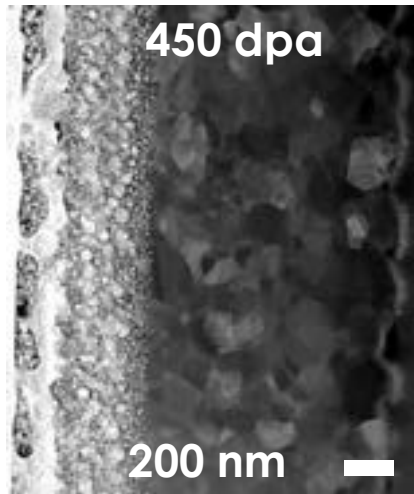
- Minimum coating thickness for nanoindentation: 1 μm
- Implantation beyond coating → negligible chemical effects
- Low ENSP ratio to simulate effect of neutrons
- Low enough absolute electronic stopping power to avoid single swift ion track formation (2 keV/nm vs ≈ 9,5 keV/nm threshold @RT)
- Different doses, corresponding to up to **250 and 450 dpa** at the interface between Al_2O_3 and BL
- dpa calculated using SRIM (Kinchin-Pease)



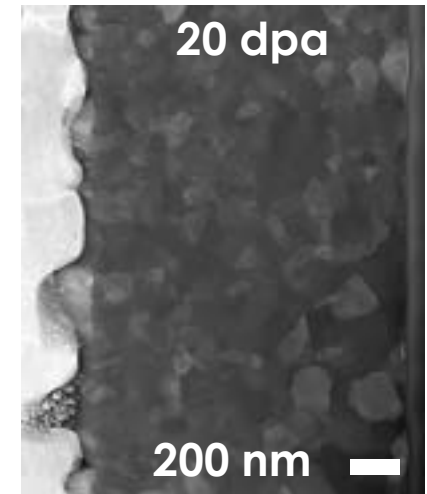
Sample holder

Role of the irradiation spectrum

4 MeV Ni²⁺



12 MeV Au⁵⁺ + 18 MeV W⁷⁺

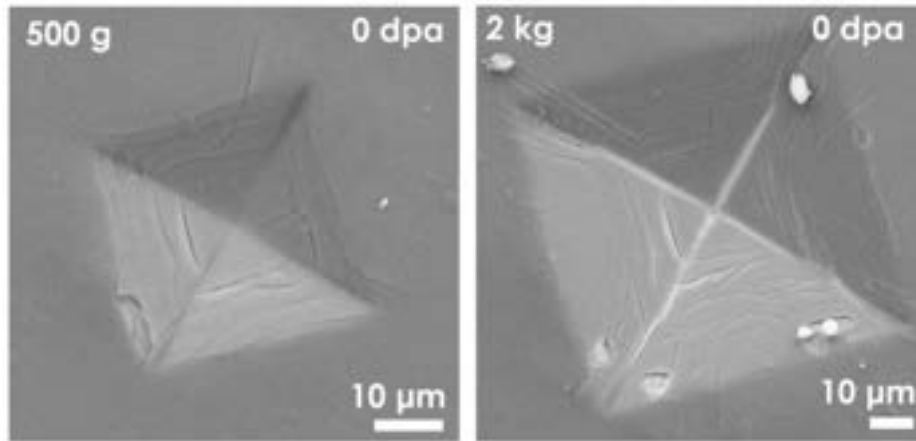


Irradiation of Al_2O_3 coatings with heavy ions yields an improvement in-situ of the material's performance

- **Nanocrystallization, grain growth and twinning**
- **Increase of hardness according to the Hall-Petch effect**
- **Increase of fracture toughness suggested by H/E ratio & nanoimpact: lattice plasticity & localized shear amorphization**
- **Effect of the irradiation spectrum: lighter ions → reduced grain coarsening**

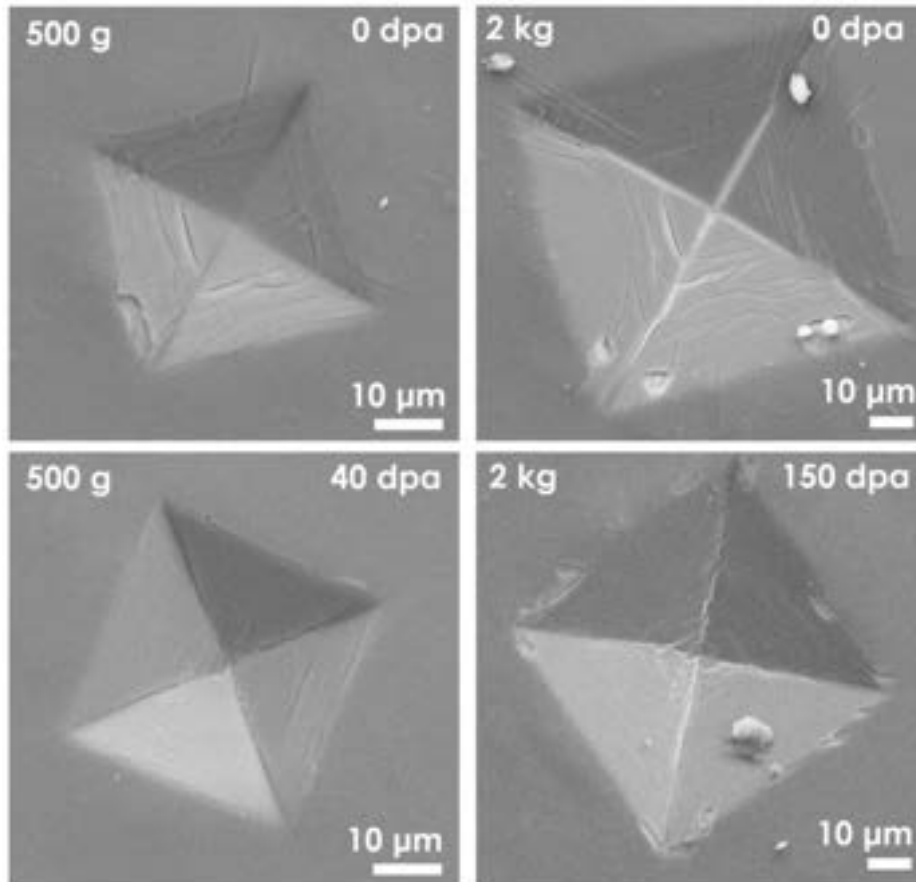


Microindentation



cracks form and propagate but a quantitative estimation of fracture toughness is not possible (indentation reaches deep into the substrate)

Microindentation



cracks form and propagate but a quantitative estimation of fracture toughness is not possible (indentation reaches deep into the substrate)

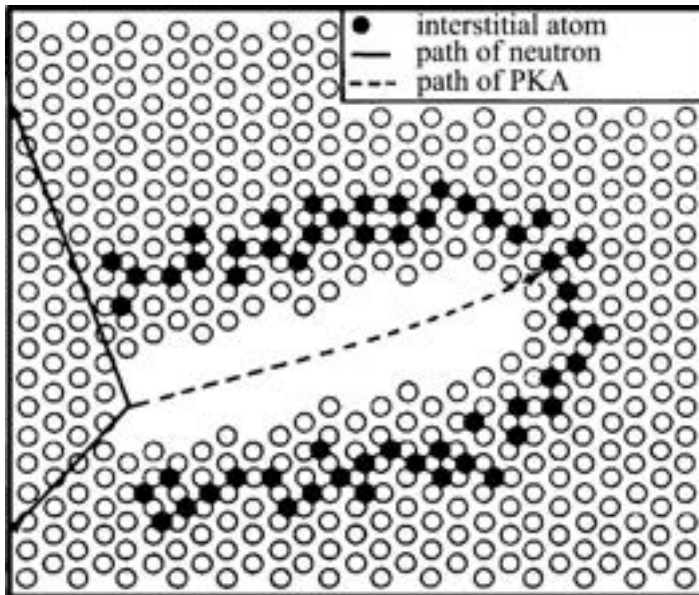
cracks form but propagation is strongly hampered, suggesting an increase of fracture toughness

Qualitative trend of fracture toughness in agreement with trend for H/E

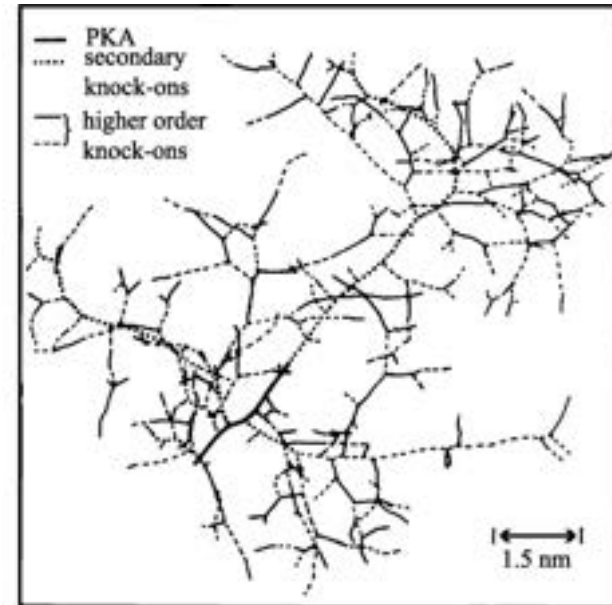
How do neutrons interact with matter?

Displacement cascades

simplified scheme



more realistic version



G.S. Was – Fundamentals of radiation materials science

- “Central” vacancy-rich zone
- “External” interstitial-rich zone
- Thermal spike (local “fusion”/amorphization)
- Number of defects above equilibrium concentration → precipitation

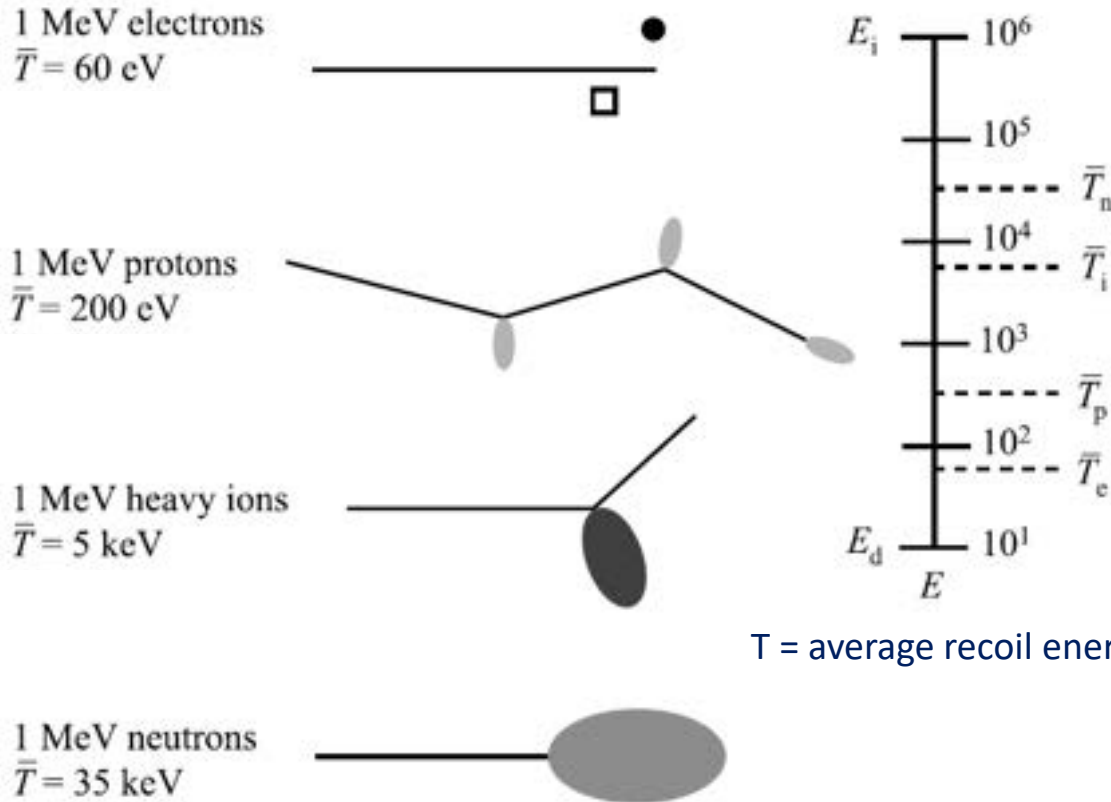
incident neutron



PKA: primary knocked-on atom



Radiation damage basics



T = average recoil energy •

- **Electrons:** low mass $\rightarrow$ low energy loss – creation of Frenkel pairs
- **Protons:** mass ratio closer to 1 $\rightarrow$ many “small” displacement cascades (Coulomb potential of interaction) – energy loss to electrons
- **Heavy ions:** mass ratio close to 1 $\rightarrow$ few displacement cascades (Coulomb potential of interaction BUT large inertia) – energy loss to electrons
- **Neutrons:** interaction through nuclear forces (no Coulomb potential) – rigid spheres with good approximation $\rightarrow$ few large displacement cascades

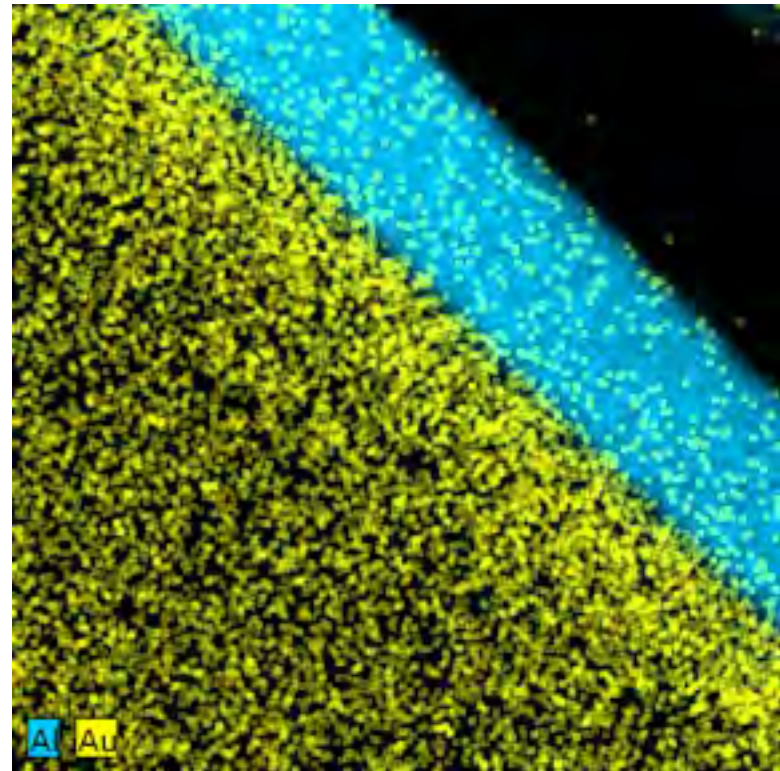
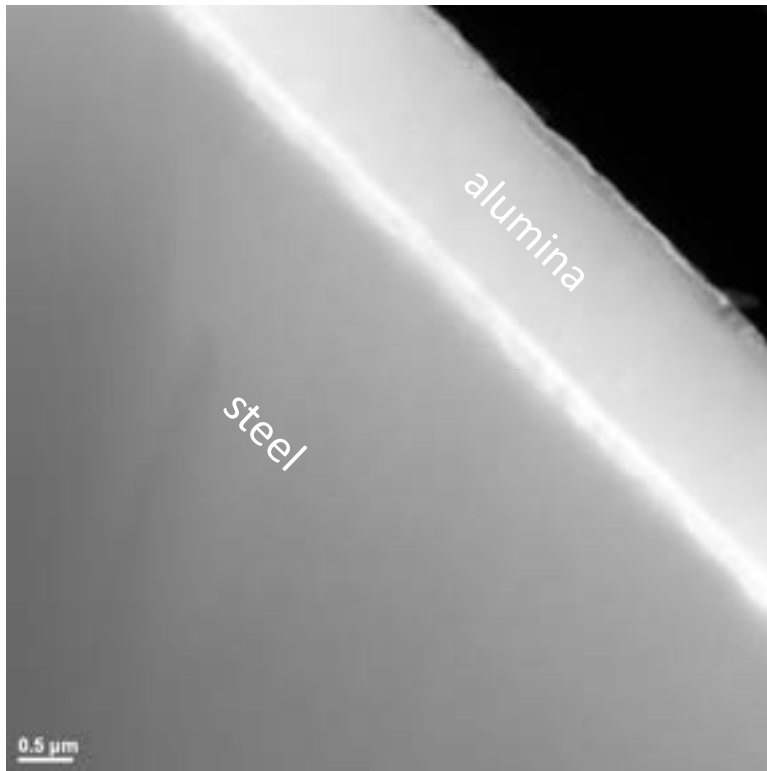
G.S. Was – Fundamentals of radiation materials science

Energy loss is proportional to mass ratio $\longrightarrow$

Different incident particles produce different types of damage

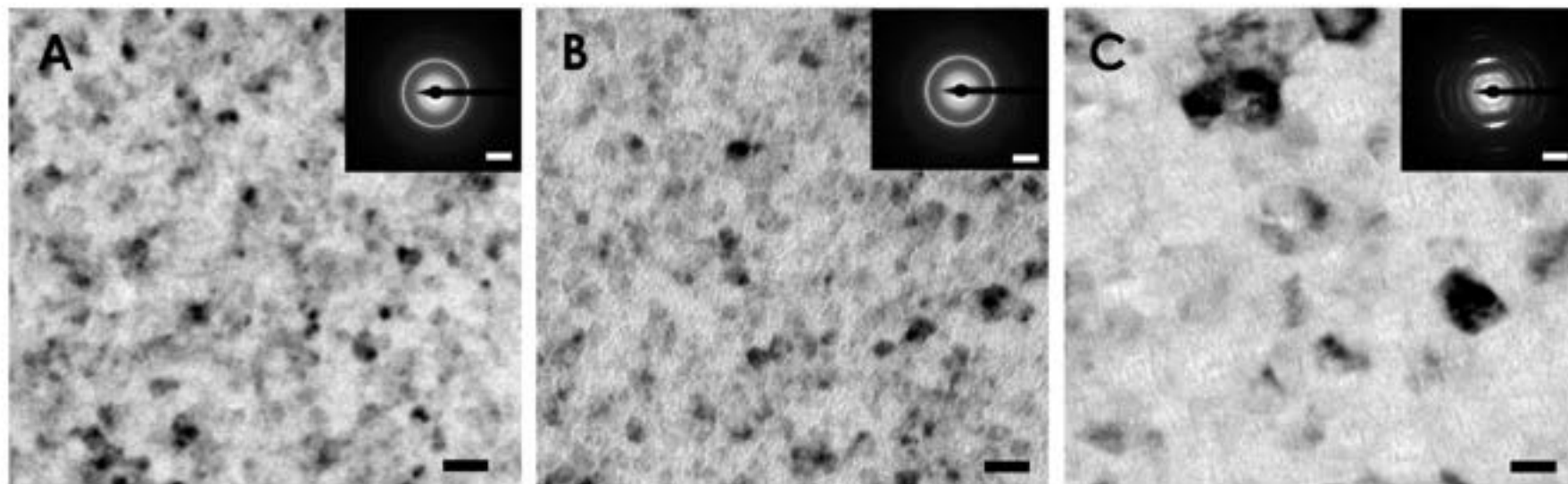
Radiation damage in bi-phase Al_2O_3 coatings

HAADF-STEM + EDS mapping



Implantation of ions beyond the coating – agreement with SRIM

Thermal stability



0 dpa

Microscratch tests

- Conical tip ($r = 200 \mu\text{m}$)
- Scratch length 10 mm
- Maximum load 30 N
- 10 mm/min

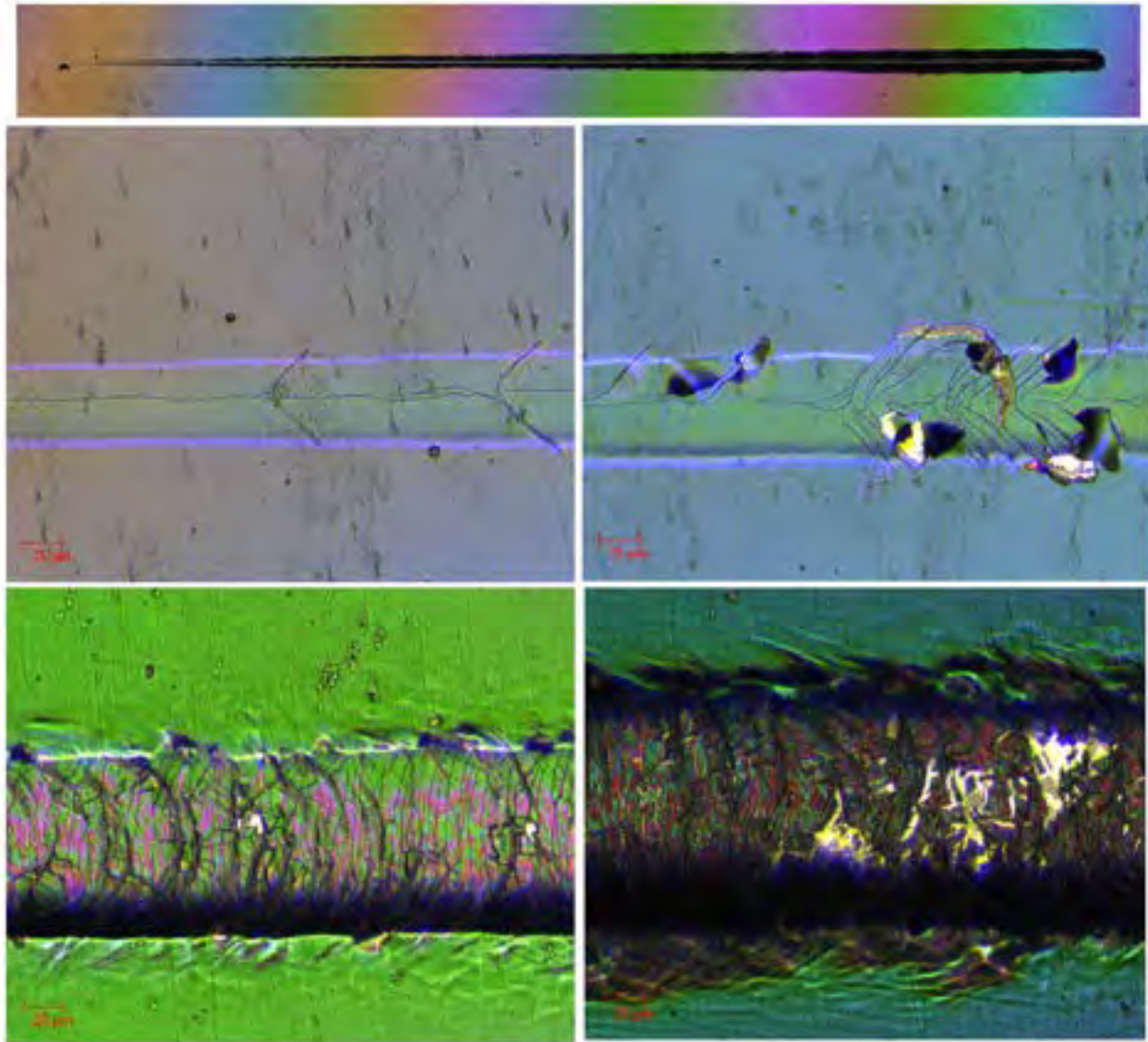
Critical loads:

- **LC1:** cracking without exposure of substrate
- **LC2:** cracking with exposure of substrate at the borders
- **LC3:** cracking with exposure of the substrate within the track

LC1 = $3,2 \pm 0,3 \text{ N}$

LC2 = $4,2 \pm 0,4 \text{ N}$

LC3 = $25,6 \pm 2,9 \text{ N}$



Adhesive strength

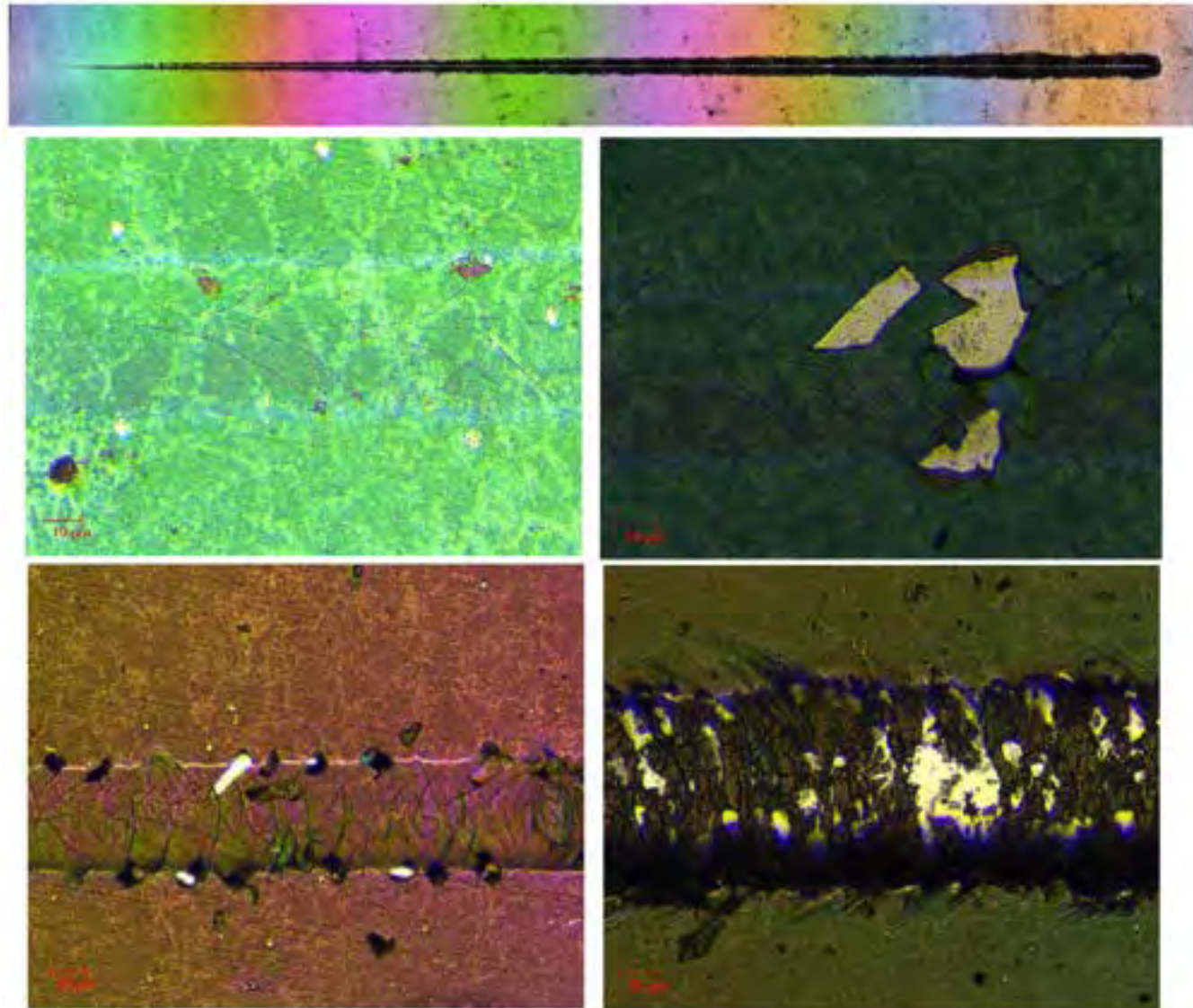
150 dpa

0 dpa

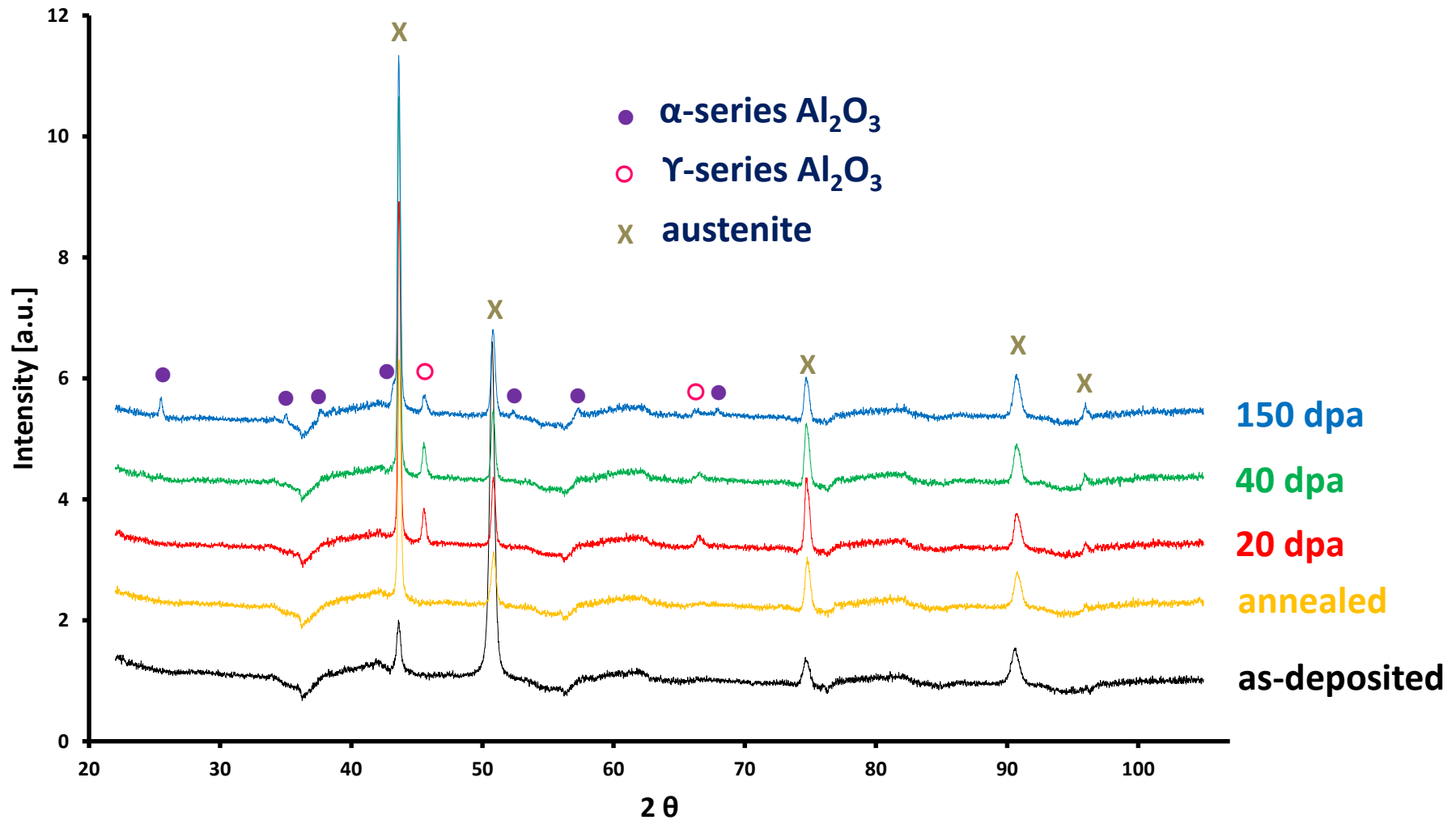
LC1 = $3,2 \pm 0,3$ N
LC2 = $4,2 \pm 0,4$ N
LC3 = $25,6 \pm 2,9$ N

150 dpa

LC1 = $1,65 \pm 0,2$ N
LC2 = $2,41 \pm 0,2$ N
LC3 = $28,87 \pm 5$ N



Radiation damage in bi-phase Al_2O_3 coatings



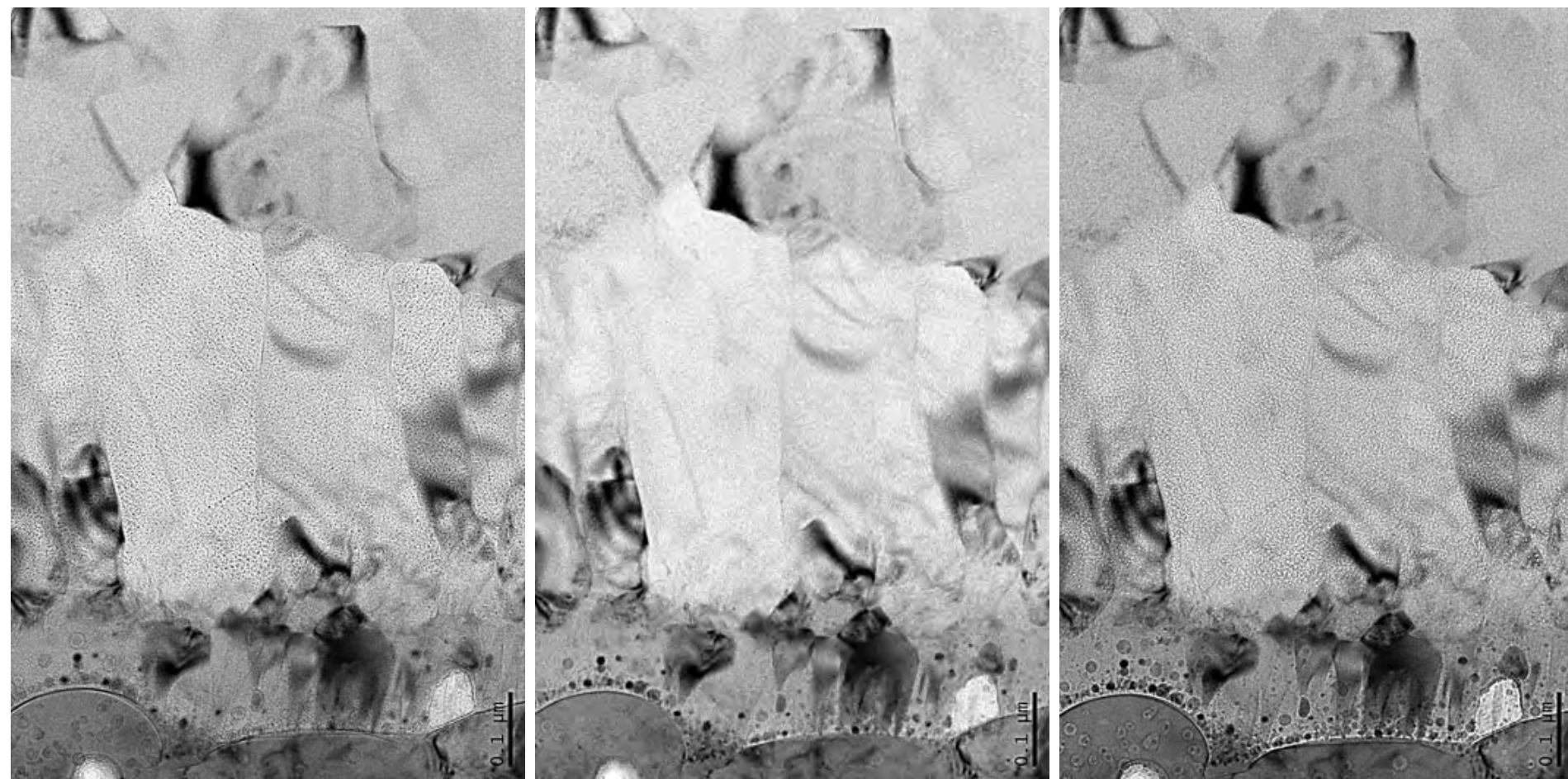
Post-irradiation XRD spectra compatible with γ - and α - Al_2O_3

Radiation damage in bi-phase Al_2O_3 coatings

BF-TEM @ 150 dpa
focus

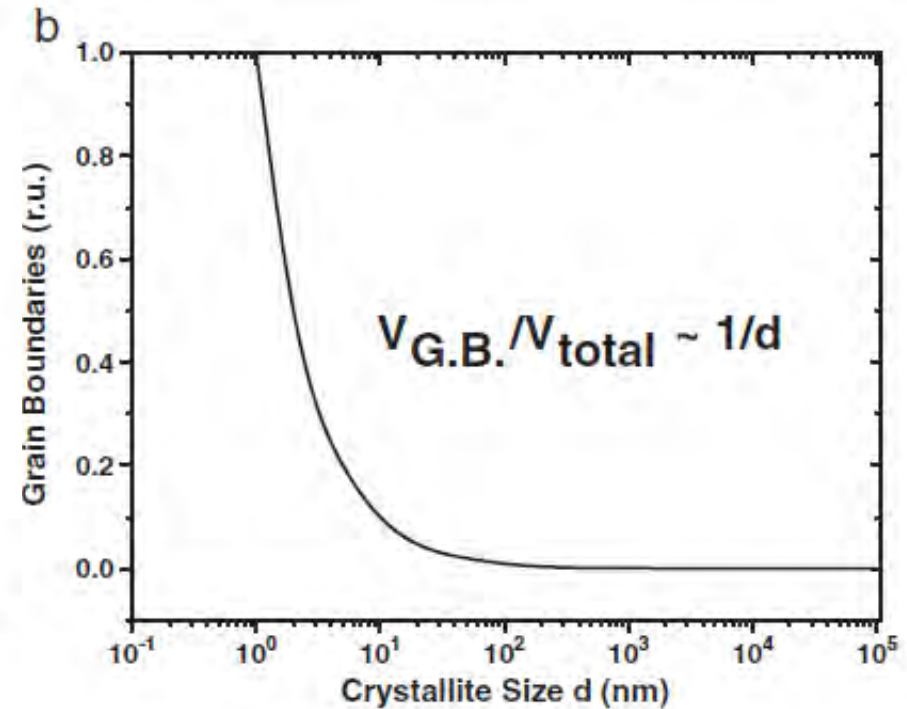
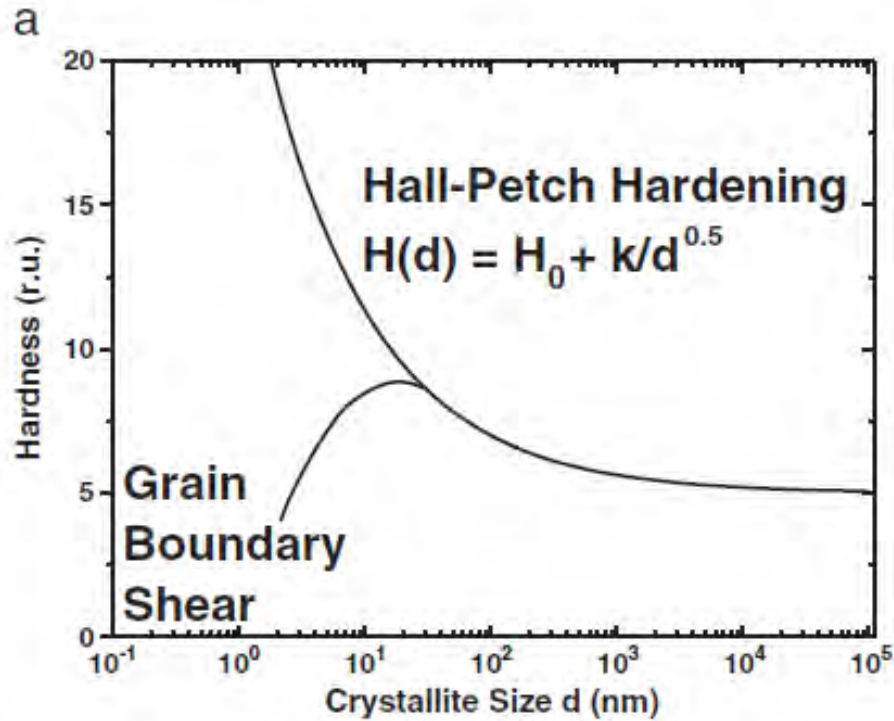
under-focus

over-focus



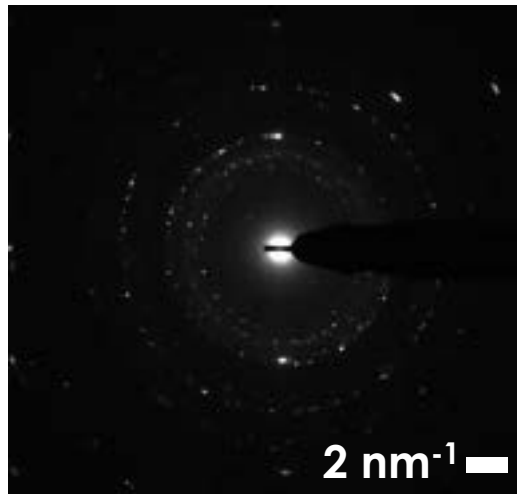
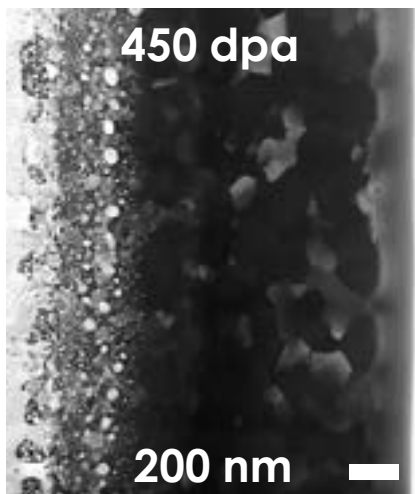
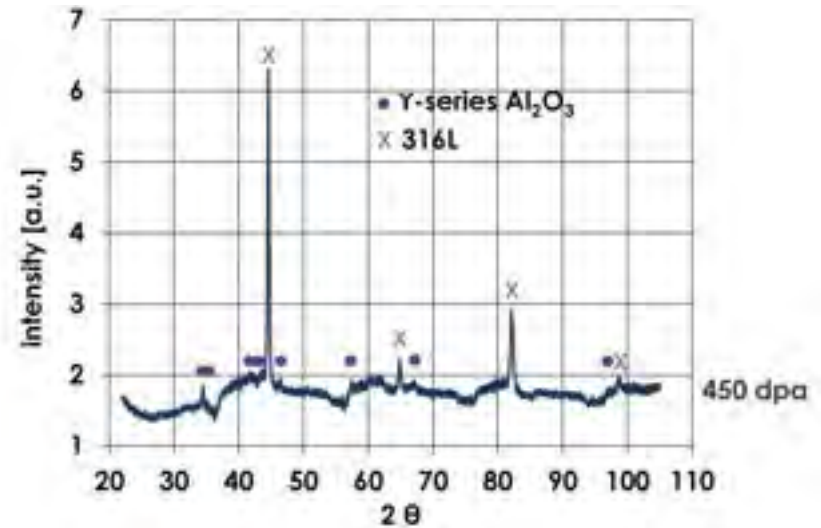
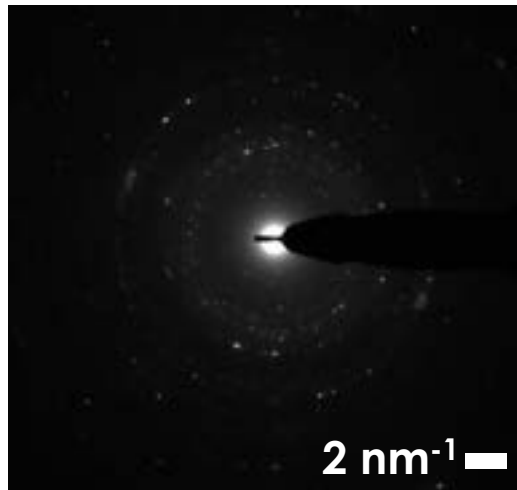
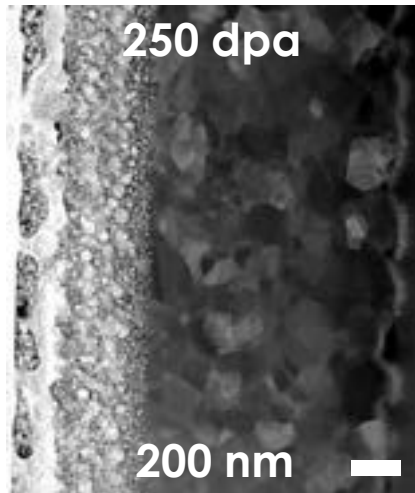
Large number of small voids, only in the inner grains

Hall-Petch hardening



Heavy ion irradiation (Ni)

STEM + DP_s @ 450 dpa



Indexing of DP_s and XRD spectra reveal tetragonal δ -Al₂O₃ (Y series)



MA.S.T. Lab - MAterial Science and Technology Laboratory
University of Rome "Tor Vergata"



Workshop Finale PT 2012-2014

LFR-GEN IV

STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO

ADP MiSE-ENEA-Progetto B3.1-LP2

CR ENEA Brasimone, 19-20 Novembre 2015

***“Report sulla caratterizzazione di materiali strutturali ricoperti
per applicazioni nucleari”***

F. Nanni, F.R. Lamastra, M. Bragaglia, G. Forasassi





Attività sperimentale UTV

•Rivestimenti di allumina *via* deposizione mediante ablazione laser (PLD):

- su substrati in acciaio 316, 316L e 15-15 Ti (lamine e tubi);
- con e senza *buffer layer* (FeCrAlY, FeCrSi);
- as-deposited*;
- sottoposti a ciclaggi termici;
- sottoposti a irraggiamento con ioni pesanti.

•Produzione provini: IIT Milano

•Caratterizzazioni: UTV

•Rivestimenti multistrato *via* tecniche di deposizione fisica da fase vapore (PVD):

Al_2O_3 (RF sputtering)/FeCrAl (arc-PVD)

- su lamine in acciaio 316;
- as-deposited*;
- sottoposti a irraggiamento con ioni pesanti.

•Diffusion Coating *via* Pack Cementation:

- su lamine in acciaio 15-15 Ti e T91;

•Rivestimenti di FeCrAlY *via* termospruzzatura HVOF (High Velocity Oxy Fuel):

- su lamine in acciaio T91;
- as-deposited* e sottoposti a ciclaggi termici.

•Produzione provini: CSM Castel Romano

•Caratterizzazioni: UTV

Caratterizzazioni Microstrutturali



MO



SEM/EDS



XRD

Caratterizzazioni Meccaniche



Prova di microdurezza
UNI EN ISO 6507-1:2005



Prova di nanoindentazione
UNI EN 14577/1-2



Prova di flessione a tre punti
ASTM-C1161

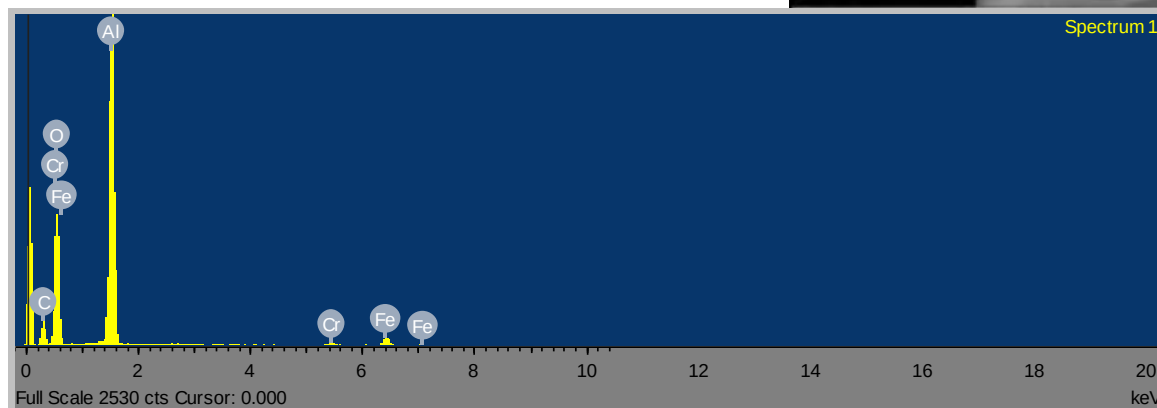
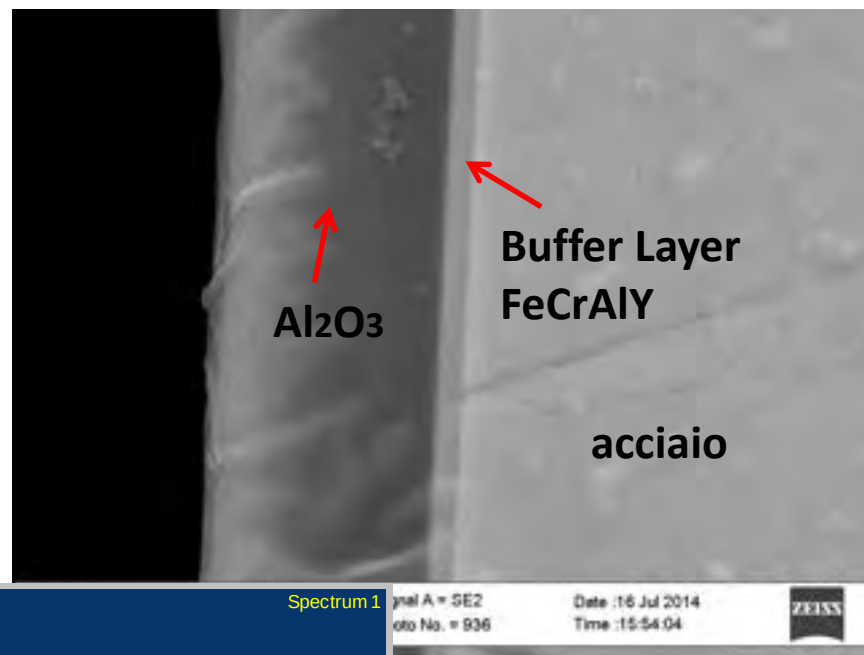
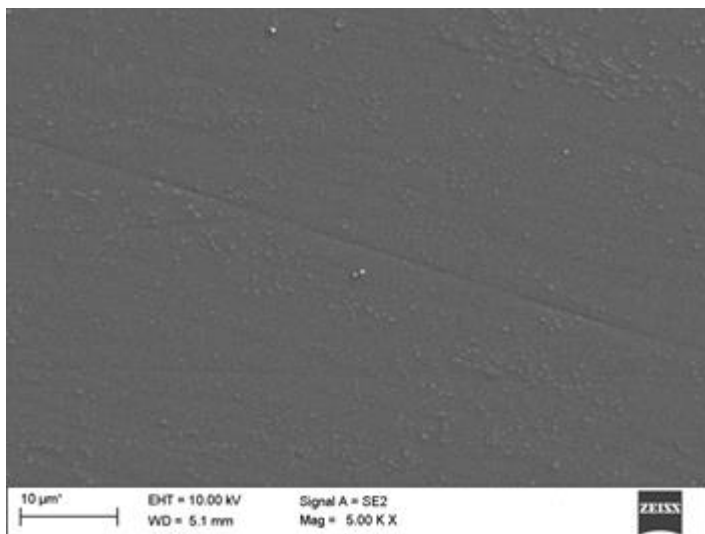


Scratch test
UNI EN 1071-3:2005

Rivestimenti PLD di Al_2O_3 : Microstruttura



5 μm Al_2O_3 /500 nm FeCrAlY/lamina 316
as-deposited



nti:
ei;
;
re uniforme;
i al substrato.

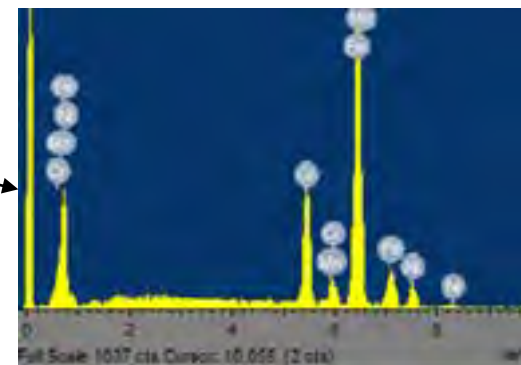
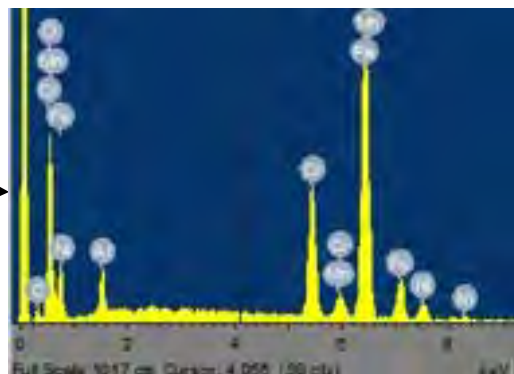
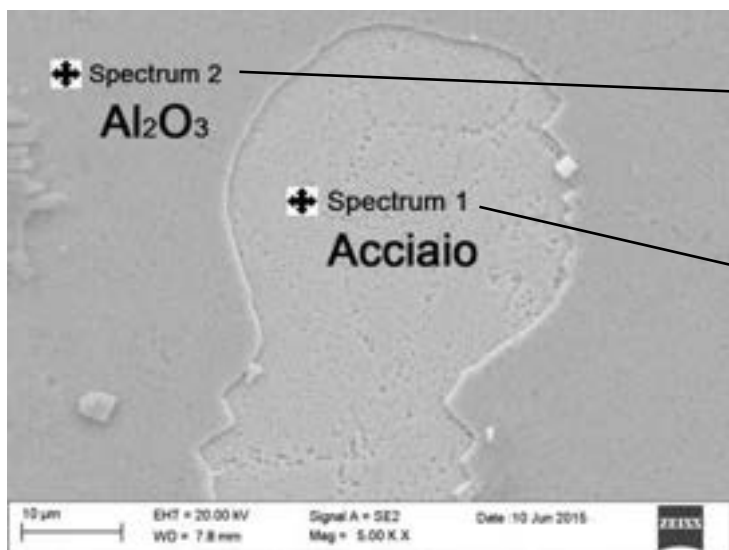
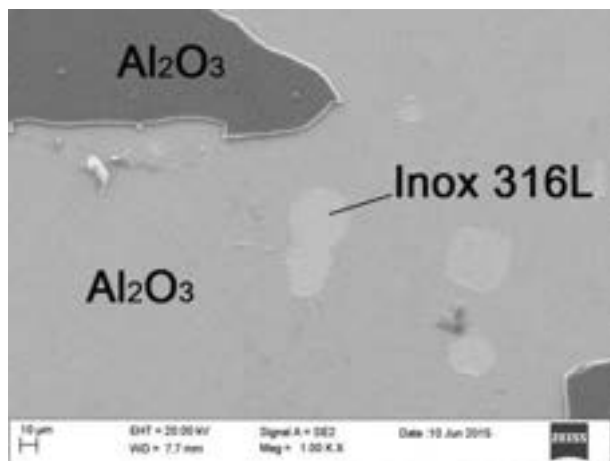
Rivestimenti PLD di Al_2O_3 : Microstruttura post-irraggiamento



5 μm Al_2O_3 /500 nm FeCrAlY/lamina 316 post-irraggiamento (110 MeV Ni^{2+} -16 dpa-RT)

A seguito dell'irraggiamento:

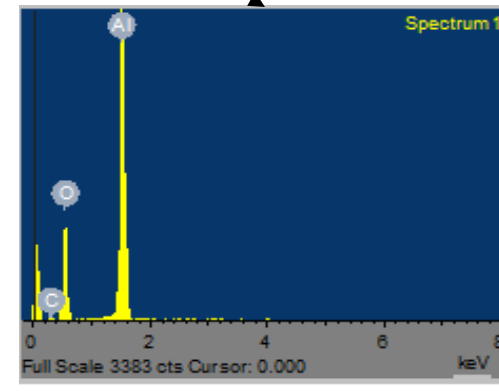
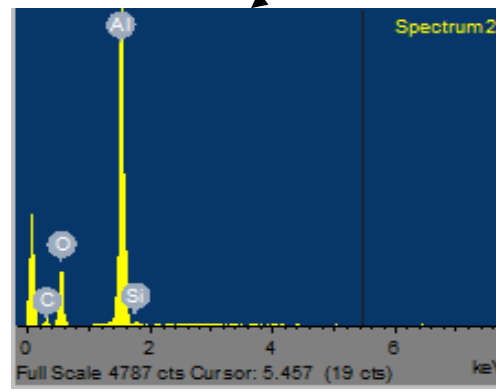
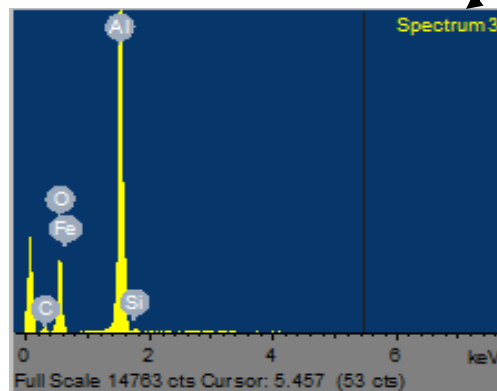
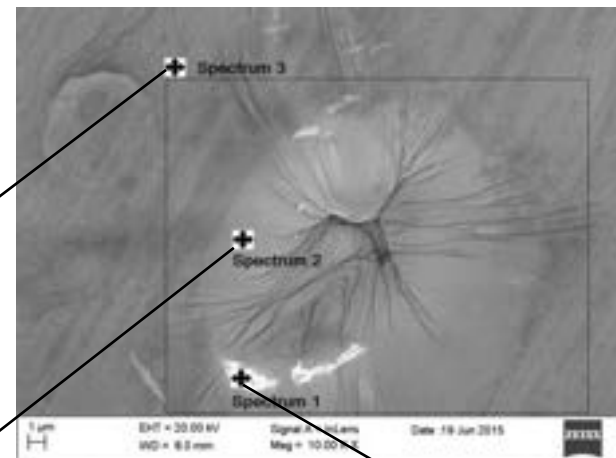
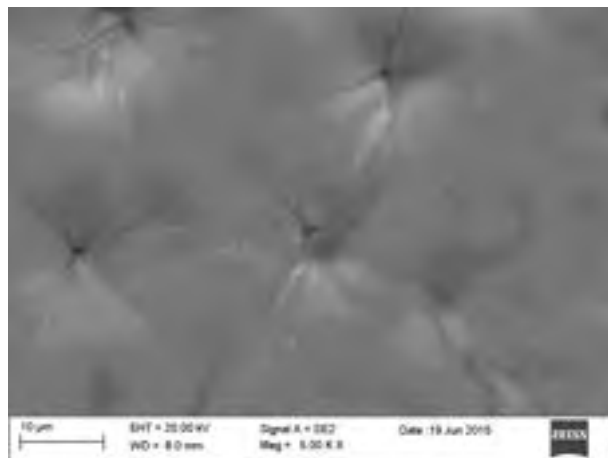
- Delaminazione del rivestimento con esposizione del substrato in zone micrometriche;
- Delaminazione degli strati più superficiali del rivestimento in estese regioni senza esposizione del substrato.



Rivestimenti PLD di Al_2O_3 : Microstruttura post-irraggiamento



5 μm Al_2O_3 /500 nm FeCrAlY/lamina 316 post-irraggiamento (110 MeV Ni^{2+} -16 dpa-550 °C)

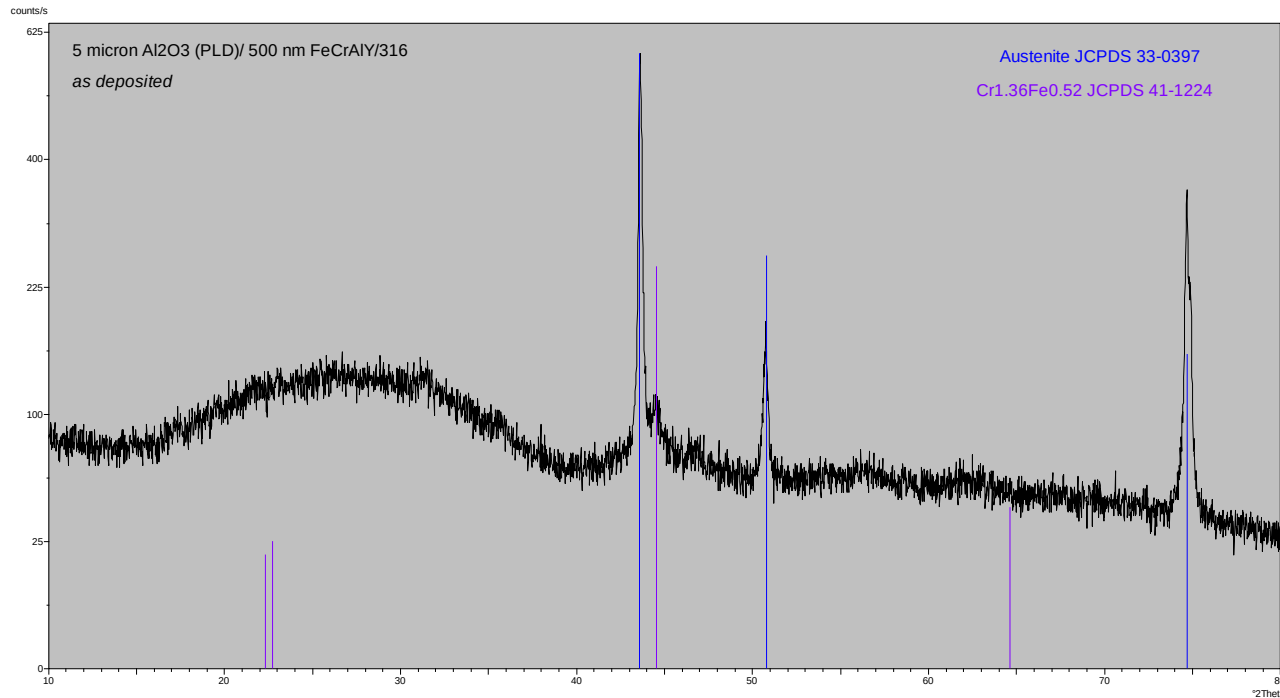


- Modifiche morfologiche del rivestimento nelle zone di impatto degli ioni;
- Assenza di delaminazione.

Rivestimenti PLD di Al_2O_3 : Analisi delle fasi cristalline



5 μm Al_2O_3 /500 nm FeCrAlY/lamina 316 *as-deposited*

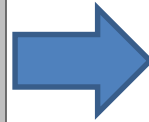
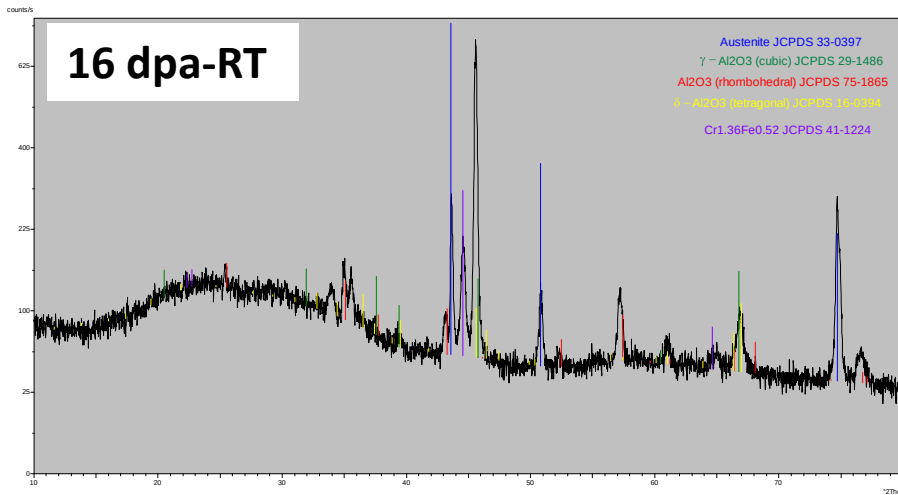


Rivestimento di allumina amorfo nel campione *as deposited*

Rivestimenti PLD di Al_2O_3 post-irraggiamento: Analisi delle fasi cristalline



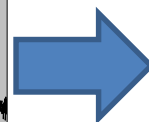
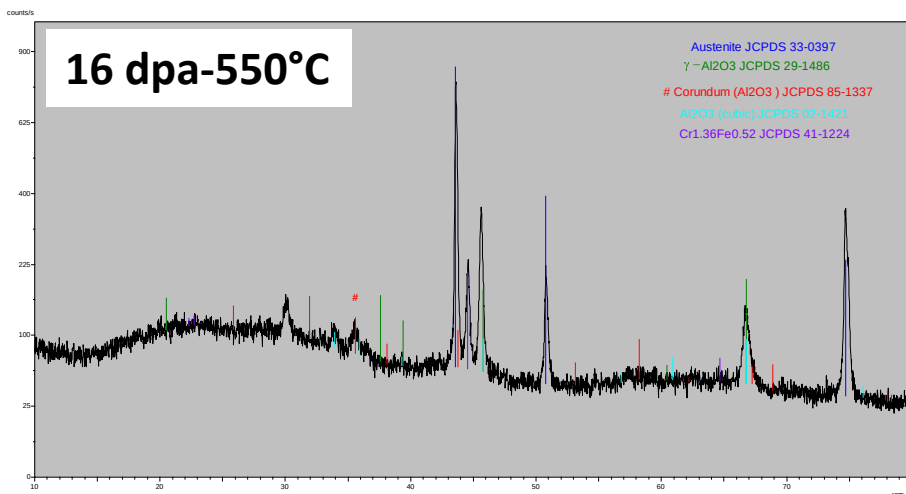
5 μm Al_2O_3 /500 nm FeCrAlY/lamina 316 post-irraggiamento (110 MeV Ni^{2+} -16 dpa-RT e 550 °C)



Fasi cristalline di allumina:

Al_2O_3 (romboedrica), $\gamma\text{-Al}_2\text{O}_3$ (cubica),
 $\delta\text{-Al}_2\text{O}_3$ (tetragonale)

- Formazione di fasi cristalline di Al_2O_3 a seguito dell'irraggiamento ionico;
- Influenza della temperatura sulle fasi cristalline.



Fasi cristalline di allumina:

Corindone (romboedrica), $\gamma\text{-Al}_2\text{O}_3$ (cubica), Al_2O_3 (cubica)

Rivestimenti PLD di Al_2O_3 : Influenza dell'irraggiamento sulla durezza



Prove di nanoindentazione (UNI EN 14577/1-2) su:

1.3 μm Al_2O_3 /200 nm FeCrAlY/ lamina 15-15 Ti:

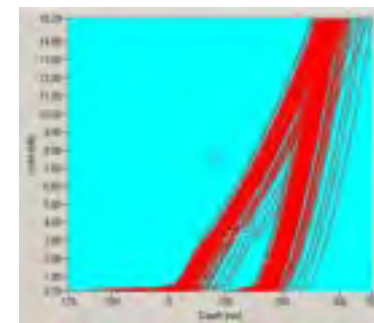
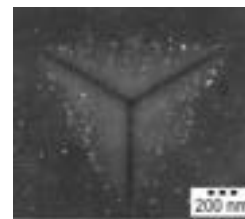
-as deposited

-post-irraggiamento (12 MeV Au^{5+} + 18 MeV W^{7+} -150 dpa- 600°C)

Parametri di prova:

-100 nanoindentazioni per provino

- P = 15 mN



indentatore piramidale Berkovich

Campione	H (Al_2O_3) GPa	E (Al_2O_3) GPa
As-deposited	12.2±1.6	165
Irraggiato 150 dpa	12.7±3	152

L'irraggiamento non influenza in modo significativo durezza e modulo elastico del rivestimento di Al_2O_3

Rivestimenti PLD di Al_2O_3 : Influenza dell'irraggiamento sull'adesione

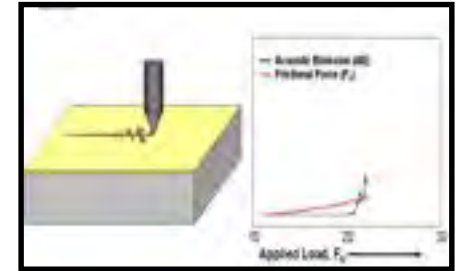


Scratch test (UNI EN 1071-3:2005) su:

1.3 μm Al_2O_3 /200 nm FeCrAlY/ lamina 15-15 Ti:

-as deposited;

-post-irraggiamento (12 MeV Au^{5+} + 18 MeV W^{7+} -150 dpa- 600°C).



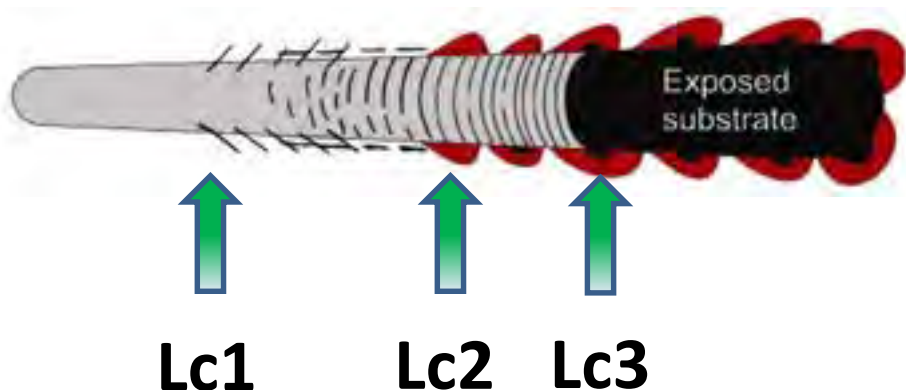
Parametri di prova:

-indentatore con profilo “Rockwell C” di diamante con raggio pari a 200 μm ;

-lunghezza traccia 10 mm;

-carico progressivo da 0.03 N iniziali fino a 30 N finali;

-velocità relativa tra punta e provino 10 mm/min.

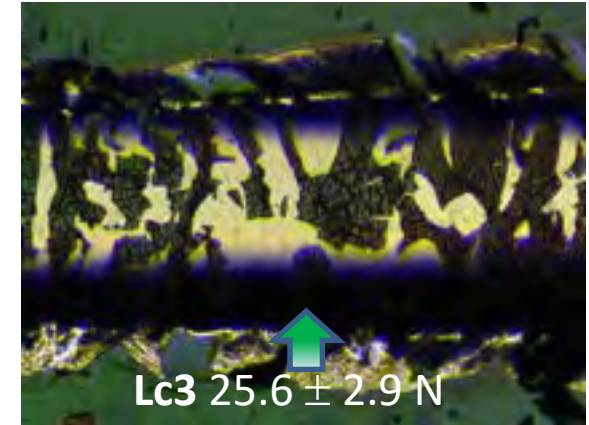
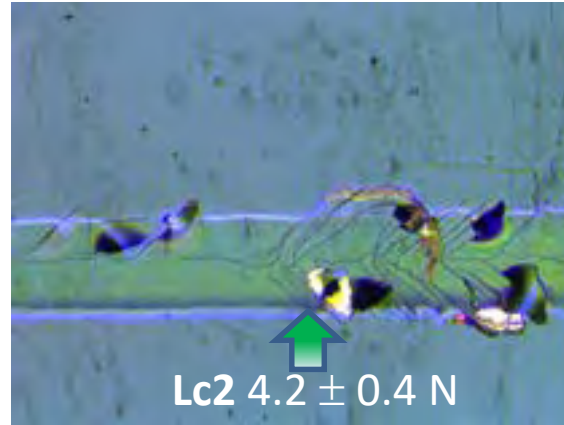
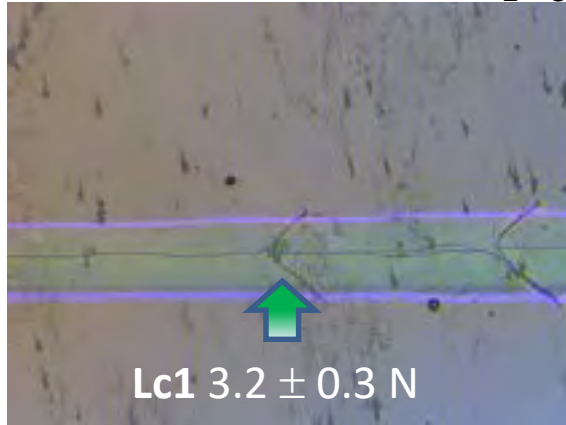


I carichi critici (L_c) dipendono dai parametri di prova e non vanno considerati in modo assoluto ma come valori comparativi dei diversi provini.

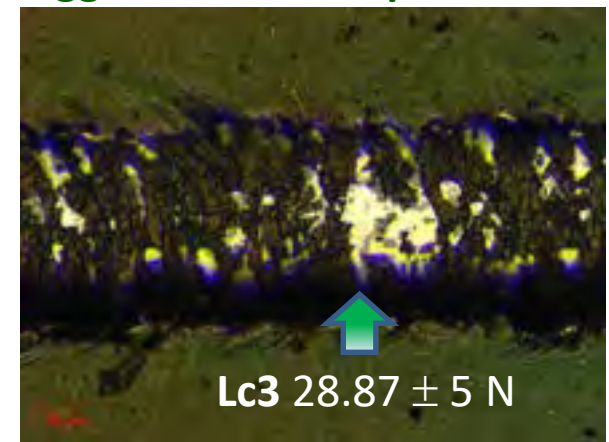
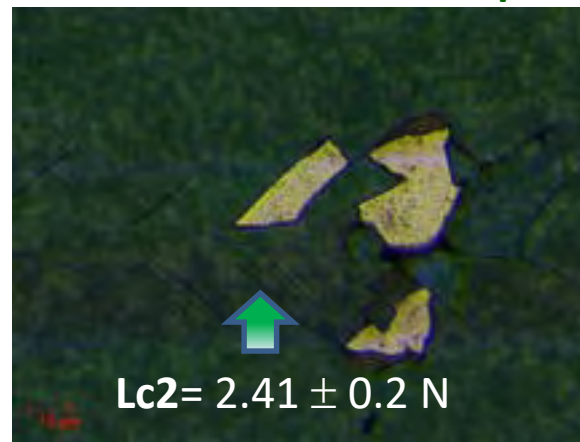
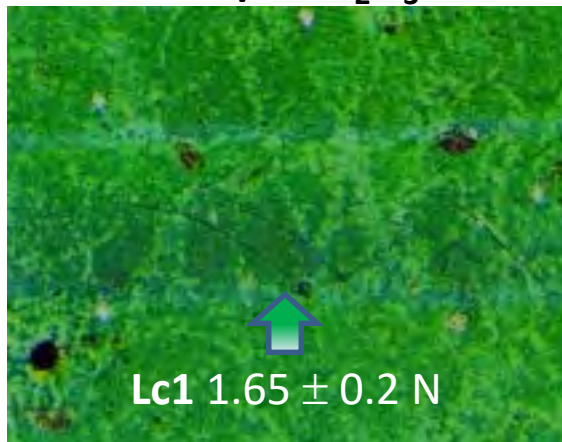
Rivestimenti PLD di Al_2O_3 : Influenza dell'irraggiamento sull'adesione



1.3 μm Al_2O_3 /200 nm FeCrAlY/ lamina 15-15 Ti *as-deposited*



1.3 μm Al_2O_3 /200 nm FeCrAlY/ lamina 15-15 Ti *post-irraggiamento 150 dpa*

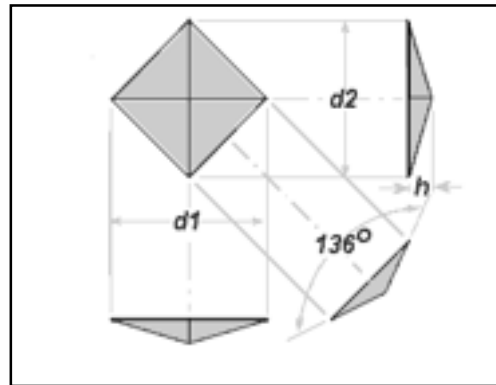
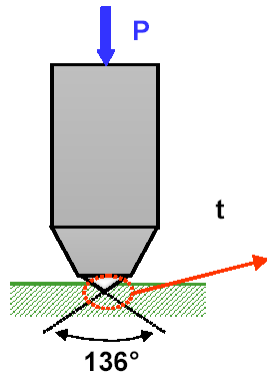


L'irraggiamento peggiora leggermente l'adesione del film di Al_2O_3

Rivestimenti PLD di Al_2O_3 su tubi: Microdurezza



Prove di microdurezza (UNI EN ISO 6507-1:2005)



$$HV = \frac{P}{S} = 0.102 \frac{P \cdot \sin\left(\frac{136^\circ}{2}\right)}{d^2}$$

Condizioni di prova:

- Indentatore Vickers
- Carichi: 2000 - 50 g
- Tempo: 30 s

Su tubi 316L rivestiti in Al_2O_3 :

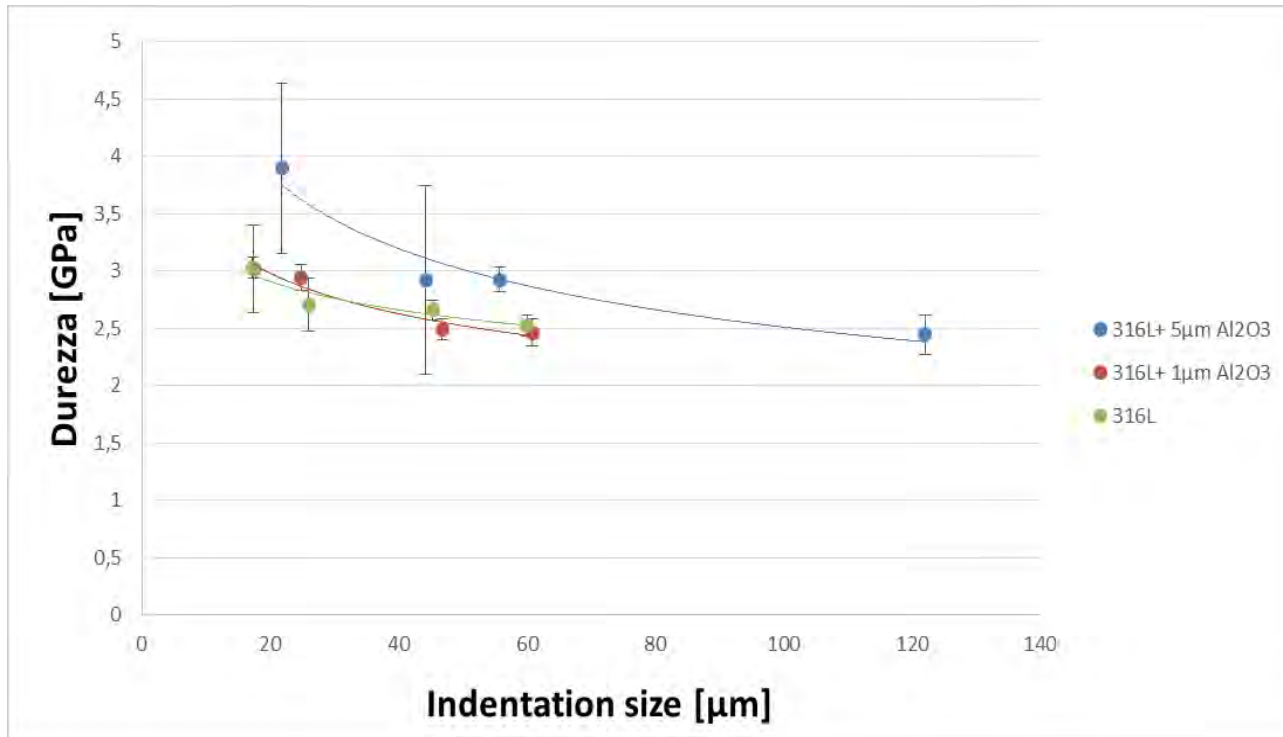
- spessori del film di Al_2O_3 1 e 5 μm ;
- con o senza buffer layer in FeCrSi;
- *as deposited*
- dopo ciclaggio termico in Ar (11 cicli tra 300 e 600°C)

Influenza dello spessore del film di Al_2O_3 , del *buffer layer* e del ciclaggio termico sulla durezza dei tubi rivestiti

Rivestimenti PLD di Al_2O_3 su tubi: Influenza dello spessore sulla microdurezza



Rivestimenti su tubi in acciaio 316L



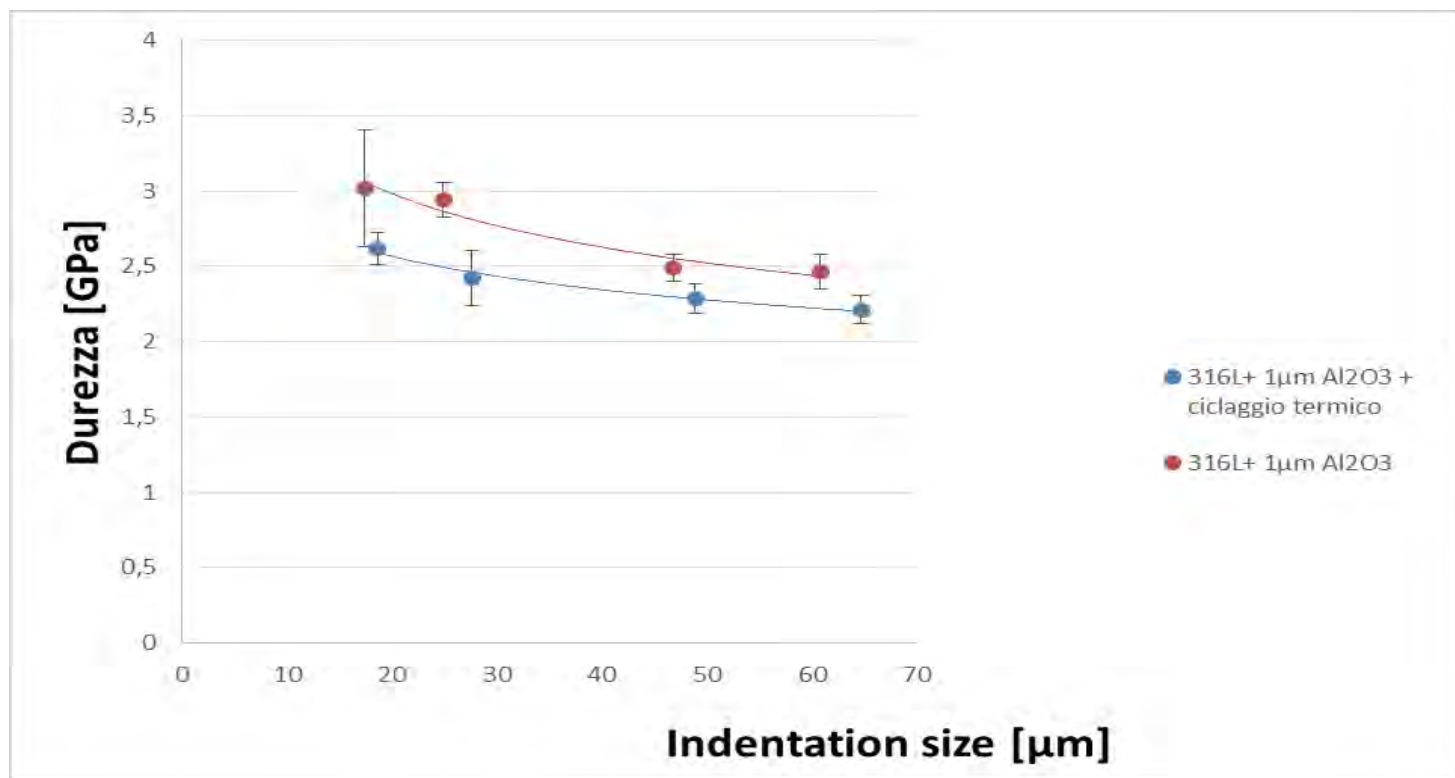
- Campione 5 μm Al_2O_3 /316L valori di microdurezza maggiori dell'acciaio 316L;
- Campione 1 μm Al_2O_3 /316L valori di microdurezza confrontabili con quelli dell'acciaio 316L.

Aumentando lo spessore del rivestimento di Al_2O_3 aumenta la microdurezza dei campioni

Rivestimenti PLD di Al_2O_3 su tubi: Influenza del ciclaggio termico sulla microdurezza



Rivestimenti su tubi in acciaio 316L



Dopo ciclaggio termico la microdurezza diminuisce di $\approx 0,3$ GPa

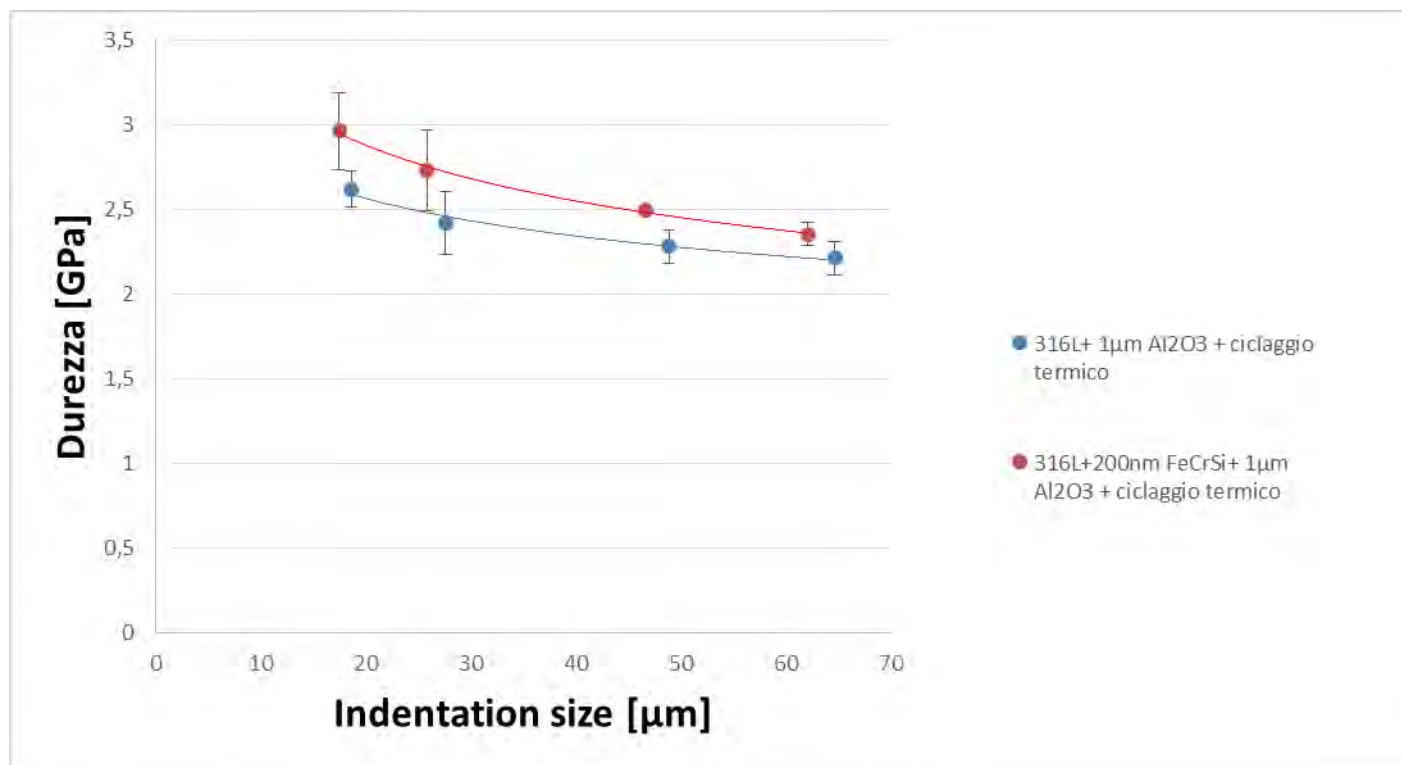


Fenomeni di distensione del substrato

Rivestimenti PLD di Al_2O_3 su tubi: Influenza del buffer layer sulla microdurezza



Rivestimenti su tubi in acciaio 316L



La presenza del *buffer layer* in FeCrSi aumenta la microdurezza dei campioni

Rivestimenti PLD di Al_2O_3 su tubi: Adesione



Prove di flessione a tre punti (ASTM-C1161)



- Distanza coltelli 30 mm;
- Velocità di applicazione del carico 0,05 mm/min;
- Corsa 2 mm

Su tubi 316L rivestiti in Al_2O_3 :

- spessori del film di Al_2O_3 1 e 5 μm ;
- con o senza buffer layer in FeCrSi;
 - as deposited
- dopo ciclaggio termico in Ar (11 cicli tra 300 e 600°C)



Caratterizzazione al microscopio ottico per osservare eventuale insorgenza di cricche o delaminazioni.

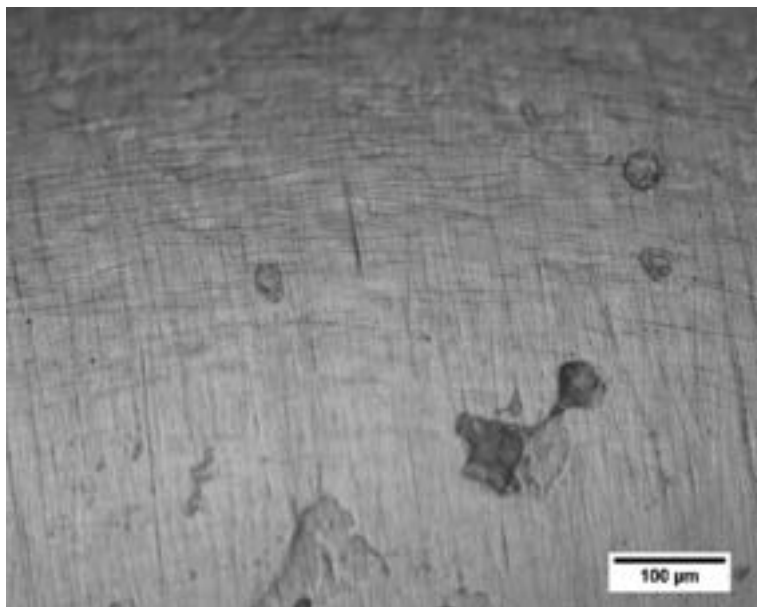


Influenza dello spessore, del *buffer layer* e del ciclaggio termico sull'adesione del rivestimento di Al_2O_3 al substrato

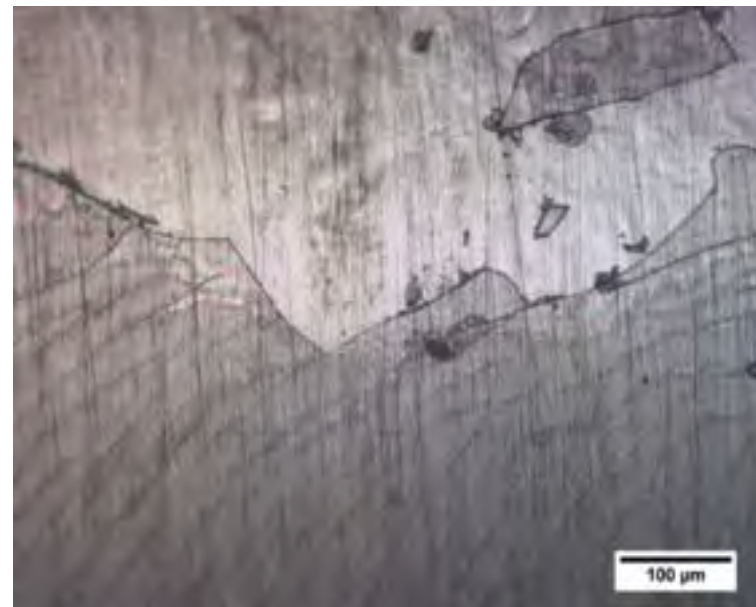
Rivestimenti PLD di Al_2O_3 su tubi: Influenza dello spessore sull'adesione



1 μm Al_2O_3 /tubo 316L



5 μm Al_2O_3 /tubo 316L



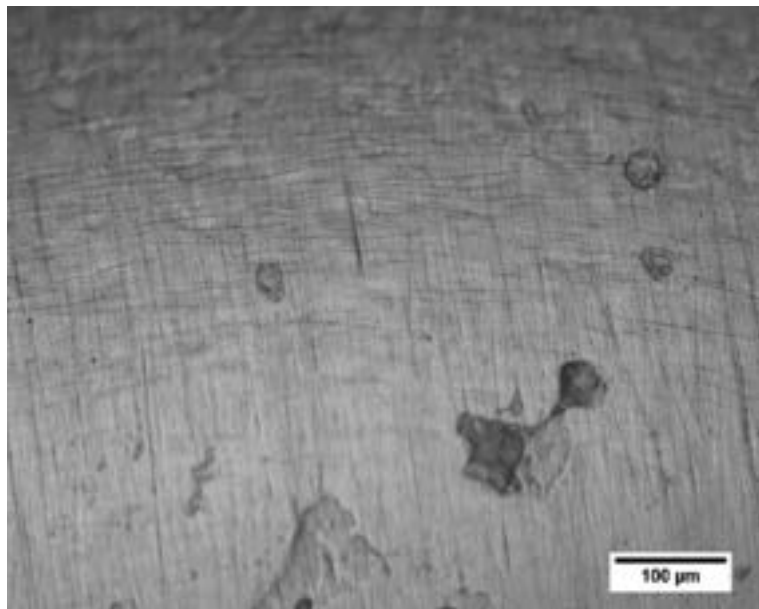
- Cricche presenti in entrambi i provini in direzione parallela all'asse del tubo;
- Il provino con 5 μm Al_2O_3 mostra vaste zone di delaminazione.

Lo spessore del rivestimento influenza l'adesione al substrato

Rivestimenti PLD di Al_2O_3 su tubi: Influenza del ciclaggio termico sull'adesione



1 μm Al_2O_3 /tubo 316L



1 μm Al_2O_3 /tubo 316L
dopo ciclaggio termico



- Cricche presenti in entrambi i provini in direzione parallela all'asse del tubo;
- Zone di delaminazione presenti nel campione ciclato termicamente.

Il ciclaggio termico ha ridotto l'adesione rivestimento-substrato

Rivestimenti PLD di Al_2O_3 su tubi: Influenza del buffer layer sull'adesione



1 μm Al_2O_3 /tubo 316L
dopo ciclaggio termico



1 μm Al_2O_3 /200 nm FeCrSi/tubo 316L
dopo ciclaggio termico



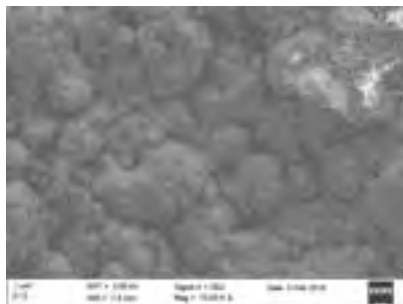
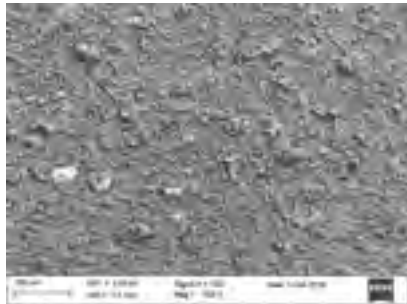
Nel campione con il *buffer layer* il rivestimento risulta in gran parte delaminato

La presenza del buffer layer influenza negativamente l'adesione del rivestimento al substrato

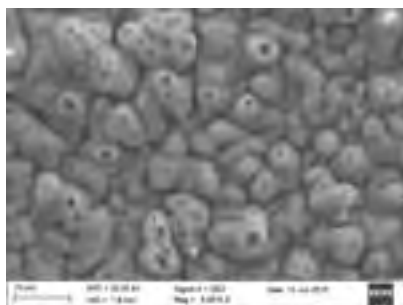
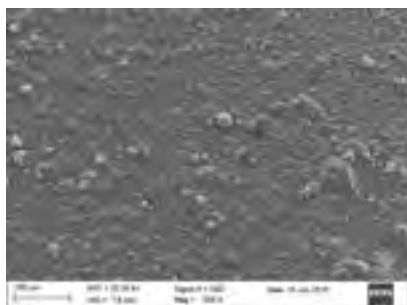
Al_2O_3 (RF sputtering)/FeCrAl (arc-PVD)/316: Microstruttura pre- e post-irraggiamento



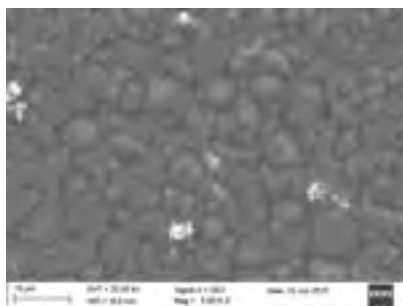
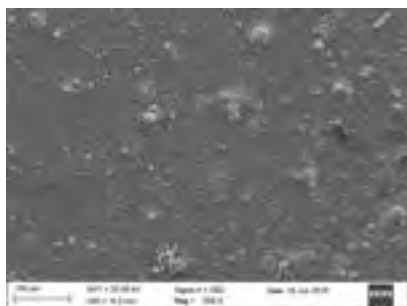
as-deposited



16 dpa-RT



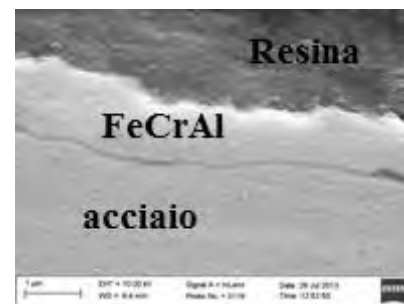
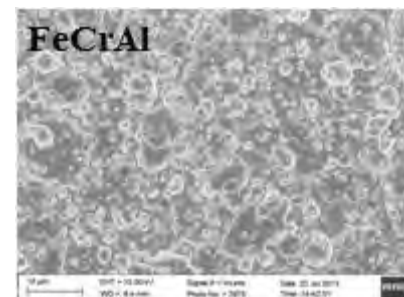
16 dpa-550°C



Irraggiamento:

110 MeV Ni^{2+} -16 dpa-RT e 550 °C

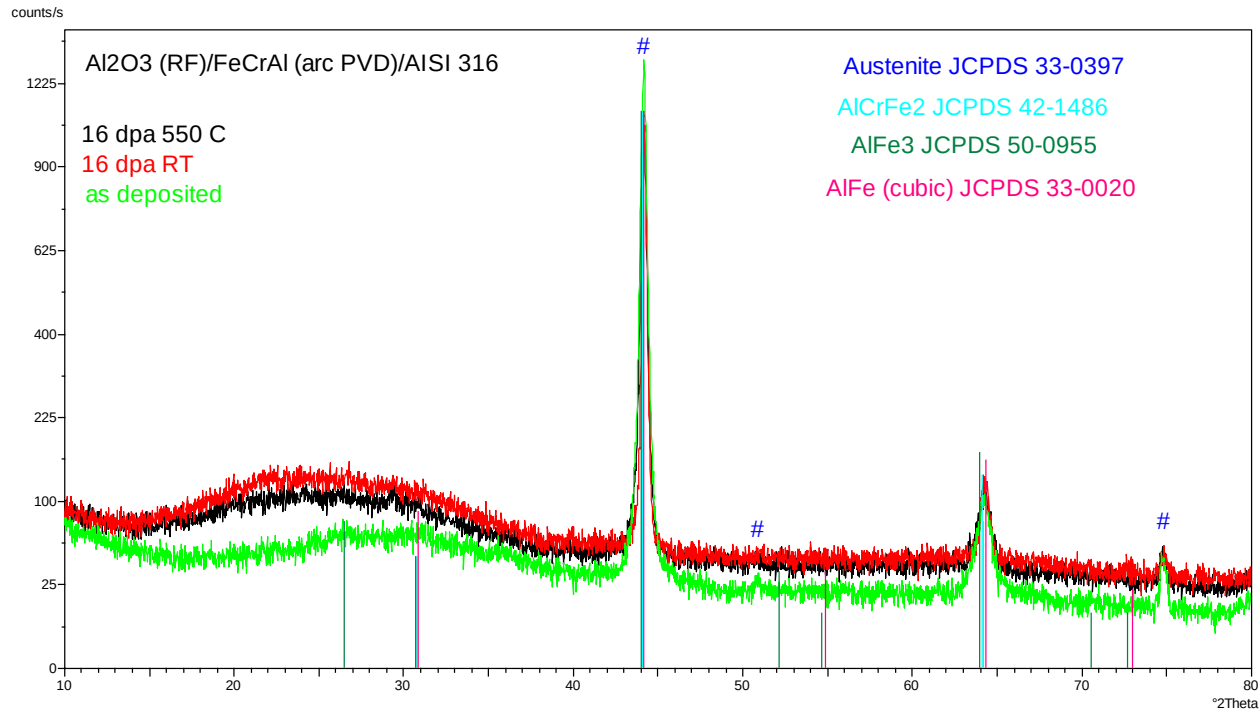
- Microstruttura allumina influenzata dalla rugosità del FeCrAl sottostante;
- L'irraggiamento non modifica in modo significativo la microstruttura superficiale del rivestimento di Al_2O_3 ;
- Assenza di delaminazione.



Al₂O₃ (RF sputtering)/FeCrAl (arc-PVD)/316: Influenza dell'irraggiamento sulle fasi cristalline



Multilayer *as deposited* e post-irraggiamento (110 MeV Ni²⁺-16 dpa-RT e 550 °C)

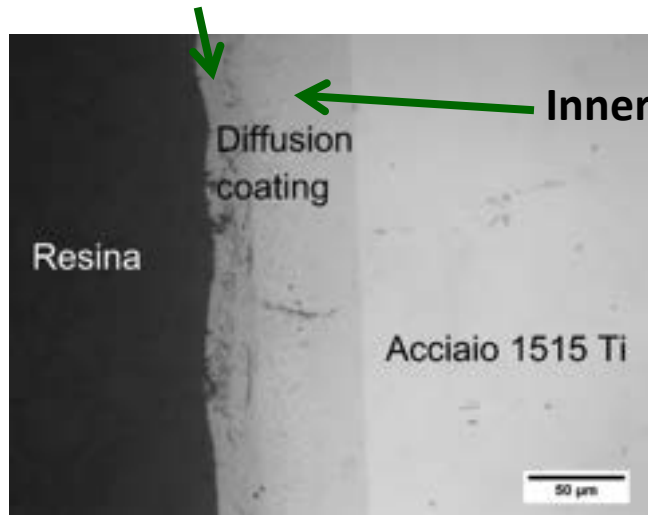


L' irraggiamento non ha influenza sulle fasi presenti:

- l'allumina rimane amorfa;
- non subiscono variazioni le fasi cristalline attribuibili al FeCrAl identificate dalle schede JCPDS relative a AlCrFe₂, AlFe₃, AlFe.

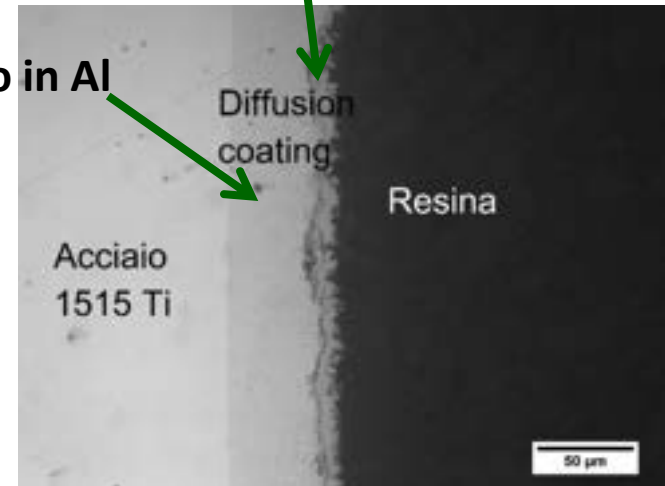
$T_{\text{Pack}} 1070^{\circ}\text{C}$, $t_{\text{Pack}} 45 \text{ min}$

outer layer, più ricco in Al



Inner layer, più povero in Al

outer layer, più ricco in Al



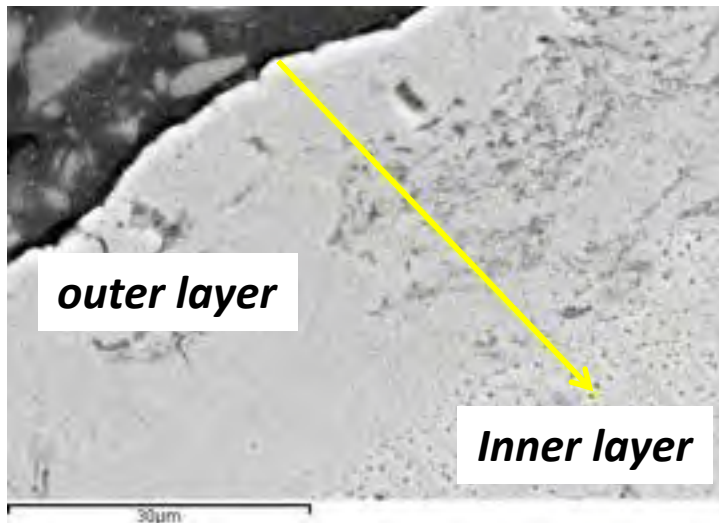
Campione 26/15:

- Alluminizzazione 15-15 Ti con granuli Al/Co;
- Spessore *diffusion coating* 70-80 µm;
- Spessore *outer layer* 20-30 µm.

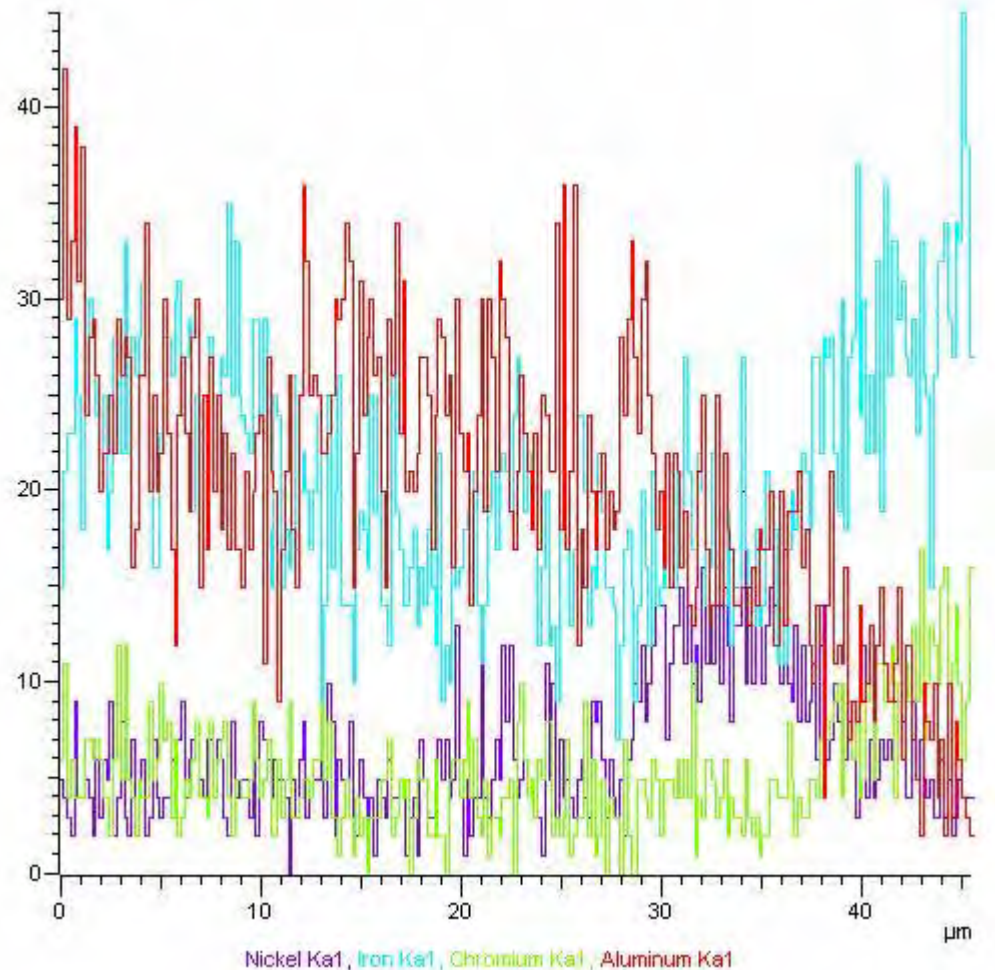
Campione 27/15:

- Alluminizzazione 15-15 Ti con granuli Al/Cr;
- Spessore *diffusion coating* 50-60 µm;
- Spessore *outer layer* 10-20 µm.

Campione 26/15: alluminizzazione 15-15 Ti con granuli Al/Co



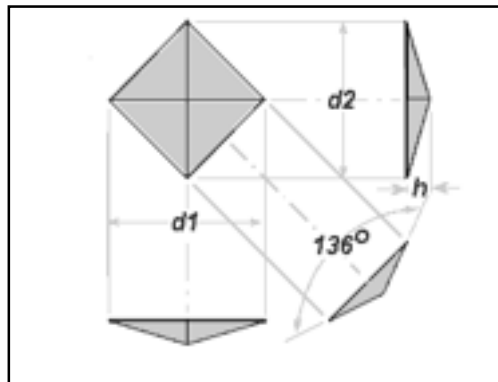
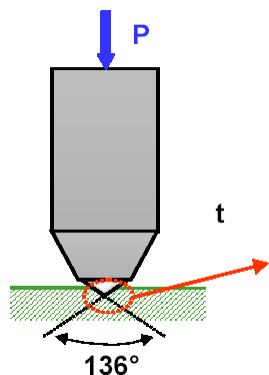
- *Outer layer* arricchito in Al
- *Inner layer* meno arricchito in Al rispetto all'*outer* e arricchito in Ni



Diffusion Coating su 15-15 Ti: Microdurezza



Prove di microdurezza (UNI EN ISO 6507-1:2005) in sezione:

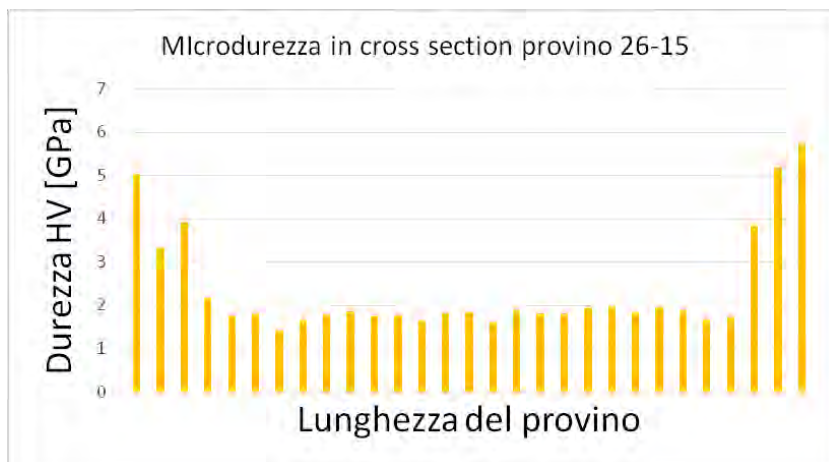


$$HV = \frac{P}{S} = 0.102 \frac{P \cdot \sin\left(\frac{136^\circ}{2}\right)}{d^2}$$

Condizioni di prova:

- Indentatore Vickers
- Carico: 100 g
- Tempo: 30 s

Influenza della differente composizione elementare lungo la sezione sulla durezza



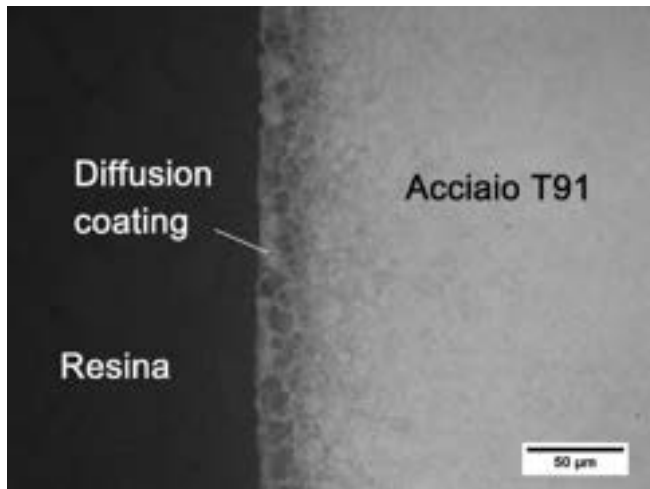
- HV 15-15 Ti pre-trattamento di alluminizzazione 3-3.5 GPa;
- HV *diffusion coating* 3.3-5.7 GPa;
- HV *outer layer* 5-5.7 GPa;
- HV 15-15 Ti post-trattamento di alluminizzazione 1.6-1.9 GPa.

Il trattamento termico impiegato nella *pack cementation* causa una diminuzione della durezza dell'acciaio 15-15 Ti (fenomeni di ricristallizzazione e distensione)

Diffusion Coating su T91: Microstruttura

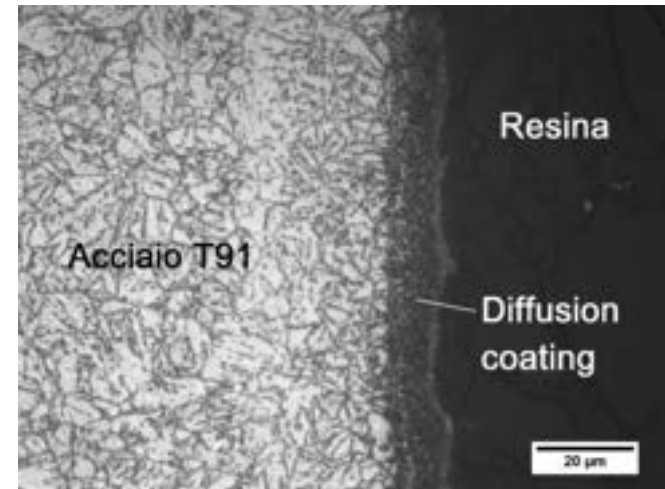


$T_{\text{Pack}} 780^{\circ}\text{C}$, $t_{\text{Pack}} 12 \text{ h}$



Campione 28/15:

- Alluminizzazione T91 con granuli Al/Co;
- Spessore *diffusion coating* 20 μm.



Campione 29/15:

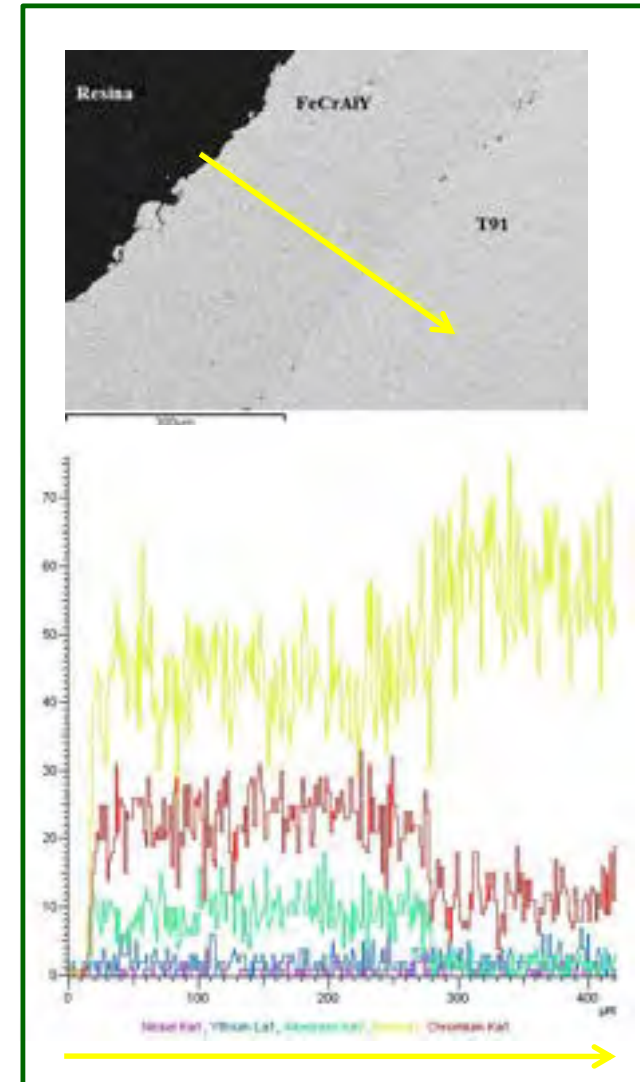
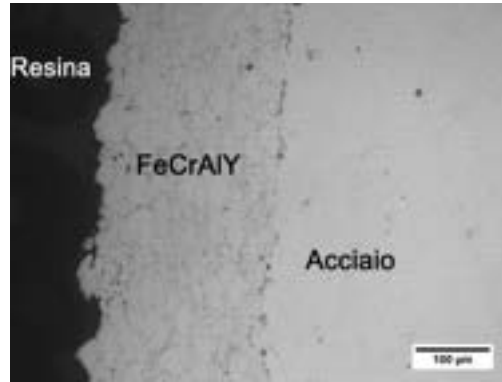
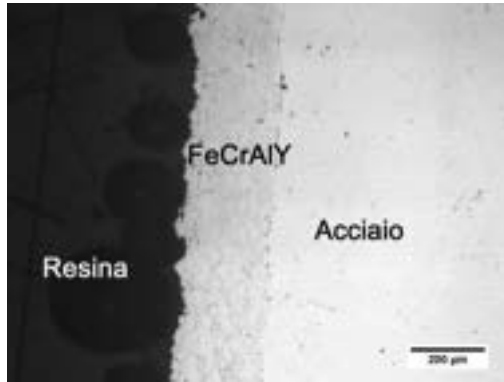
- Alluminizzazione T91 con granuli Al/Cr;
- Spessore *diffusion coating* 10 μm.

- *Diffusion coating* a basso spessore;
- HV T91 (~2 GPa) non è influenzata dal trattamento termico impiegato nella *pack cementation* (T del processo relativamente bassa).

Rivestimenti FeCrAlY (HVOF) su T91: Microstruttura

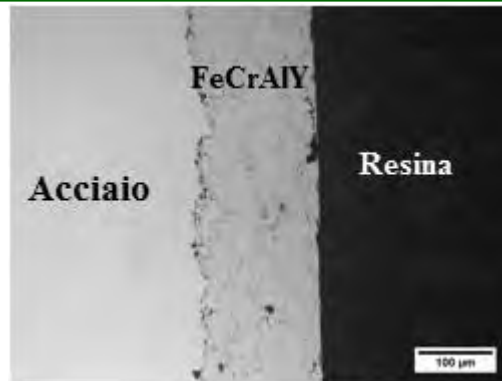


Campione H34/15-1 *as-deposited*



- Rivestimento compatto;
- Spessore 240 µm;
- Zone scure attribuibili probabilmente alla presenza di ossidi;
- Possibilità di ottenere un profilo regolare della superficie superiore a seguito di un processo di rettifica.

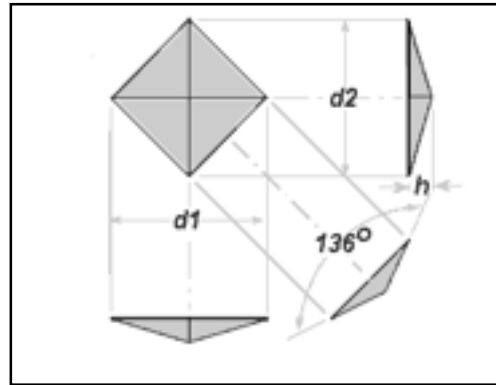
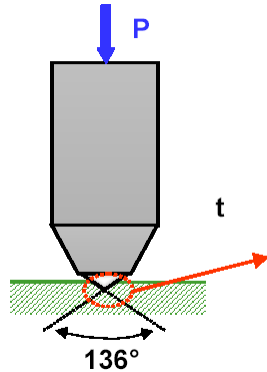
Superficie rivestimento
FeCrAlY rettificata



Rivestimenti FeCrAlY (HVOF) su T91: Microdurezza



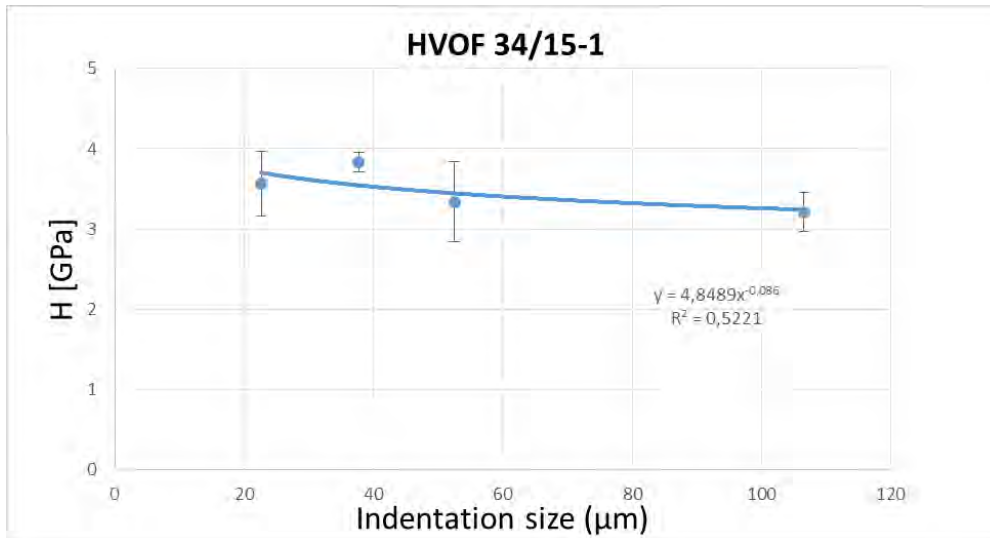
Prove di microdurezza (UNI EN ISO 6507-1:2005) in sezione:



$$HV = \frac{P}{S} = 0.102 \frac{P \cdot \sin\left(\frac{136^\circ}{2}\right)}{d^2}$$

Condizioni di prova:

- Indentatore Vickers
- Carichi: 2000- 100g
- Tempo: 30 s

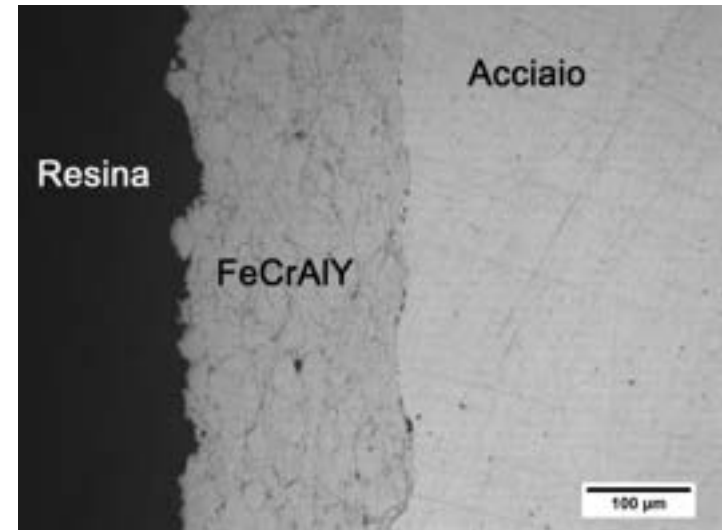
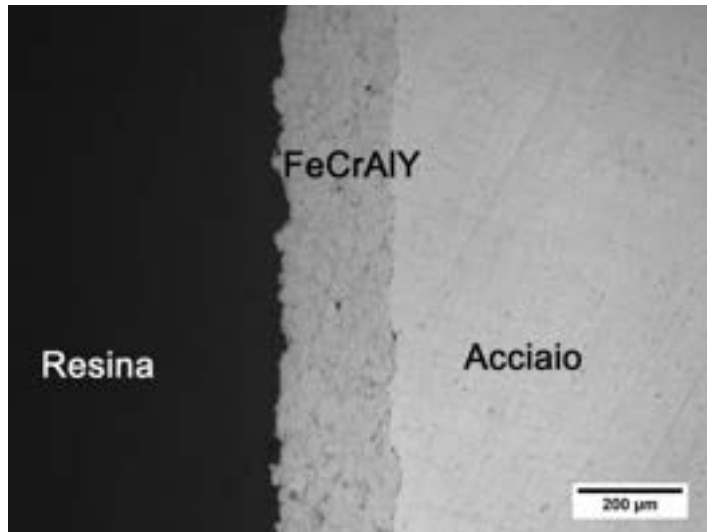


HV: 3.2-3.8 GPa

Rivestimenti FeCrAlY (HVOF) su T91: Microstruttura dopo ciclaggio termico



Campione H34/15-1 dopo ciclaggio termico in aria (25 cicli tra 380 e 630°C)



Assenza di delaminazione dopo ciclaggio termico in aria

Rivestimenti PLD di Al_2O_3 su lamine 316

A seguito dell'irraggiamento:

delaminazione parziale (RT) e modifiche morfologiche (550°C) del rivestimento; formazione di fasi cristalline dell'allumina; durezza e modulo elastico del rivestimento di Al_2O_3 non variano in modo significativo; peggiora leggermente l'adesione del film di Al_2O_3 .

Rivestimenti PLD di Al_2O_3 su tubi 316L:

-la durezza dei tubi rivestiti aumenta con lo spessore di Al_2O_3 e in presenza del *buffer layer* in FeCrSi; la durezza diminuisce dopo ciclaggio termico;
-l'adesione rivestimento-substrato è minore aumentando lo spessore del film di Al_2O_3 ; dopo ciclaggio termico; in presenza del *buffer layer* in FeCrSi.

Multilayer Al_2O_3 (RF sputtering)/FeCrAl (arc-PVD)/316:

l'irraggiamento non modifica in modo significativo la microstruttura superficiale del rivestimento di Al_2O_3 e che non ha influenza sulle fasi presenti nel campione *as-deposited*.

Diffusion Coating su 1515 Ti:

spessori maggiori (70-80 μm) utilizzando granuli Al/Co; HV *diffusion coating* 3.3-5.7 GPa; HV *outer layer* più ricco in Al 5-5.7 GPa; Il trattamento termico impiegato nella *pack cementation* causa una diminuzione della durezza dell'acciaio 15-15 Ti.

Diffusion Coating su T91:

bassi spessori ottenuti (20 μm utilizzando granuli Al/Co, 10 μm utilizzando granuli Al/Cr; HV T91 (~ 2 GPa) non è influenzata dal trattamento termico impiegato nella *pack cementation* (T del processo relativamente bassa).

Rivestimenti FeCrAlY (HVOF) su T91:

compatti; profili regolari della superficie superiore a seguito di un processo di rettifica; HV 3.2-3.8 GPa; Assenza di delaminazione dopo ciclaggio termico in aria.

Alessandro Merli

“Caratterizzazione microstrutturale meccanica e tribologica di rivestimenti PLD in allumina su acciai inox per applicazioni nucleari”

Laurea in Ingegneria Meccanica

Fabrizio Mario Ferrarese

“Caratterizzazione di film ceramic sottili per applicazioni nei reattori nucleari di quarta generazione”

Laurea in Scienza dei Materiali

Mario Bragaglia

“Caratterizzazione di materiali strutturali ricoperti per applicazioni nucleari”

Dottorato di ricerca in Ingegneria Industriale

PROVE DI CORROSIONE IN PIOMBO STAGNANTE E FLUENTE E CONTROLLO DELL'OSSIGENO IN IMPIANTI A PIOMBO

S. Bassini, A. Antonelli, I. Di Piazza, M. Tarantino

**Workshop ADP ENEA-MSE PAR2014-LP2
C.R. ENEA Brasimone, 19-20 Nov. 2015**

MATERIALS BEHAVIOUR IN LEAD

CORROSION OF CONVENTIONAL STEELS

- high capability of liquid Pb to dissolve the chemical elements of steels (**Ni and Cr in particular**);
- dissolved alloy elements contribute to **plugging**.

Surface “ferritization” due to Ni and Cr dissolution in 316L steel exposed to flowing LBE at 400°C with low C_O for 1500 h.

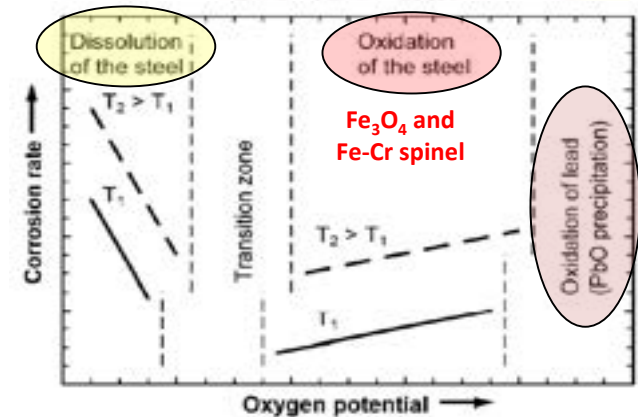
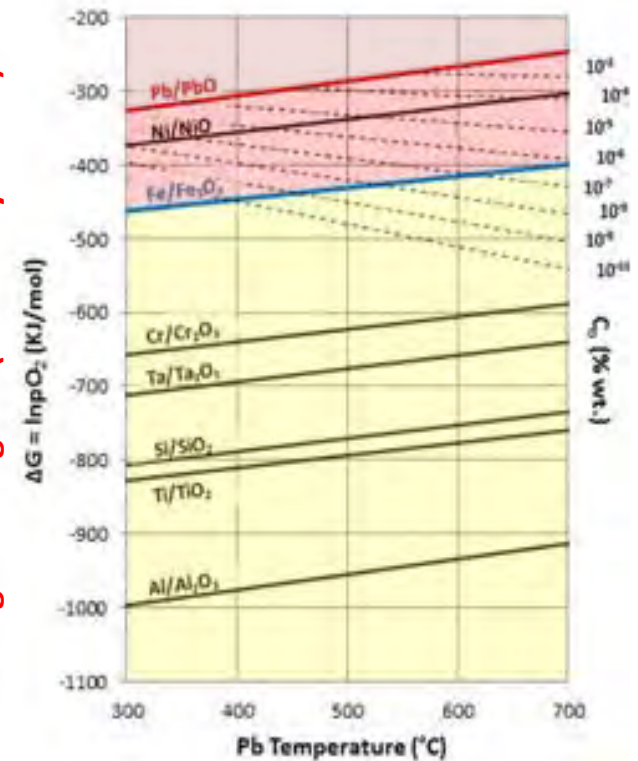


*Benamati, Journal of Nuclear Materials 335 (2004) 169–173.

Strategy against Metal Dissolution:

- **active oxygen** in Pb for steel **passivation (Fe_3O_4 formation)** to minimize degradation of structures exposed to $T < 480^\circ C$
- use of **coatings** above structures exposed to $T > 480^\circ C$ (e.g. **fuel cladding tubes** at $550^\circ C$)

Ellingham Diagram (Thermodynamics)

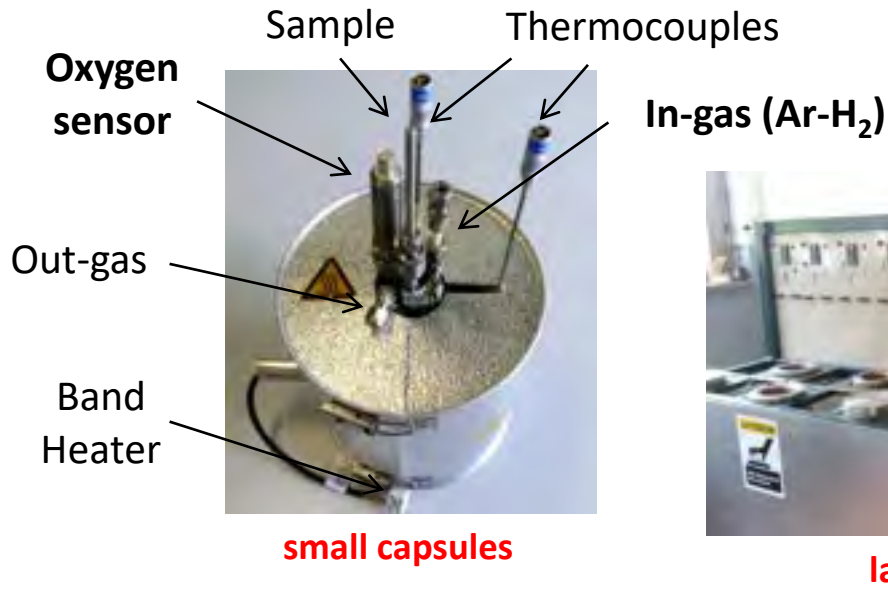


*C. Schroer, Nuclear Engineering and Design, 241 (2011) 4913–4923.

STATIC CORROSION TESTS: EXPERIMENTAL

Experimental Capsules for Corrosion Tests in Pb with low C_O

STUDY AND IMPLEMENTATION OF CAPSULE SETUPS



Different cover gas to obtain different C_O in Pb:

- Argon gas for oxygen saturation level (formation of PbO crust on liquid Pb free surface)
- Ar/H₂ mixture for low oxygen level (C_O monitored with oxygen sensor for HLM)

Muffle furnace for Corrosion Tests in Pb with high C_O (sat. level)

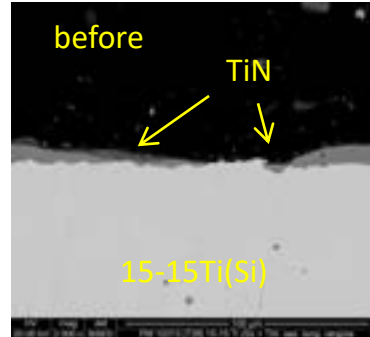
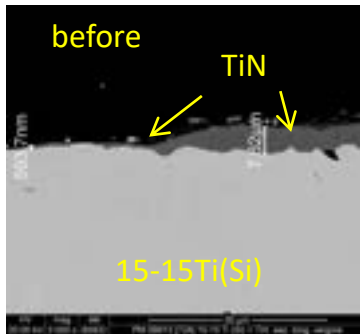


- alumina crucible containing liquid Pb and samples
- Ar/air flowing gas on Pb free surface
- C_O % wt. = 10^{-4} - 10^{-3} at 480-550°C

CORROSION TESTS OF TiN COATING

TiN coating: arc-PVD (Physical Vapor Deposition)

- ✓ produced by CSM (Centro Sviluppo Materiali)
- ✓ industrial availability and good oxidation resistance in air

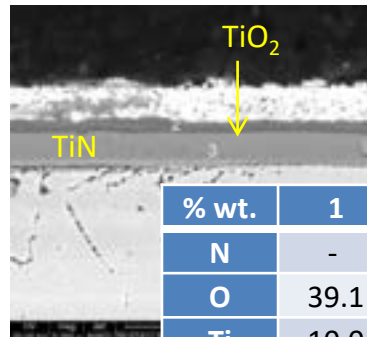
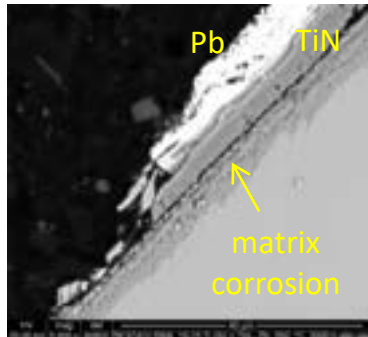


- ✓ Defects on TiN coating

Parameters	
Samples	n°2 TiN at 550°C and n°3 at 480°C
HLM	Pb (static)
C _O % wt.	10 ⁻³ - 10 ⁻⁴ (sat.)
Exposure Time	1000 and 2000 hours
Cover gas	Ar and Ar/air

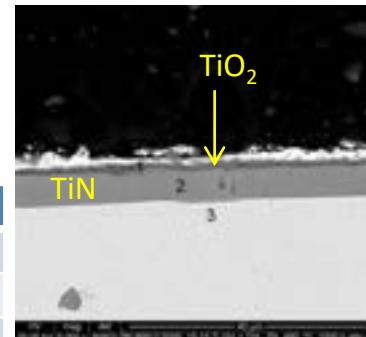


Test at 550°C for 2000 h



% wt.	1	2	3
N	-	-	30.4
O	39.1	46.9	-
Ti	10.0	46.2	69.6
Fe	6.1	7.0	-
Pb	44.9	-	-

Test at 480°C for 1000 h



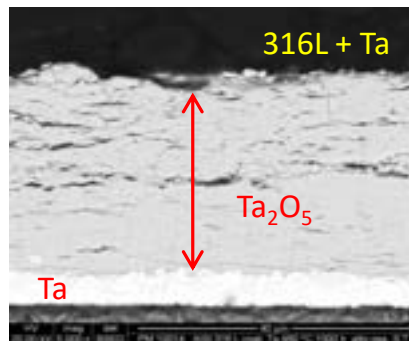
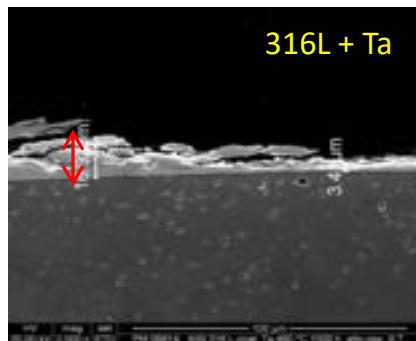
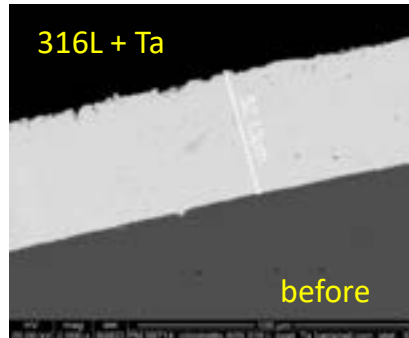
- ✓ Oxidation and Ti release in Pb

According to literature:
 $2\text{TiN} + 2\text{O}_2 \rightarrow 2\text{TiO}_2 + \text{N}_2$
 at 450-700°C in air

CORROSION TESTS OF Ta COATING (1)

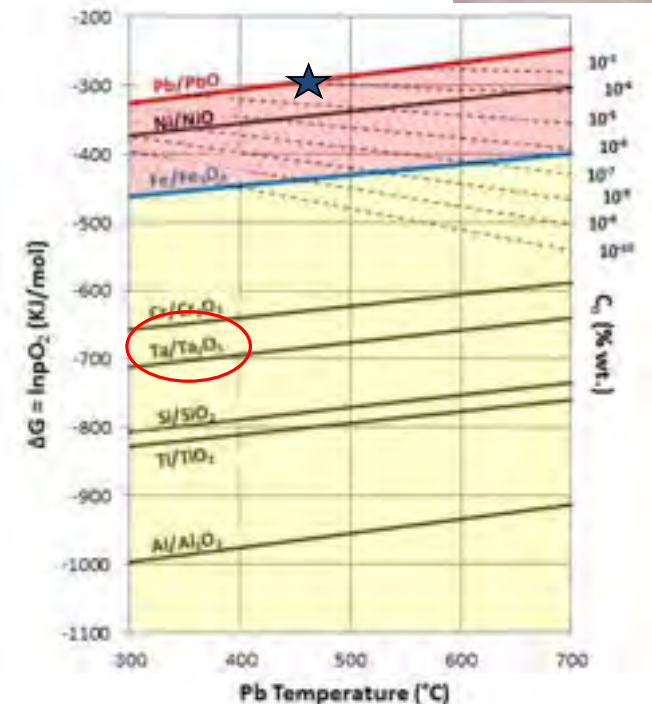
Ta coating: CVD (Chemical Vapor Deposition)

- ✓ proposed for heat exchanger and primary pumps protection in ALFRED reactor
- ✓ produced by Tantaline (Denmark)
- ✓ Ta low solubility in liquid Pb and industrial availability



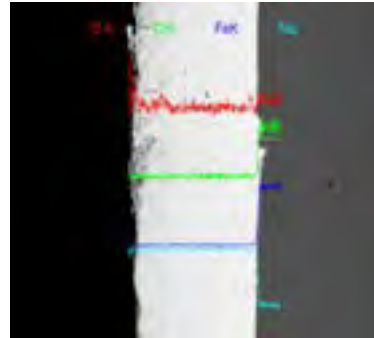
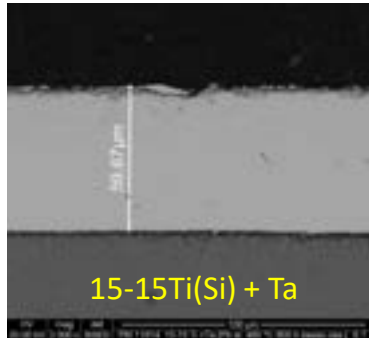
- ✓ loss of coating due to oxidation (very low oxidation resistance)

Parameters	
Samples	n°3 Ta coating
HLM	Pb (static)
Temperature	480°C (HX and Pumps T)
C _O % wt.	10 ⁻⁴ (sat.)
Exposure Time	1000 hours
Cover gas	Ar/air



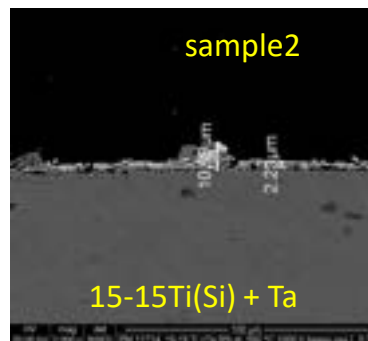
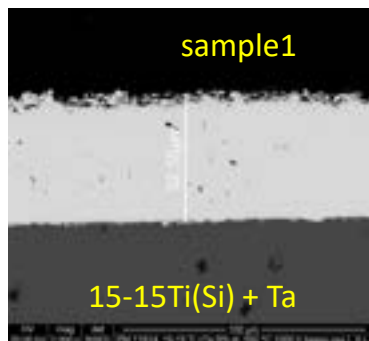
CORROSION TESTS OF Ta COATING (2)

Test in Pb at 480°C, low C_O for 700 h



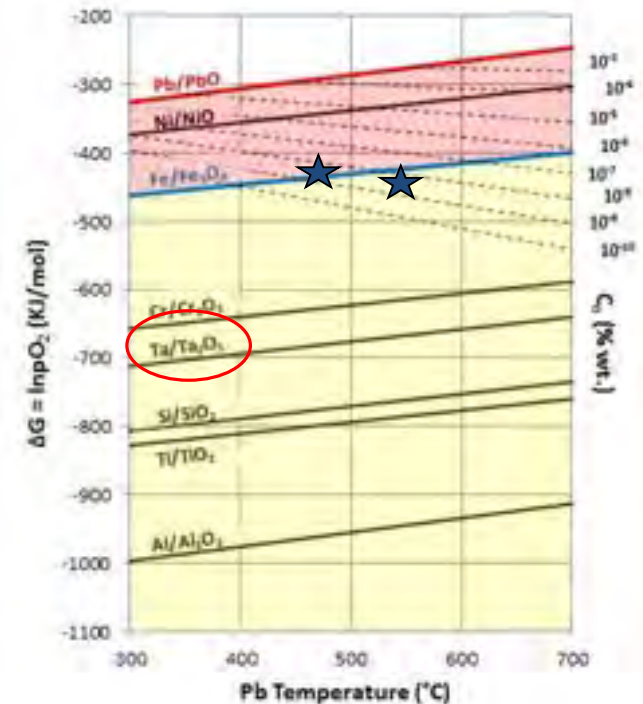
- ✓ no oxidation, no Ta dissolution
- ✓ no migration of chemical elements (to be confirmed)

Tests in Pb at 550°C, low C_O for 1000 h: mismatch



- ✓ no oxidation
 - ✓ no Ta dissolution
 - ✓ total Ta oxidation
 - ✓ sample not dipped in Pb?
- (to be confirmed)

Parameters	
Samples	n°1 Ta at 480°C and n°2 Ta at 550°C
HLM	Pb (static)
C_O % wt.	10^{-9} - 10^{-8} (low oxygen)
Exposure Time	≈ 1000 hours
Cover gas	Ar- H_2 with $C_{H_2} \approx 10\%$



CORROSION TESTS OF Ta COATING (3)

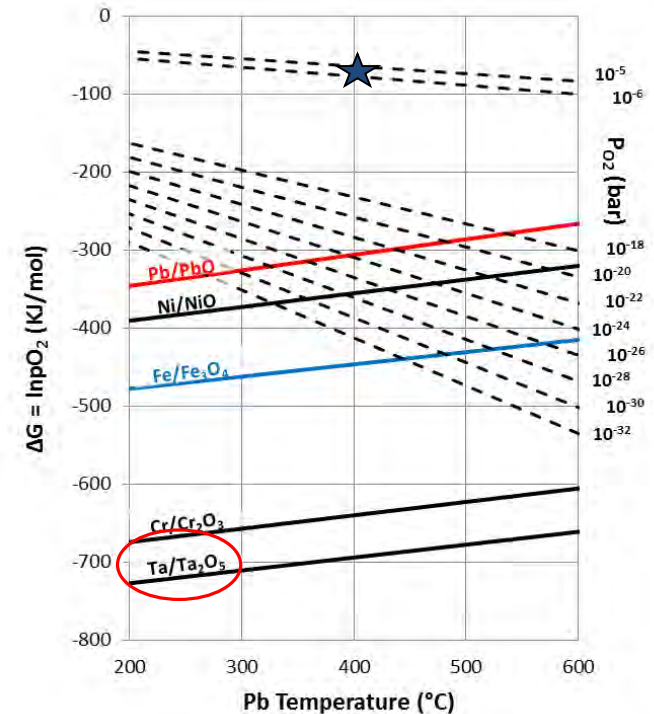
SIMULATION OF REACTOR PRE-HEATING
Oxidation Test in Argon gas at 400°C for 500 h



Parameters	
Samples	n°6 Ta
Cover gas	Ar 99.9999 %, Sovra-p = 0.7 bar
C _O % Vol.	0.1 ppmv
Temperature	400°C (reactor pre-heating)
Exposure Time	≈ 500 hours (21 days)



✓ Ta coating completely spalled off due to oxidation



CORROSION TESTS OF Al_2O_3 COATING

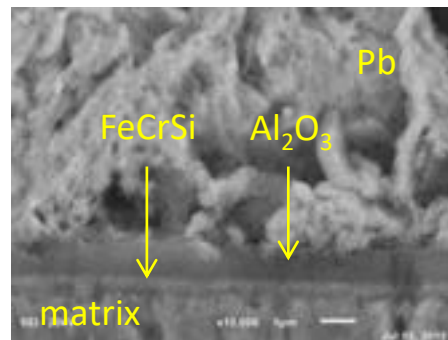
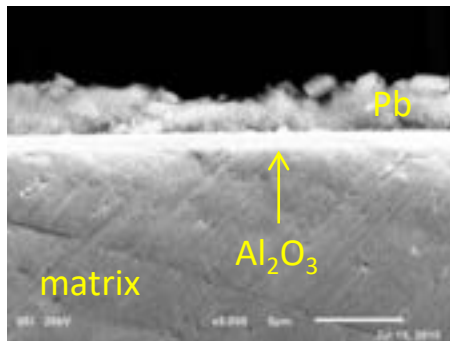
Al_2O_3 coating: PLD (Pulsed Laser Deposition)

- ✓ coating candidate for fuel cladding tubes protection in ALFRED reactor
- ✓ amorphous Al_2O_3 with nano-crystalline inclusions, excellent mechanical and corrosion behaviour
- ✓ produced by IIT (Istituto Italiano di Tecnologia)

PLD- Al_2O_3 1 μm
on 15-15Ti matrix



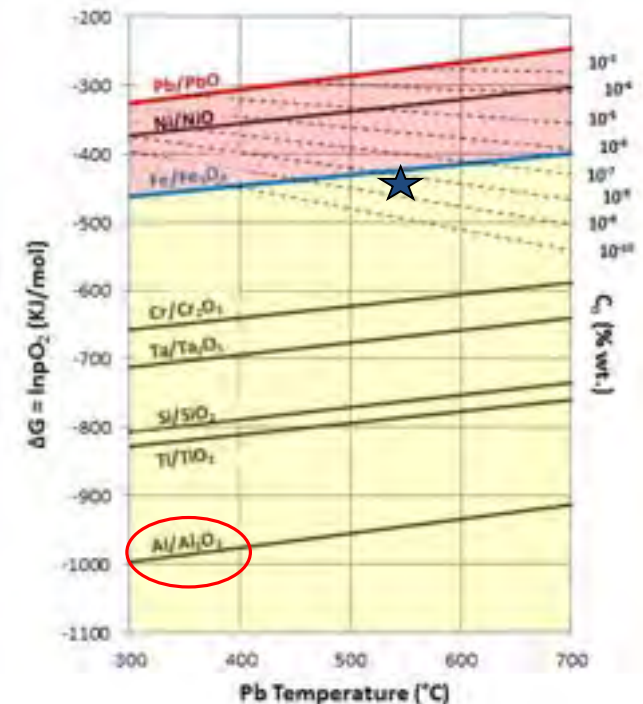
FeCrSi 0.4 μm PLD- Al_2O_3 1 μm
on 15-15Ti matrix



- ✓ no corrosion/degradation
- ✓ low interaction coating-Pb
- ✓ no expected corrosion

Parameters

Samples	n°1 Al_2O_3 + n°1 FeCrSi + Al_2O_3
HLM	Pb (static)
Temperature	550°C (fuel cladding T)
C_0 % wt.	10^{-9} - 10^{-8} (low oxygen)
Exposure Time	1000 hours
Cover gas	Ar- H_2 with $\text{C}_{\text{H}_2} \approx 10\%$

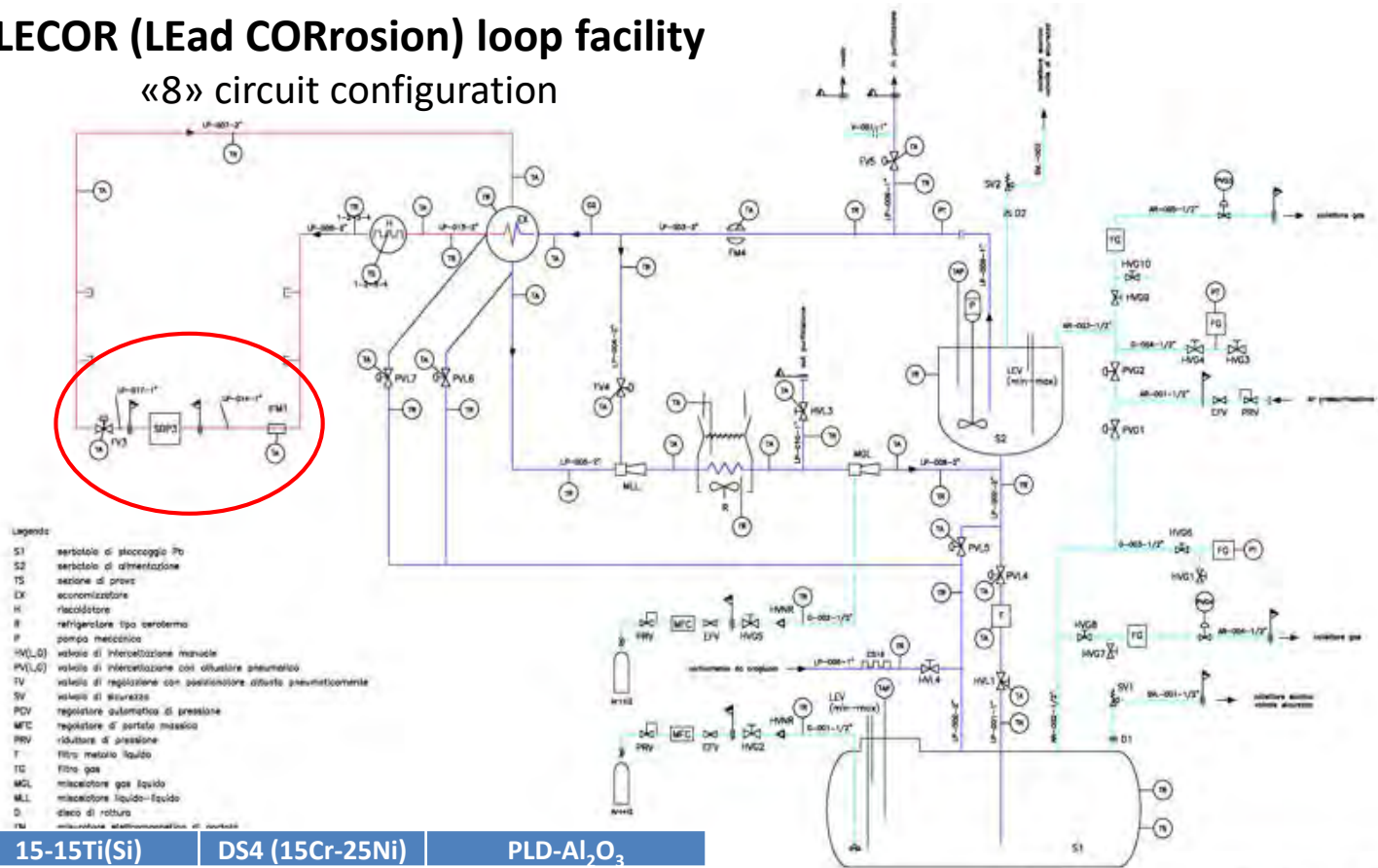


FLOWING CORROSION TESTS: LECOR LOOP

Test Section

- ❑ $T = 550^{\circ}\text{C}$
- ❑ 32 samples
- ❑ $V_{pb} = 0.3 - 1 \text{ m/s}$
- ❑ $C_o \approx 10^{-5} \% \text{ wt.}$
- ❑ C_o in Pb monitored with an oxygen sensor
- ❑ Pb flow velocity monitored with inductive flowmeter

LECOR (LEad CORrosion) loop facility «8» circuit configuration



Test Matrix for 1000 hours

N° samples	PVD-TiN	15-15Ti(Si)	DS4 (15Cr-25Ni)	PLD-Al ₂ O ₃
1	PM 08813	PM 06113	PM 01915	PM 80112 (10 μm)
2	PM 08913	PM 06213	PM 02015	PM 80412 (10 μm)
3	PM 09013	PM 06313	PM 02115	PM 80312 (5 μm)
4	PM 09113	PM 06413	PM 02215	PM 81212 (5 μm)
5	PM 09213	PM 06513	PM 02315	PM 80912 (1 μm)
6	PM 09313	PM 06613	PM 02415	PM 80612 (1 μm)
7	PM 09413	PM 06713	PM 02515	PM 79812 (1 μm)
8	PM 09513	PM 06813	PM 02615	-

Exposure up to
4000 and 8000h

OXYGEN CONTROL AND MONITORING

FORMATION and DEPOSITION of PbO

- when $C_O = C_{O, \text{sat.}}$
- **plugging** phenomena in ΔT loop
- **reduced heat exchange capability**

T (°C)	C _O sat. in Pb		C _O sat. in LBE	
	wt. %	ppm or µg/g	wt. %	ppm or µg/g
330	8.1E-06	0.1	3.66E-05	0.4
400	5.9E-05	0.6	1.41E-04	1.4
450	1.9E-04	1.9	3.15E-04	3.2
500	5.4E-04	5.4	6.34E-04	6.3
550	1.3E-03	13	1.17E-03	12
600	3.0E-03	30	2.02E-03	20

*Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-Hydraulics and Technologies, 2007.

Strategy against PbO formation:

- **control C_O in liquid Pb at low values**
- ➔ $C_O < C_{O, \text{sat.}}$ at the min. working T

deposition of PbO and plugging in Pb-Bi cooled K-27 Soviet Nuclear Submarine



Slag in pipeline



Slag deposit in the circuit during circulation pump tests



Slag deposit in heat exchanger

C_O MYRRHA = 10^{-7} % wt.
300-450°C

HELENA, NACIE, LECOR
(loop), CIRCE (pool)

C_O ALFRED = 10^{-6} - 10^{-8} % wt.
400-550°C

OXYGEN SENSOR FOR LOOPS (HELENA, NACIE, LECOR)

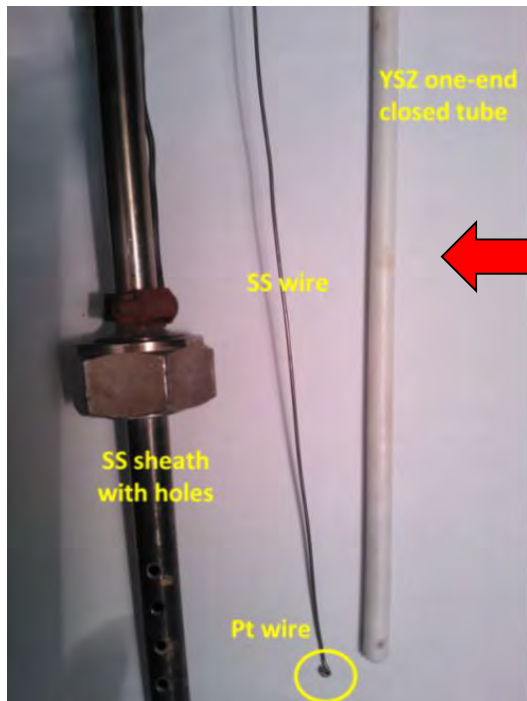
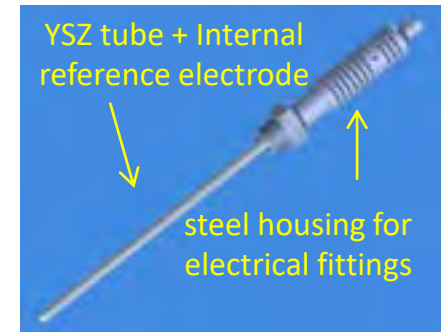
- ❑ Follows the Nernst law;

$$E_{th} = \frac{RT}{4F} \cdot \ln \frac{P_{O_2(\text{reference})}}{P_{O_2(\text{Pb, LBE})}}$$

known

to be monitored

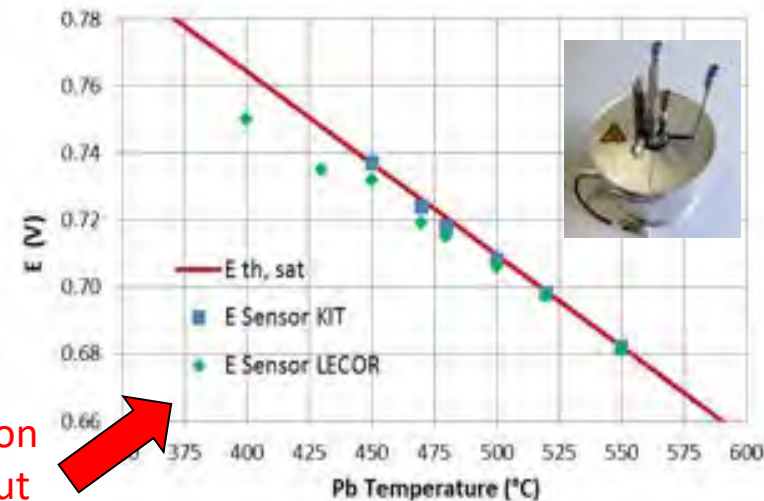
- ❑ One end-close tube of “stabilized ZrO_2 ” as solid electrolyte sensitive to oxygen and internal reference electrode within the tube (basic configuration for small scale experiments)
- ❑ Various Internal Reference electrode with different performances
(air reference with Pt or Perovskite electrode and solid and liquid metal/metal oxide reference such as $\text{Cu/Cu}_2\text{O}$ or $\text{Bi/Bi}_2\text{O}_3$)



oxygen sensor for LECOR loop

Components for Pt-air oxygen sensor assembly

Sensor calibration: comparison between LECOR sensor output (E_{LECOR}) and the theoretical one (E_{th})



OXYGEN SENSOR FOR CIRCE POOL (1)



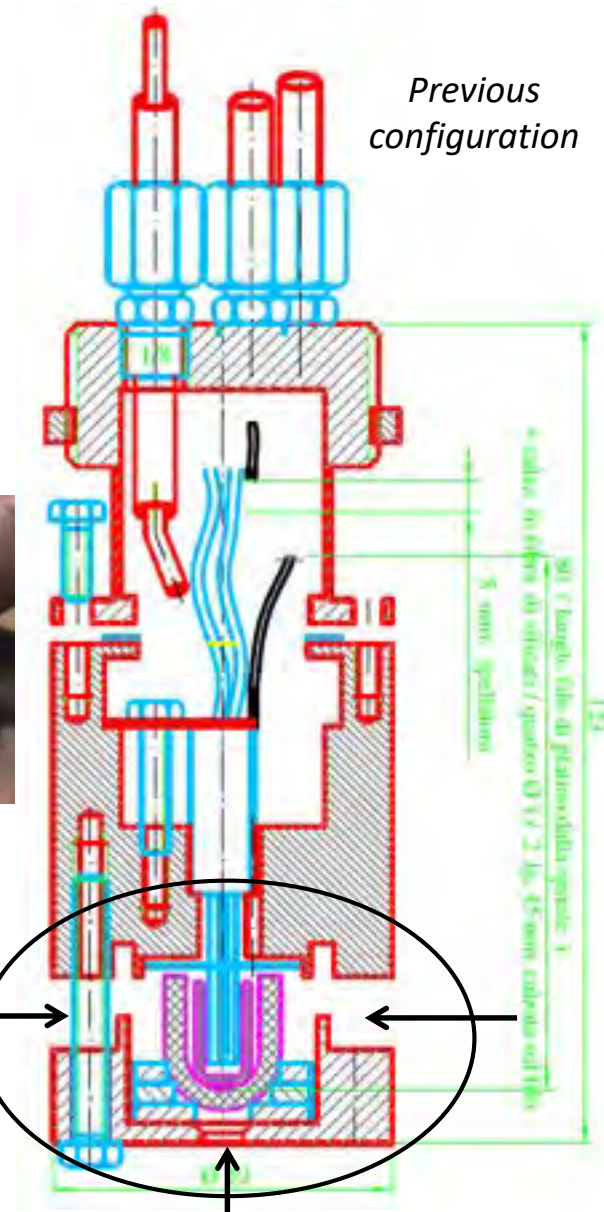
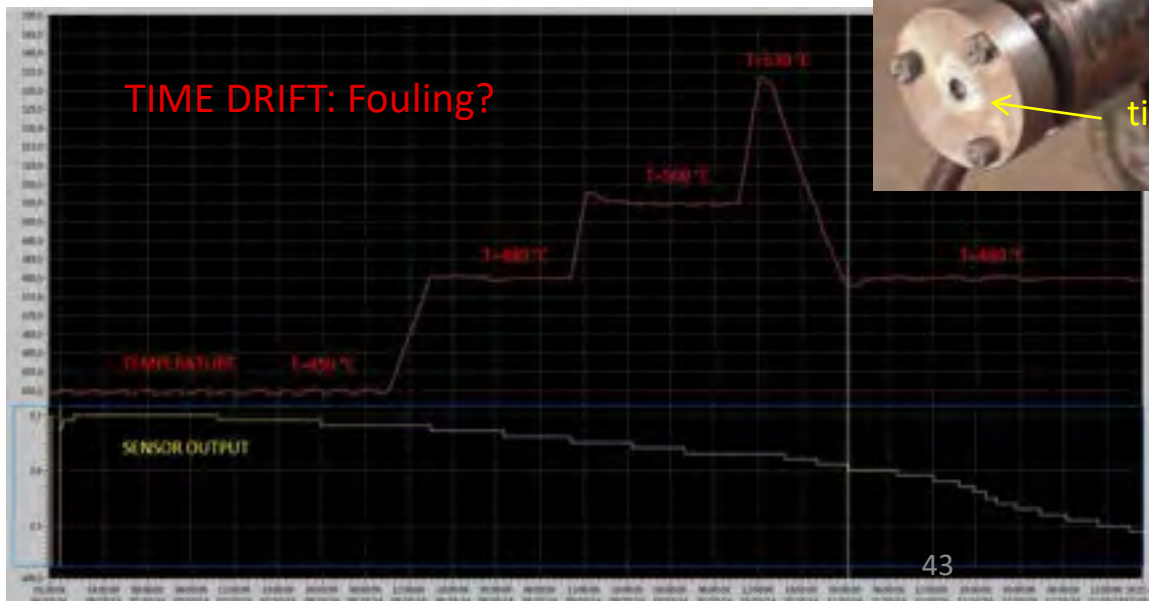
Pt/air based sensor ENEA/FER-Strumenti (Milan)

- Pt(Ni)/air reference electrode and YSZ electrolyte cell
- cell pressed against the sensor steel body by a flange and the tightness ensured by a graphite gasket (previous configuration)
- reference air blown into the cell through a steel tube
- need of a «internal heater» to lower the Pt-air cell resistance
- the length has to be adapted up to 8 m

Test in HELENA tank
(oxygen-saturated Pb)



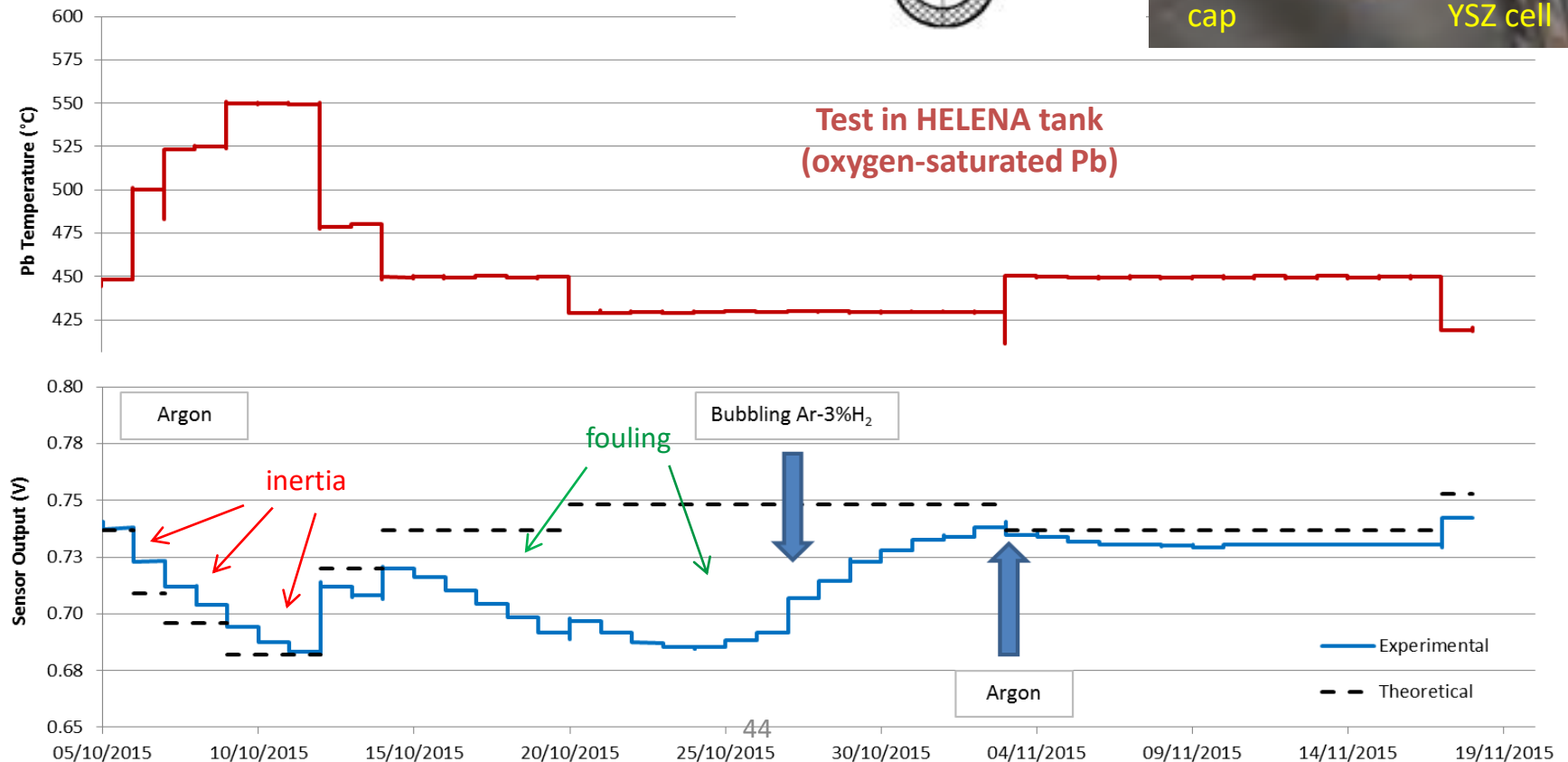
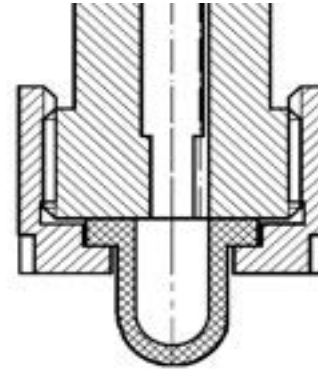
TIME DRIFT: Fouling?



OXYGEN SENSOR FOR CIRCE POOL (2)

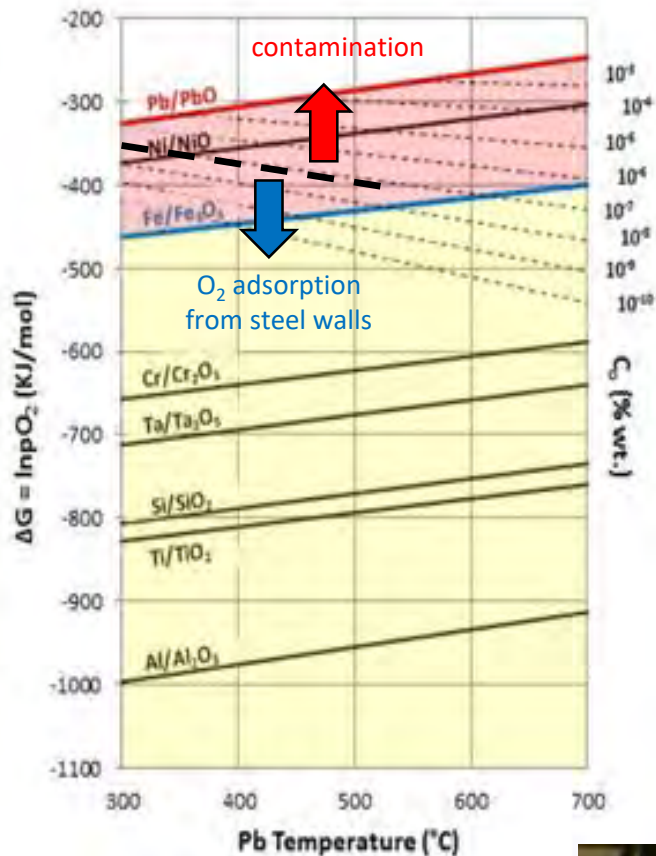
Sensor new configuration:

- YSZ cell with a lateral step
- YSZ cell pressed against the sensor body by a perforated cap which pushes on the step
- YSZ completely exposed to HLM



OXYGEN CONTROL METHODS

OPTIMAL OXYGEN CONTENT

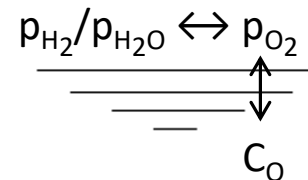


H₂/O₂ direct injection

dynamic conditions to remove or supply oxygen;
already used to condition HLM at low values in storage tank;
simple method

Ar/H₂/H₂O cover gas

equilibrium condition;
 C_O in HLM controlled by a specific H₂/H₂O ratio in the cover gas;
needs to be coupled with H₂/O₂ injection in case of huge deviations



HELENA, NACIE,
LECOR (loops),
BID1, CIRCE (pools)

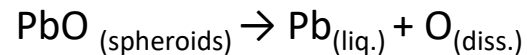
BID1

Oxygen Getters

oxygen removing method;
e.g. Ti, Zr, Mg, Ta steal $O_{(diss.)}$ from HLM to form very stable oxides;
need to be restored after the consumption

PbO Mass Exchanger

oxygen giving method



needs accurate control of parameters
needs to be restored after the consumption

CAPSULES
(screening test),
BID1, HELENA

CIRCE



BID1 FACILITY

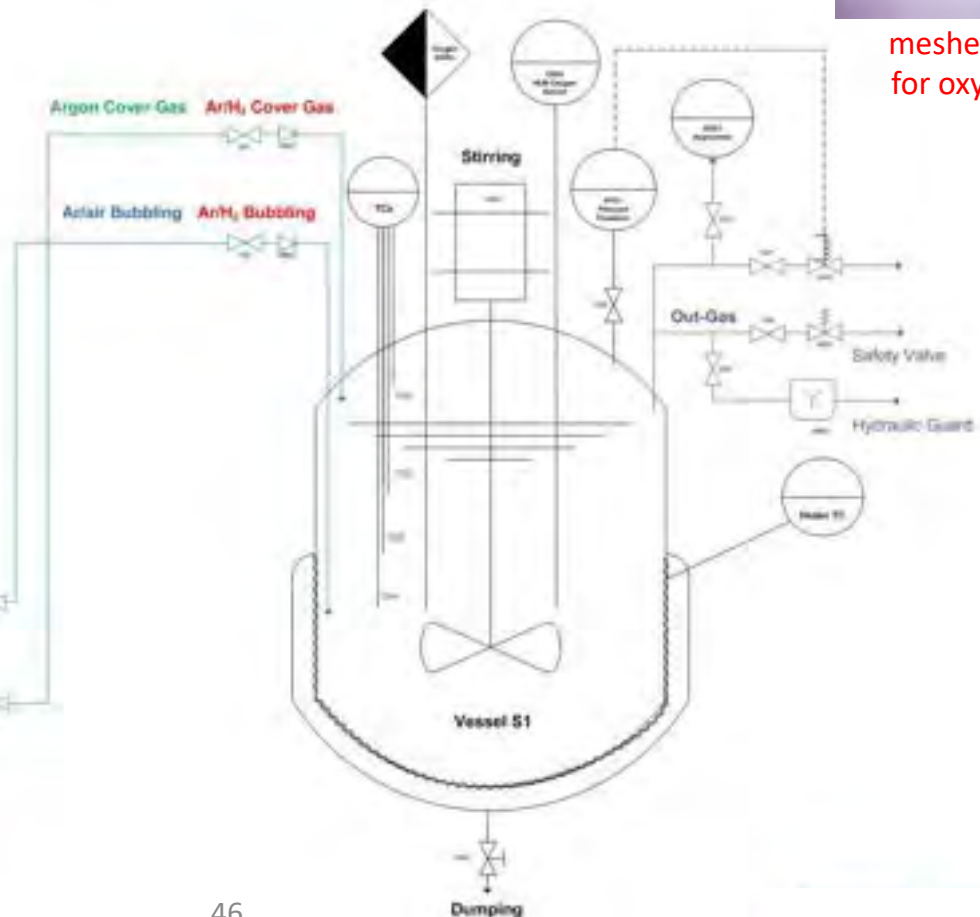
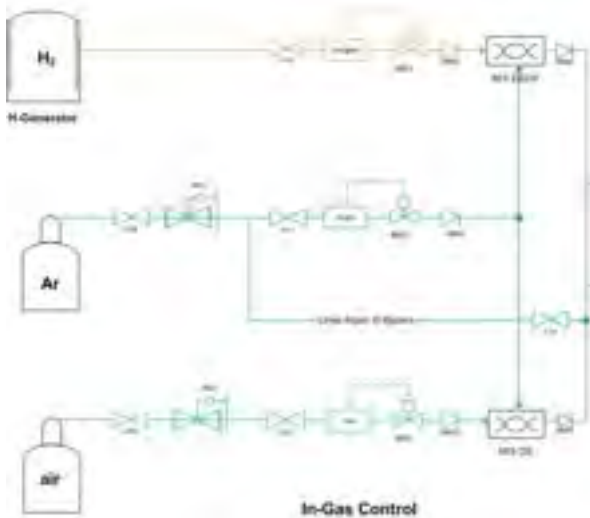
BRASIMONE GAS INJECTION DEVICE:

small pool (150L Pb) aimed to test the oxygen control methods:

- $\text{H}_2/\text{O}_2(\text{air})$ injection
- oxygen getters
- $\text{Ar}/\text{H}_2/\text{H}_2\text{O}$ cover gas
- oxygen sensors performances



H-generator +
mass flow controller
for dosing c_{H_2} in argon



meshed cartridge
for oxygen getter

CONCLUSIVE REMARKS & PLANNED ACTIVITIES

Corrosion Tests

- **TiN** coating **has low oxidation resistance** and it oxidizes in static Pb with high C_O
- **Ta** coating **strongly oxidizes** in static Pb with high C_O and in **argon gas** (reactor pre-heating)
- **Al₂O₃** coating shows **good corrosion resistance** in static Pb with low C_O (in agreement with thermodynamic considerations) and it is going to be exposed to static Pb at longer exposure times
- exposure tests in flowing Pb of **15-15Ti** and **15Cr-25Ni (DS4)** austenitic steels and **Al₂O₃** and **TiN** coating are going to be performed in **LECOR loop** (start by the end of Nov.)

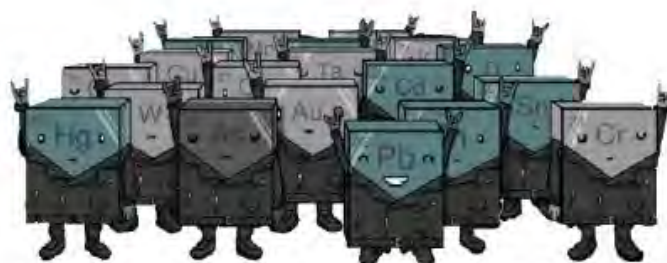
Oxygen Control and Monitoring in HLM systems

- manufacturing of **oxygen sensors for loops** (based on LECOR sensor configuration, using different Internal Reference according to the operating T)
- **oxygen sensor for CIRCE pool** (last design) exhibits good tightness and potential output in accordance with the theoretical up to 450°C. Next step: **installation of the internal heater** to lower the Pt-air cell resistance (allowing the reading at 300°C, working T of CIRCE)
- **operation of BID1 pool** and testing of the oxygen control methods (starting from H₂/O₂ injection and oxygen getters)

Thank you for the attention

RACHEL Lab

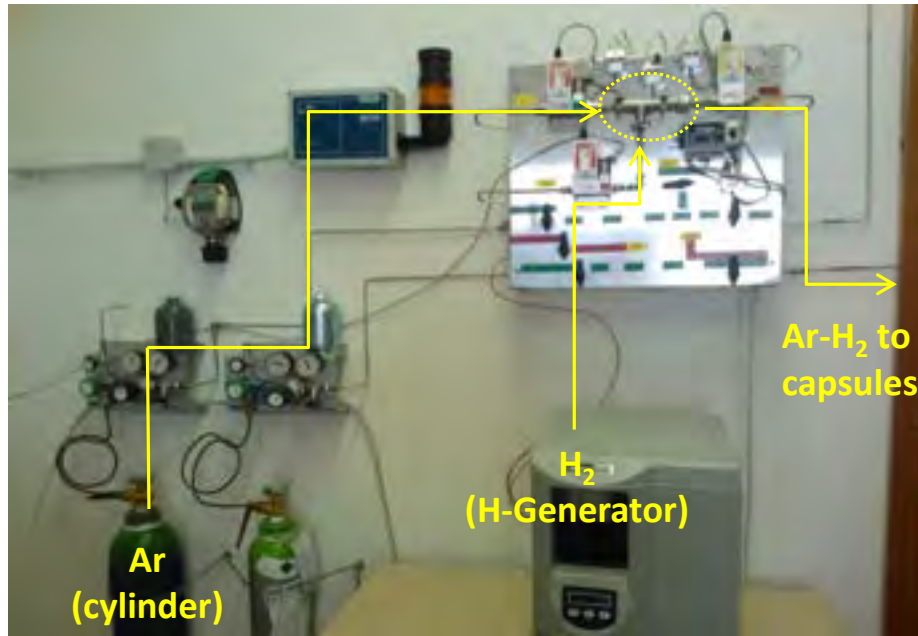
REACTIONS AND ADVANCED CHEMISTRY FOR LEAD



LONG LIVE HEAVY METALS

BACK-UP SLIDES

Pb CONDITIONING AT LOW C_O

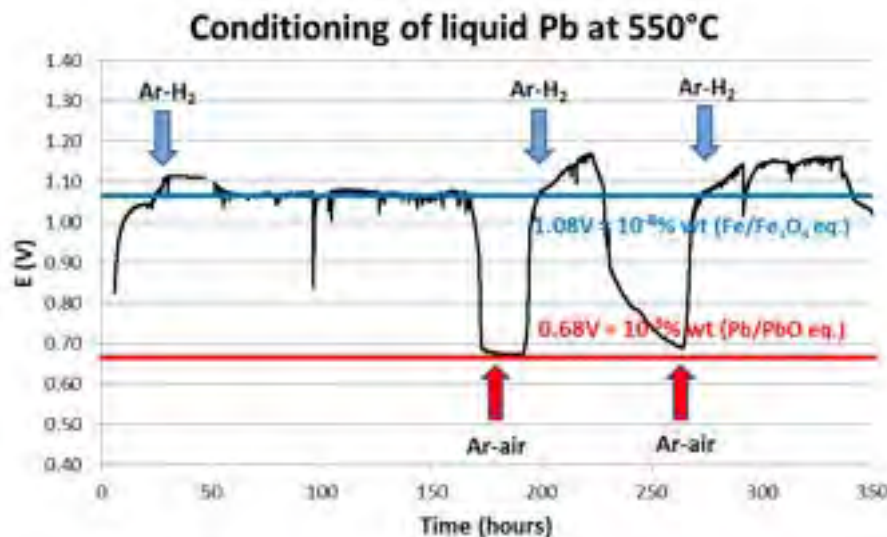


IMPLEMENTATION OF A GAS CONTROL SYSTEM

Ar-H₂ mixture obtained by mixing pure Ar (cylinder) and pure H₂ (H-generator) for laboratory use

Gas Mixture Control:

- 2 flow-meters (one for Ar and one for H₂)
- 1 mixing chamber
- 1 pressure transducer
- remote control PC



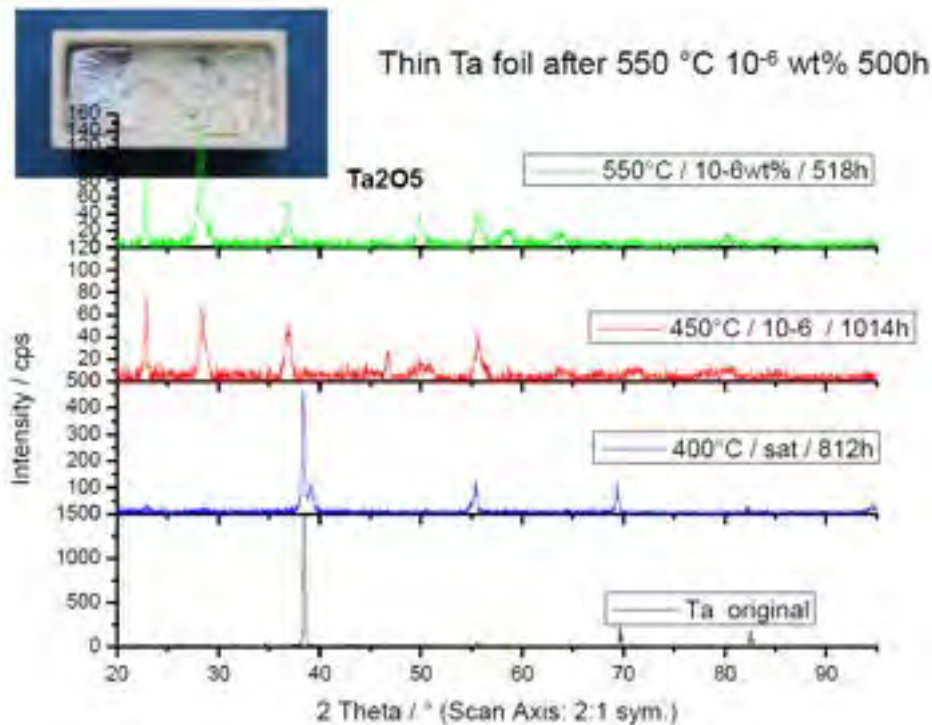
C_O in Pb monitored
with a Pt-air
oxygen sensor



Test in Pb using Ar/H₂ mixture with $C_{H_2} \leq 10\%$:

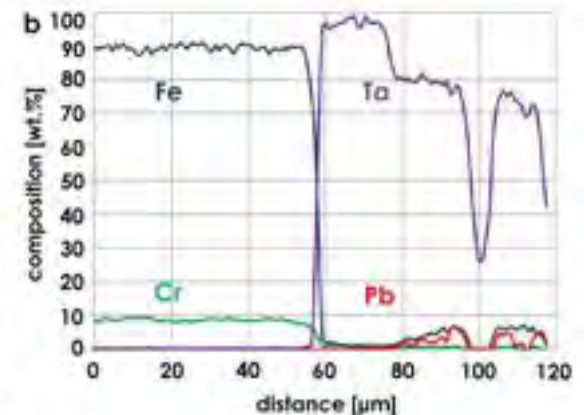
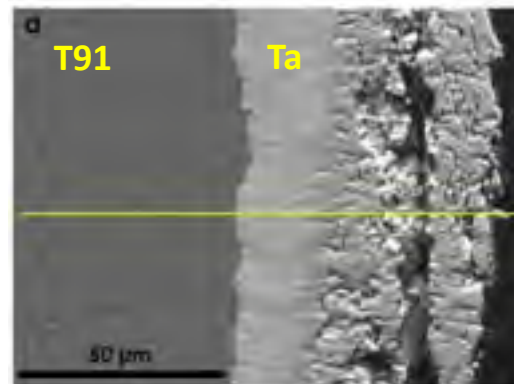
- ✓ fast and easy deoxygenation
- ✓ different C_O by selecting different C_{H_2}

Ta CORROSION



*A. Weisenburger, «Lead Cooled Reactors – Material Issue», Nuclear 2012 – May 16-18, Pitesti, Romania.

*C. Cristalli et al., «Corrosion behaviour of reference materials exposed to Pb after fast neutrons irradiation in the BOR60 reactor up to 16 dpa». NUMAT Conference, Florida, 2014.



low-oxygen Pb, 550°C for 7500h and 16 dpa

Characterization of mechanical properties and Corrosion behavior in lead of DS4 steel

C. Cristalli, L. Pilloni, C. Testani (CSM), S. Storai

Workshop PAR 2014, Brasimone, 19/11/2015

Introduzione sullo sviluppo storico degli acciai DS

All'inizio degli anni 80, all'interno di un programma sperimentale portato avanti a Saclay, una serie di test di irraggiamento (1 MeV) dimostrò l'efficacia della contemporanea presenza di Ti e Nb sulla resistenza a swelling di matrici austenitiche 316 e 15-15.

Realizzazione della **Prima Generazione** di Acciai Doppio Stabilizzati:

316DS

15-15DS

Nei doppio-stabilizzati di prima generazione la temperatura di ricottura utilizzata, 1125°C, non risultò sufficiente a ottenere una buona solubilizzazione di Ti e Nb anche a causa dell'alto rapporto di stabilizzazione (3,18 per il 316DS e 2,04 per il 15-15DS)



Revisione della composizione



Rapporto di Stabilizzazione:

$$R = \frac{[Ti] + [Nb] - [N]}{[C]}$$

Nascita della **Seconda Generazione** di Acciai Doppio Stabilizzati:

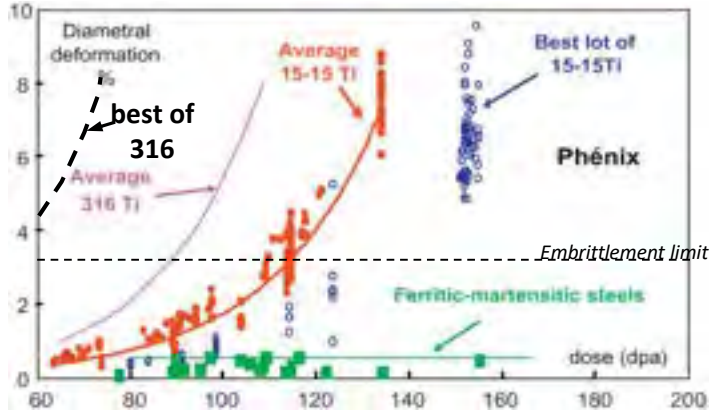
DS3 (15Cr-15Ni); R=1,38

DS4 (15Cr-25Ni); R=0,55

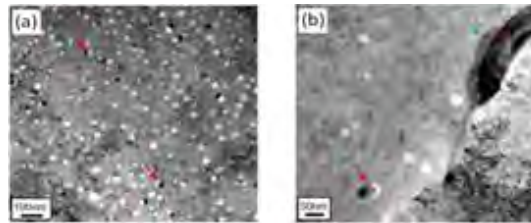
DS5(15Cr-25Ni)

Risultati: Swelling dei Doppio Stabilizzati

Letteratura; swelling del 15-15Ti



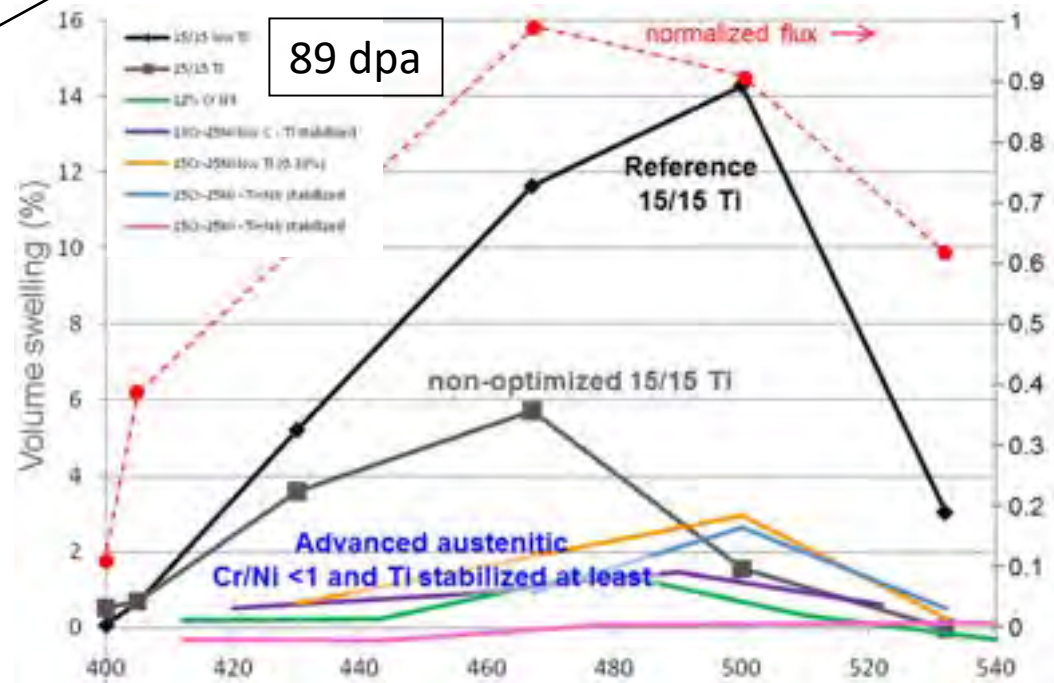
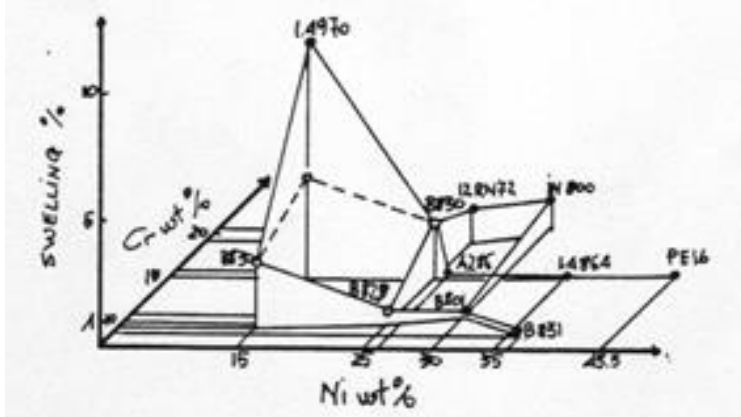
[Séran et al.]



Basso numero di cavità negli austenitici DS di 2° Generazione (b) se confrontati con il 15-15 Ti non ottimizzato (a)

acciaio	Voto (da * scarso a *** ottimo)
15-15 std	*
DS3 (15-15)	No dati
DS4 (15-25)	***
DS5 (15-25)	**

Effetto del contenuto di Ni sullo swelling



Produzione lingotto DS4; processo fusorio VIM

Impianto VIM (Vacuum Induction Melting) CSM



Lingotto DS4



Certificato composizione chimica

Rapporto d'analisi N. 8352

Data di richiesta : 2014-07-15

-0195-VM 2882

SIGLA CAMP.	BAL Fe	% C	% S	% N	% P	% Mo	% Co	% Cr	% Si	% Ti
-0195-	BAL	0.041	0.0082	0.013	0.037	1.46	<0.01	14.8	0.88	0.17
MINIMO	BAL	0.0400	0	0	0.0350	1.20	0	14.0	0.80	0.100
MAXIMO	BAL	0.060	<0.015	<0.02	0.0450	1.80	<0.1	16.0	1.00	0.300
SIGLA CAMP.	% Mn	% Cu	% Nb	% B	% Al	% Zr	% W	% Ca	% Ta	% Ni
-0195-	1.48	0.06	0.20		0.013		<0.05			24.6
MINIMO	1.20	0	0.100	0	0	0	0	0	0	24.5
MAXIMO	1.80	<0.1	0.300	0	0.015	0.03	0.03	0.03	0.03	25.5

ESEGUITO DA : /MARCHESINI/PACIELLO

Responsabile di laboratorio
Firma

[Handwritten signature]

Produzione lingotto DS4; laminazione a caldo

NP pass	Tipo di prova	Campione	Materiale	Temperatura °C				% Riduzione	Spessore (mm)			Forza applicata (t)		
				Riscaldamento	Laminazione misurata		Calcolata		Iniziale	Finale	Ottenuto			
					Richiesta	Pirometro							Termocopp.	
1	Laminato Danielli Sbazzatura	2882 A	DS4	1200		nd		20,0	120,0	96,0		53,4		
2						1078		25,0	96,0	72,0		66,3		
3						1068		25,0	72,0	54,0		82,6		
4						1034		25,0	54,0	40,5		88,1		
5						1029		22,0	40,5	31,6		97,3		
6						1018		22,2	31,6	24,6		95,3		
7					850	1011		21,1	24,6	19,4		106,6		
														21,0
1	Laminato Danielli Sbazzatura	2882 B	DS4	1200		nd		20,0	120,0	96,0		49,8		
2						1086		25,0	96,0	72,0		60,9		
3						1071		25,0	72,0	54,0		77,3		
4						1046		25,0	54,0	40,5		83,4		
5						1040		22,0	40,5	31,6		91,9		
6						1036		22,2	31,6	24,6		90,7		
7					850	1021		21,1	24,6	19,4		106,8		
														21,0

Inizio
laminazione
lingotto (Pre-
riscaldato a
1200°C)

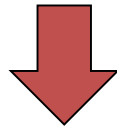


laminato finale
dopo l'ultima
riduzione
(919°C) spessore
20 mm



Produzione lingotto DS4; incrudimento 20%

- Solubilizzazione delle lamiere; 5 minuti a 1135° C



- Laminazione a freddo; 20% riduzione spessore (ca. 20 passate da 1%)

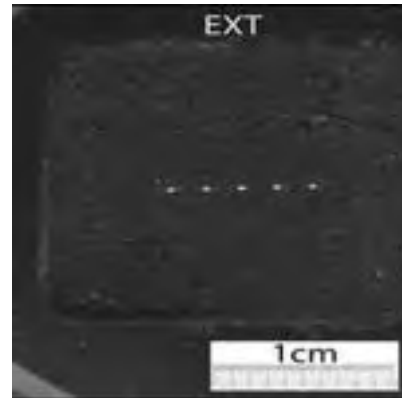
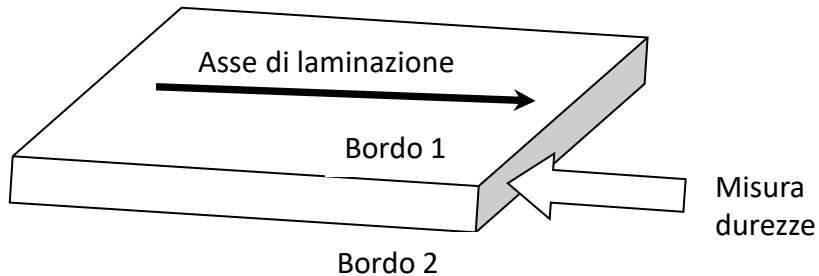
Lamiera finale (s=15 mm)
dopo cold-working



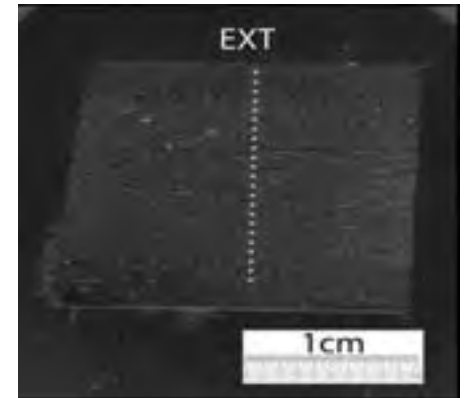
Effetto di «waving» sulla direzione di
laminazione della lamiera



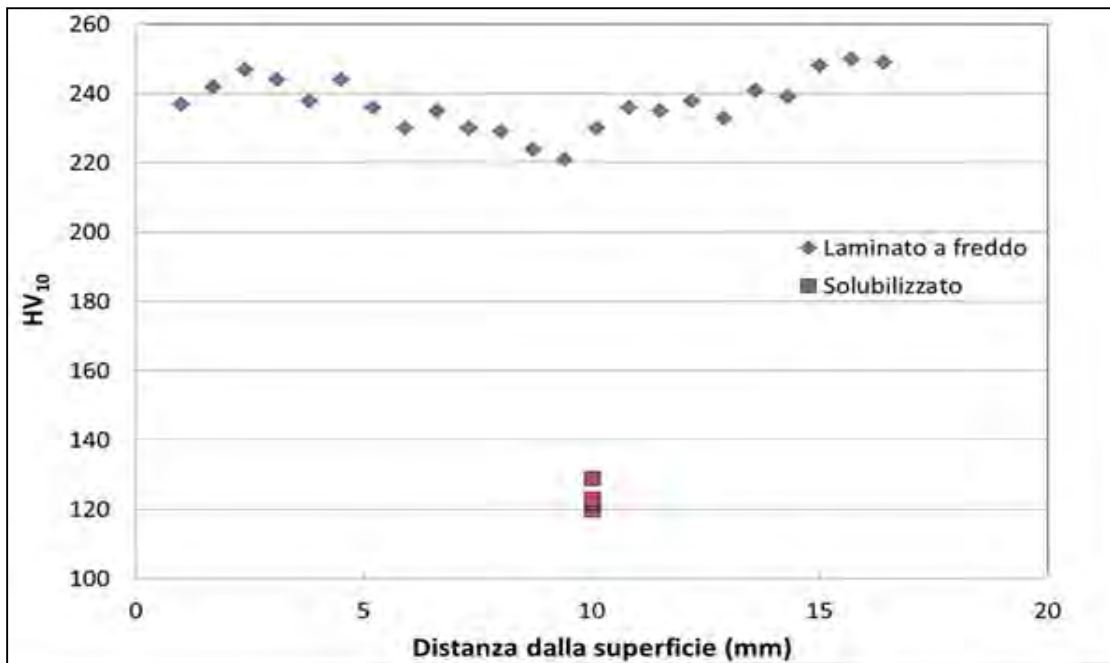
Produzione lingotto DS4; Durezza HV



solubilizzato
(sezione trasversale)



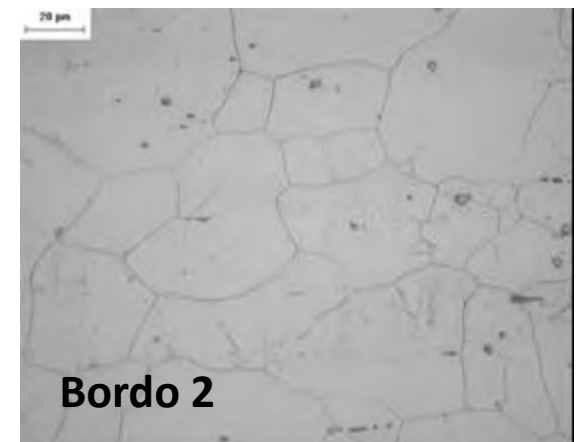
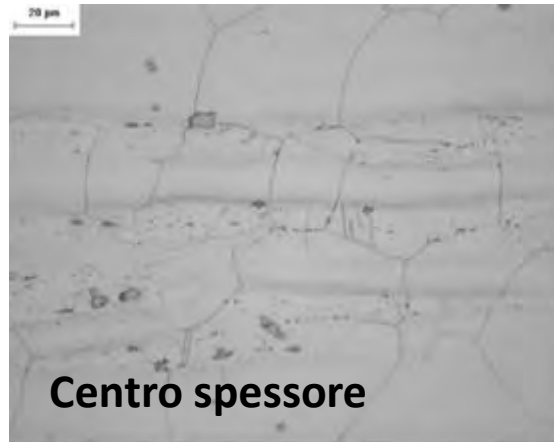
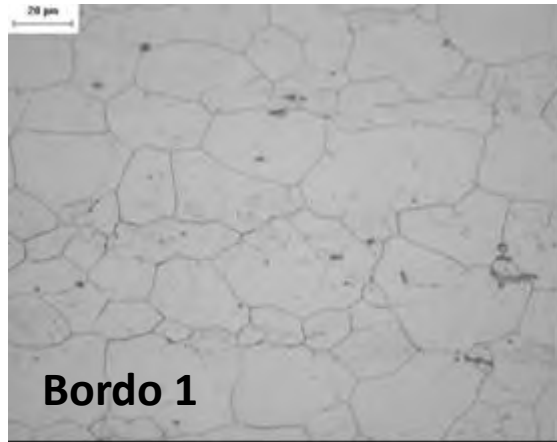
laminato a freddo
(sezione longitudinale)



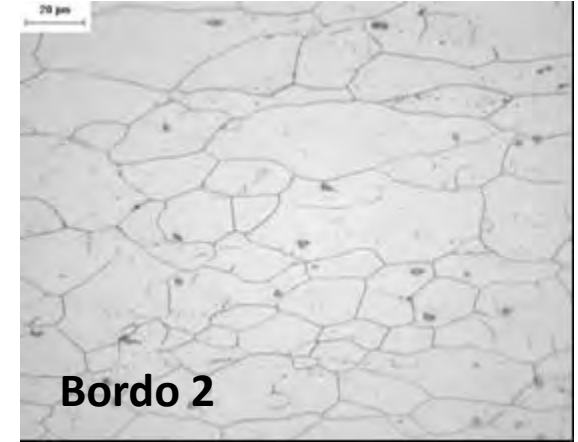
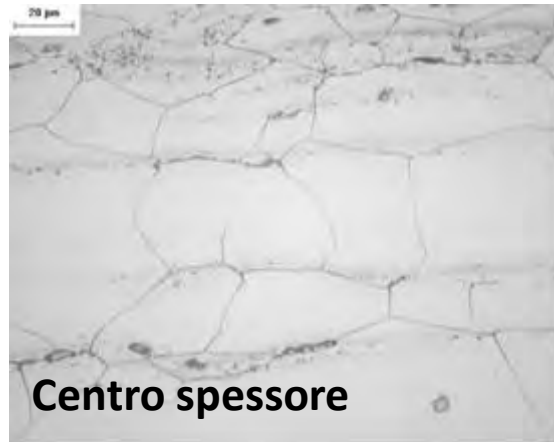
**Lotto anni '80 (DS4):
260 HV**

Grain Size sezione trasversale

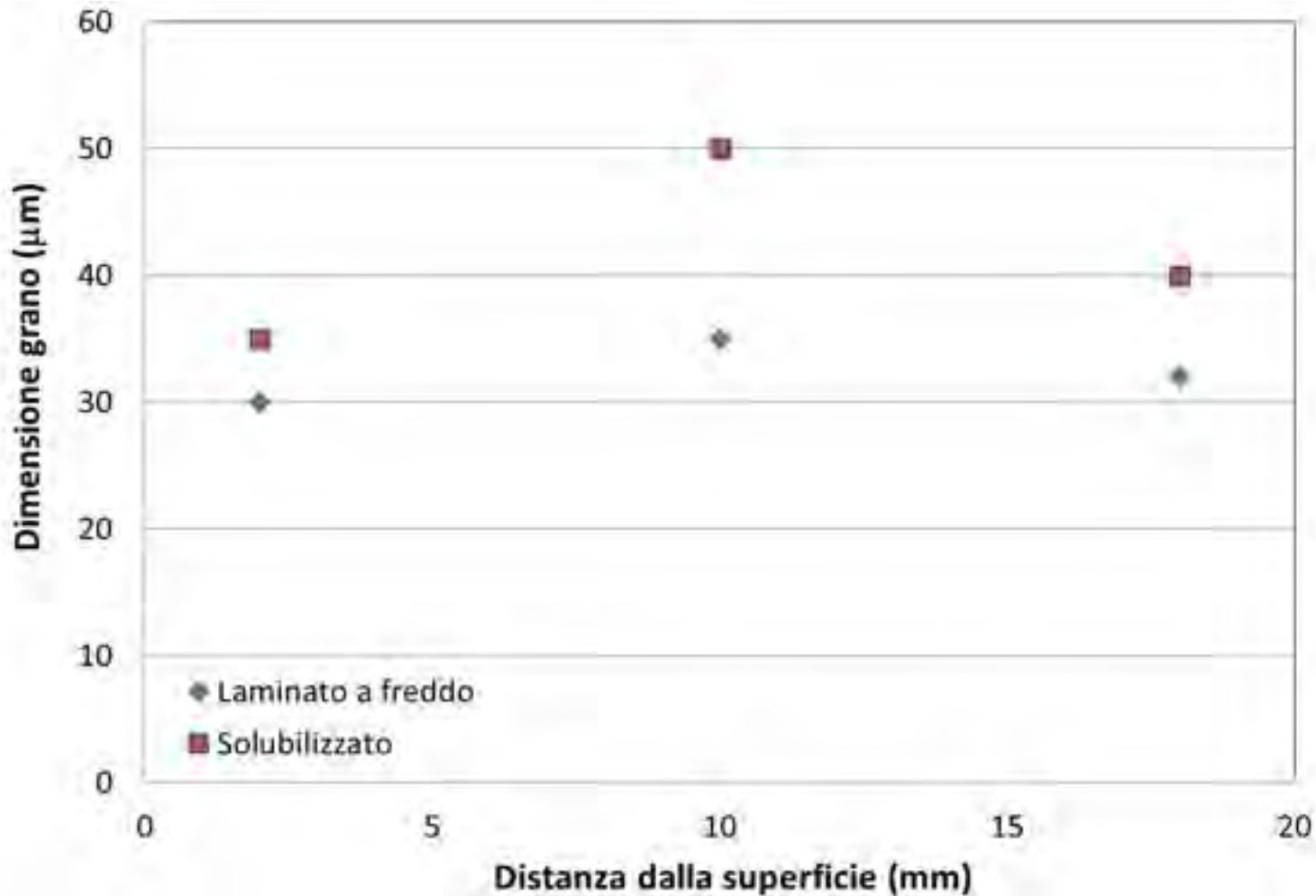
Materiale solubilizzato



Materiale incrudito al 20%



Grain Size; confronto

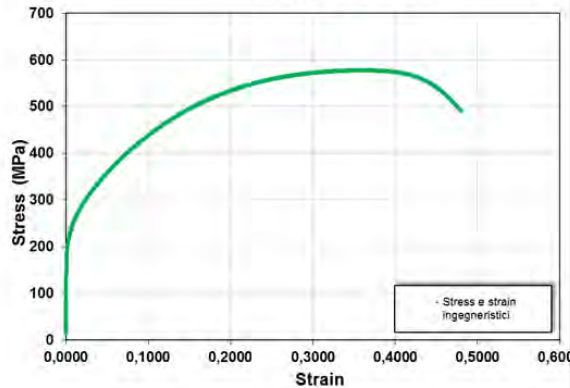


**Lotto anni
'80 (DS4):
32-45
micron
(N°6 and 7
ASTM)**

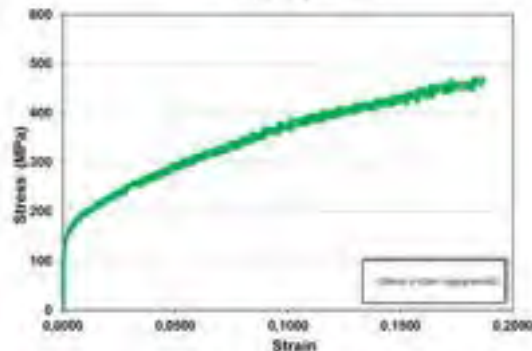
Prove di Trazione; Curve Tensile

Materiale solubilizzato (RT, 550°C, 650°C)

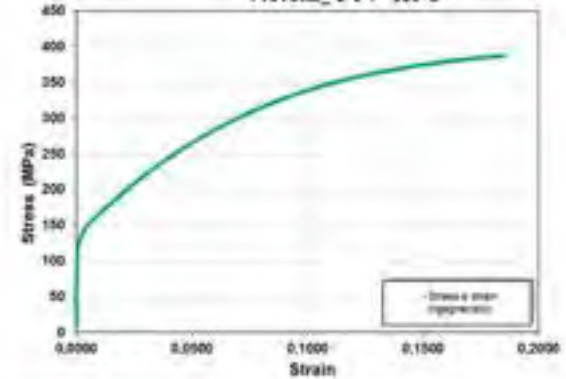
Provetta_S-1 T= R.T.



Provetta_ T=550°C

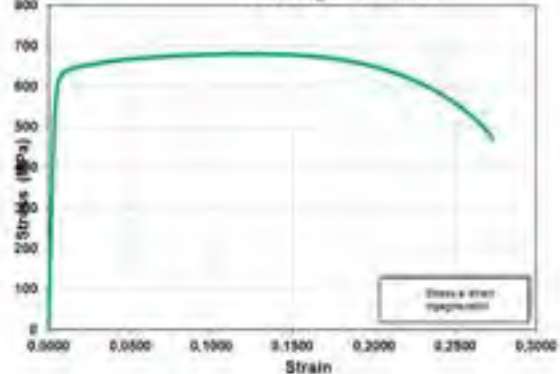


Provetta_S-6 T= 650°C

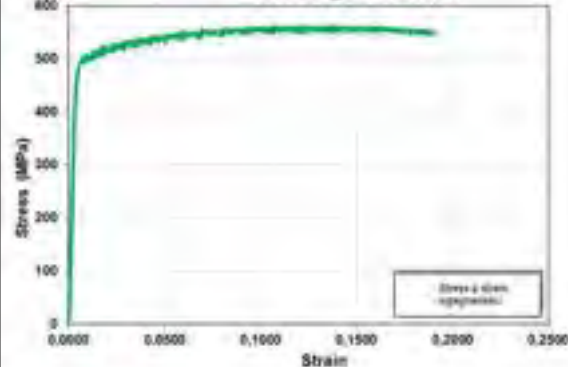


Materiale Laminato a freddo 20% (RT, 550°C, 650°C)

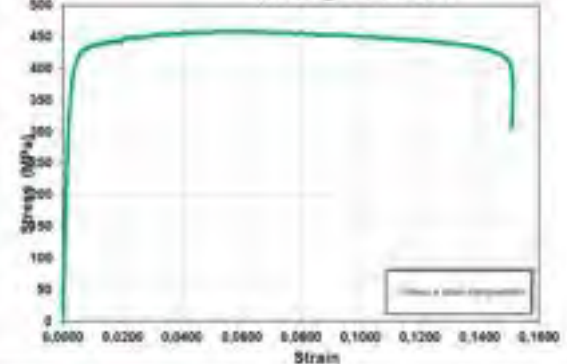
Provetta_LF-1 T= R.T.



Provetta_LF-3 T= 550°C



Provetta_LF-5 T= 650°C



Prove di Trazione (RT, 550,650°C)

**Materiale
solubilizzato**



T (° C)	YS (MPa)	UTS(MPa)	A(%)	Z(%)	E (GPa)
RT	209	579	50	68	209
RT	204	577	50	69	197
RT	209	584	51	68	209
MEDIA	207	580	50	68	205
550	160	503	-	46	180
550	163	512	-	46	182
550	156	496	-	47	173
MEDIA	159	503	nd	46	178
650	139	379		59	155
650	137	390		58	165
650	137	386		58	160
MEDIA	137	385	nd	58	160



**Materiale
Laminato
a freddo 20%**

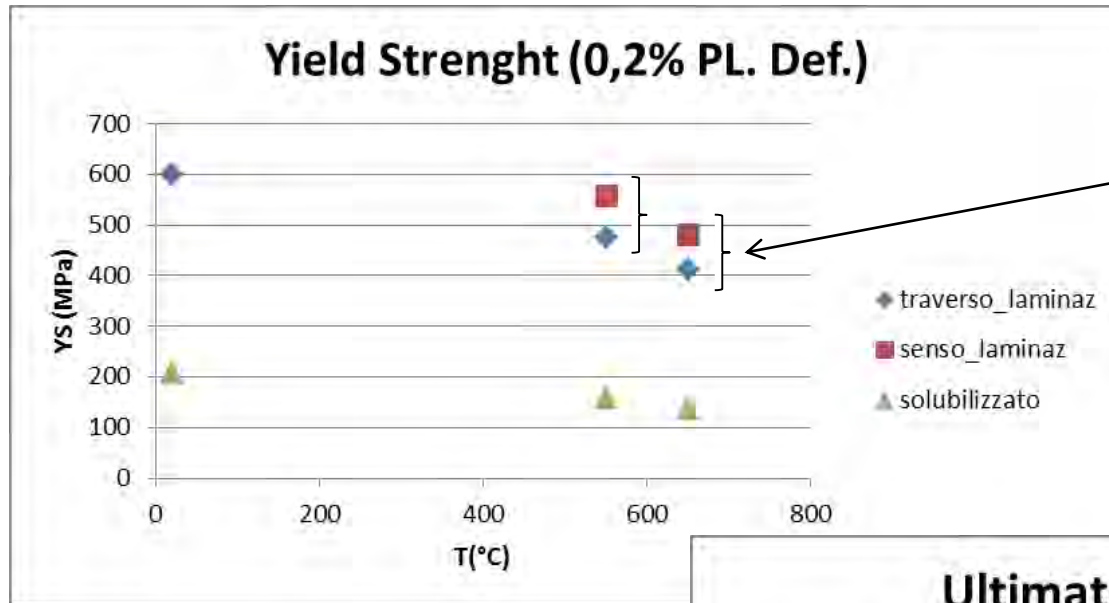


T (° C)	YS (MPa)	UTS(MPa)	A(%)	Z(%)	E (GPa)
RT	609	681	27	63	210
RT	585	665	30	65	205
RT	608	688	27	63	203
MEDIA	600	678	28	63	206
550	489	560		42	181
550	468	560		44	185
550	468	561		44	186
MEDIA	475	560	nd	43	184
650	405	459		54	167
650	421	466		52	164
650	414	459		51	167
MEDIA	413	461	nd	52	166

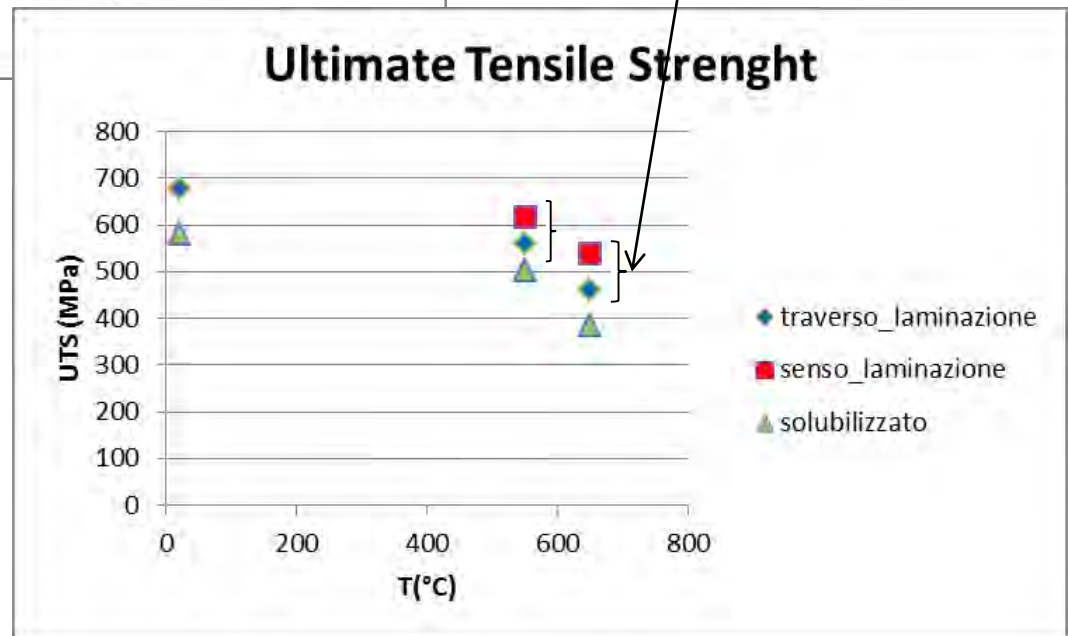
Prove di Trazione senso di laminazione (550,650°C)

T (° C)	YS (MPa)	UTS(MPa)	A(%)	E (GPa)
550	559	623	18 %	133,1
550	556,7	609	18 %	143
MEDIA	558	616	18 %	138
650	472,5	531,4	21 %	137,7
650	487,4	549	17 %	141,4
MEDIA	480	540	19 %	140

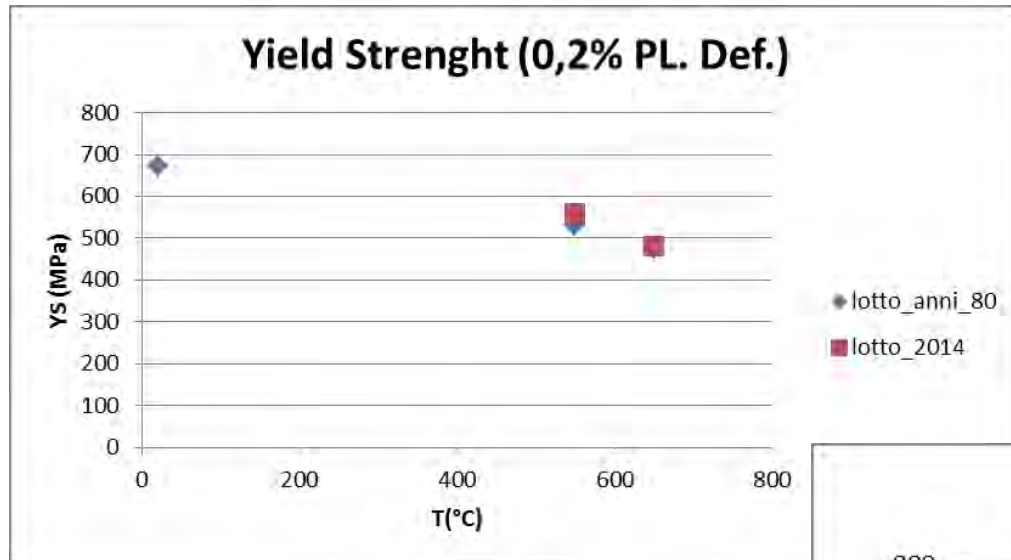
Anisotropia del materiale; confronto tra le direzioni di estrazione



Anisotropia del materiale



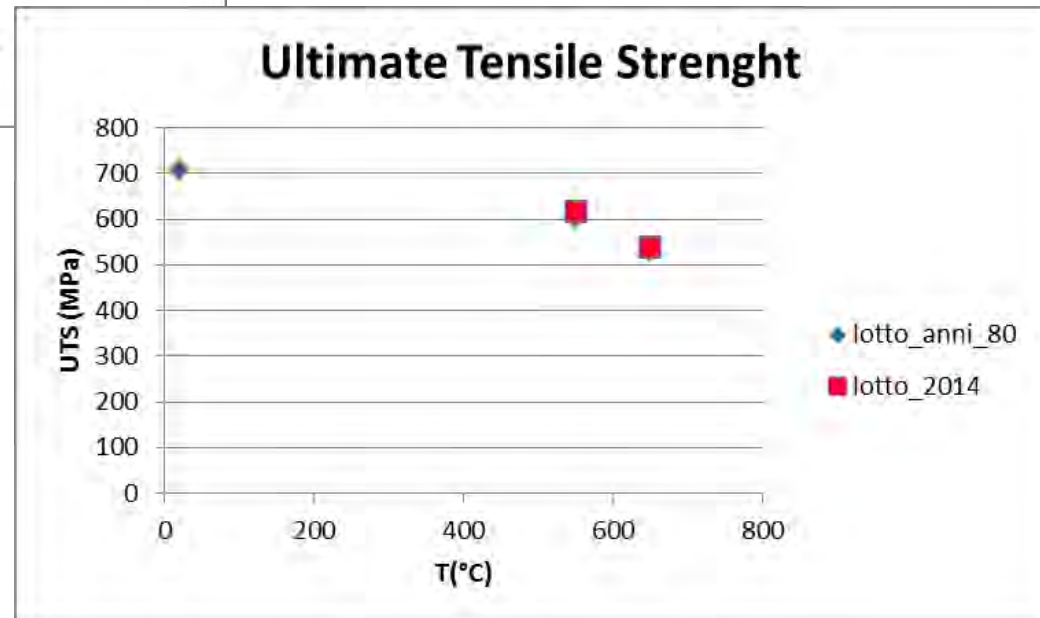
Confronto DS4; barre anni 80-laminato 2014



Dati lotto anni 80:

G. Filacchioni, U. de Angelis, D. Ferrara, L. Pilloni / Proceedings B.N.E.S., London, 1990

Proprietà meccaniche della nuova colata in linea con quelle del lotto di fine anni 80



Caratterizzazione del lingotto DS4

AdP PAR 2013: Produzione lingotto DS4

AdP PAR 2014: Caratterizzazione meccanica e microstrutturale

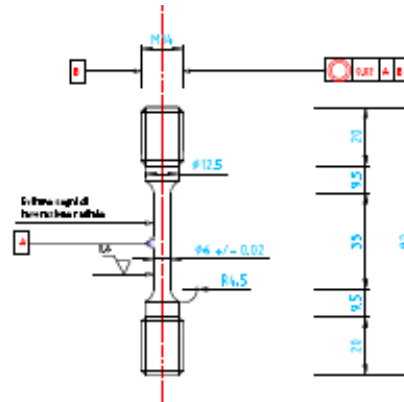
- Fasi del trattamento termico; materiale solubilizzato vs materiale laminato a freddo; misure di durezza (HV), Diametro di Grano (Microscopio Ottico), Prove di Trazione; anisotropia tra senso di laminazione e trasverso di lamiera;
- **Task 1, Prove di Corrosione Pb fluente**, atmosfera ossidante;
- **Task 2, Irraggiamento con Ioni**; inoltro della proposta a LNL, fabbricazione provino ed esecuzione primo turno di irraggiamento (secondo turno a dicembre);
- **Task 3, Prove di Creep** (fabbricazione provini e ripristino funzionamento macchine trasferite da Casaccia a Brasimone);
- **Task 4, Collaborazione Università di Pisa e laboratori USA** (fornitura materiale e fabbricazione provini)

Fabbricazione provini

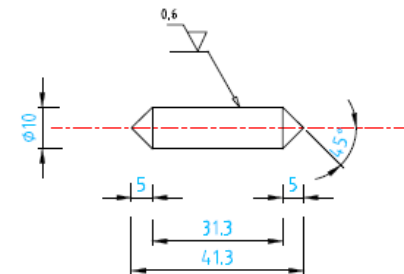
Provino Ion Irradiation (1° turno irraggiamento eseguito)



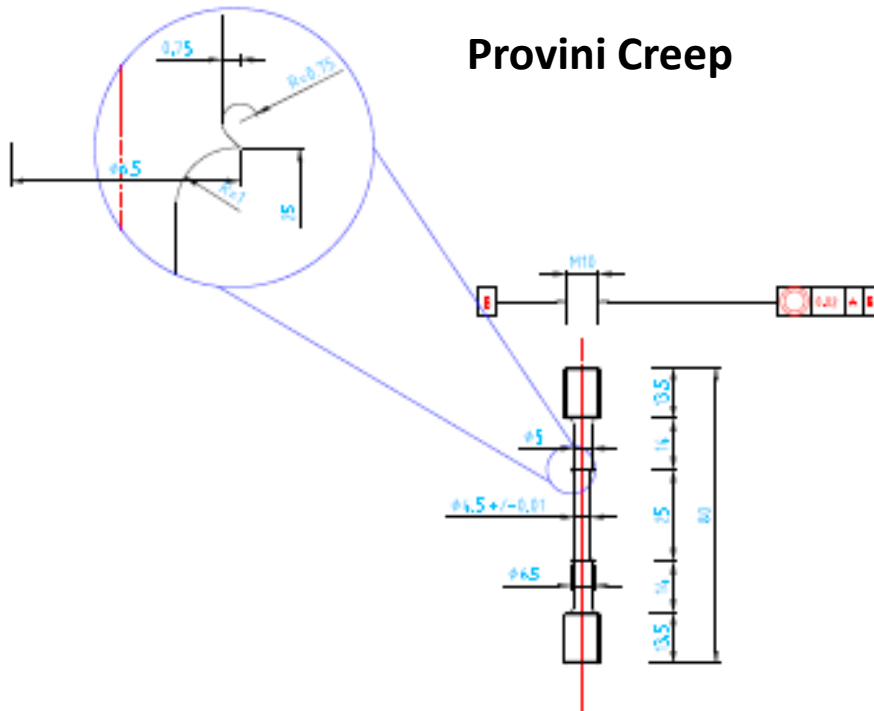
Provini Trazione



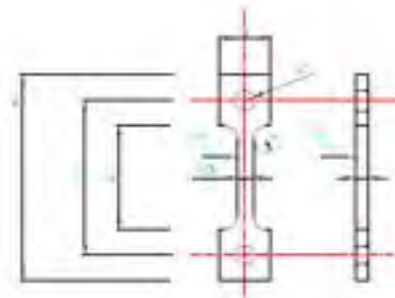
Provini Corrosione



Provini Creep



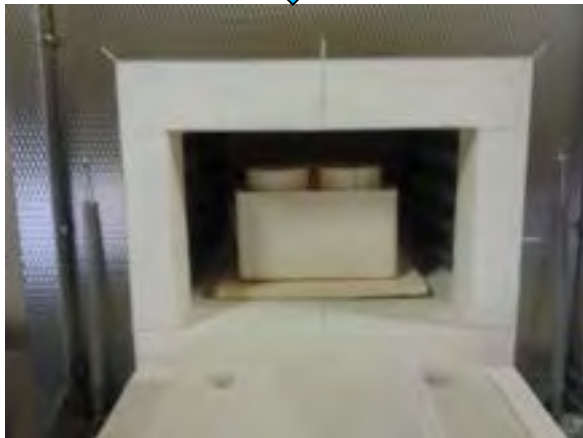
Micro Provini Trazione (UniPi)



Pregresso Test di corrosione; Pb stagnante 2013

Parametri di prova:

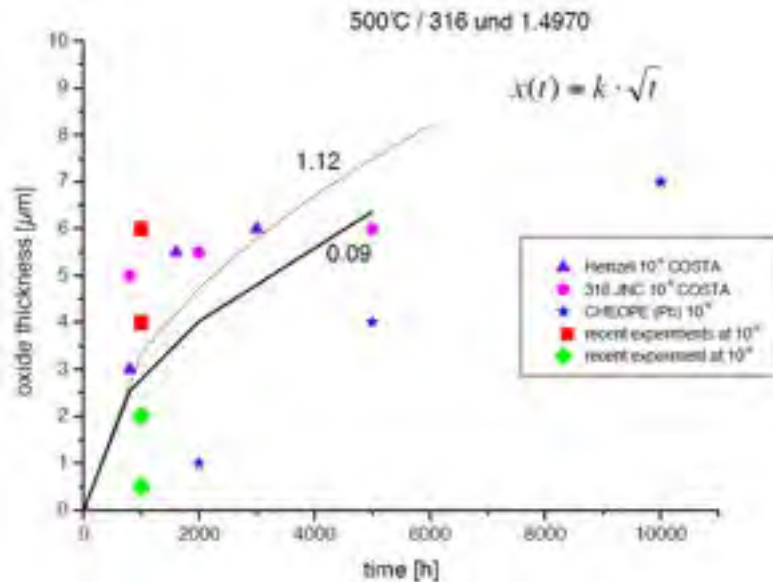
Il provino è immerso per metà della sua lunghezza in un bicchiere in Al₂O₃ riempito di Pb; il forno è flussato internamente con Argon.



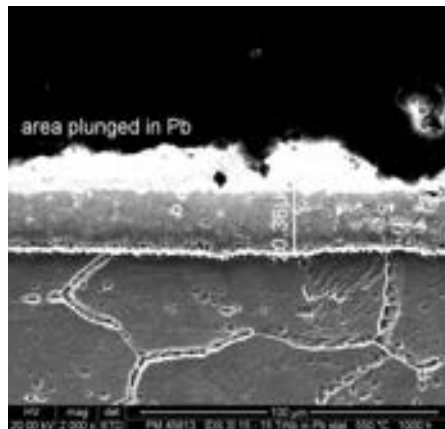
Provini testati	DS3 (15Cr-15Ni) DS4 (15Cr-25Ni) e DS5 (15Cr-25Ni)
Ambiente	Piombo Stagnante
Temperatura(°C)	550
O wt%	10^{-6} / $5 \cdot 10^{-4}$
Durata di prova (h)	900 (DS3) 1000 (DS4 and DS5)

Corrosione dei DS in atmosfera ossidativa

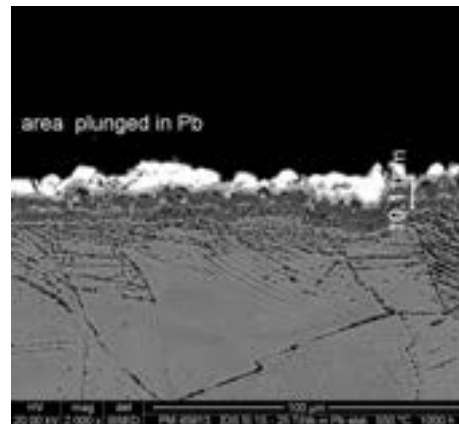
Vari austenitici di matrice 15-15 testati a 10⁻⁶ wt% Ossigeno



In DS3 e DS5 notiamo uno spessore di 8-10 μm, solamente qualche μm più ampio di quello che si misura in AISI 316 and 15-15 Ti dopo 1000 h a 500°C in Pb-Bi.
Nel DS4, invece, l'ampiezza dell'ossido risulta 15-20 μm.



DS4 = 15-20 μm



DS3 e DS5 = 8-10 μm

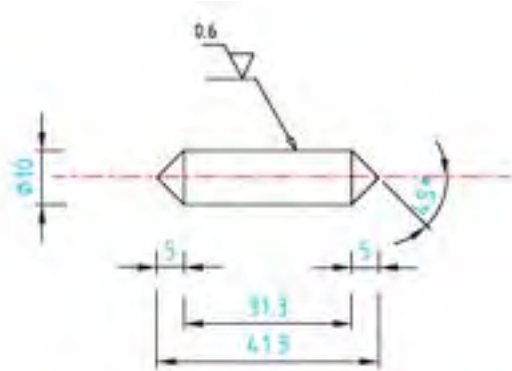
acciaio	Voto (da * a ***)
15-15 std	***
DS3 (15-15)	**
DS4 (15-25)	*
DS5 (15-25)	**

Attività 2015

Task 1: Prove di corrosione

Prove 550 ° C, Pb fluente, 1000-2000 ore. Necessaria operatività dell'impianto a Pb fluente LECOR. Atmosfera: 10^{-5} wt% O₂.

Fabbricazione 20 campioni.

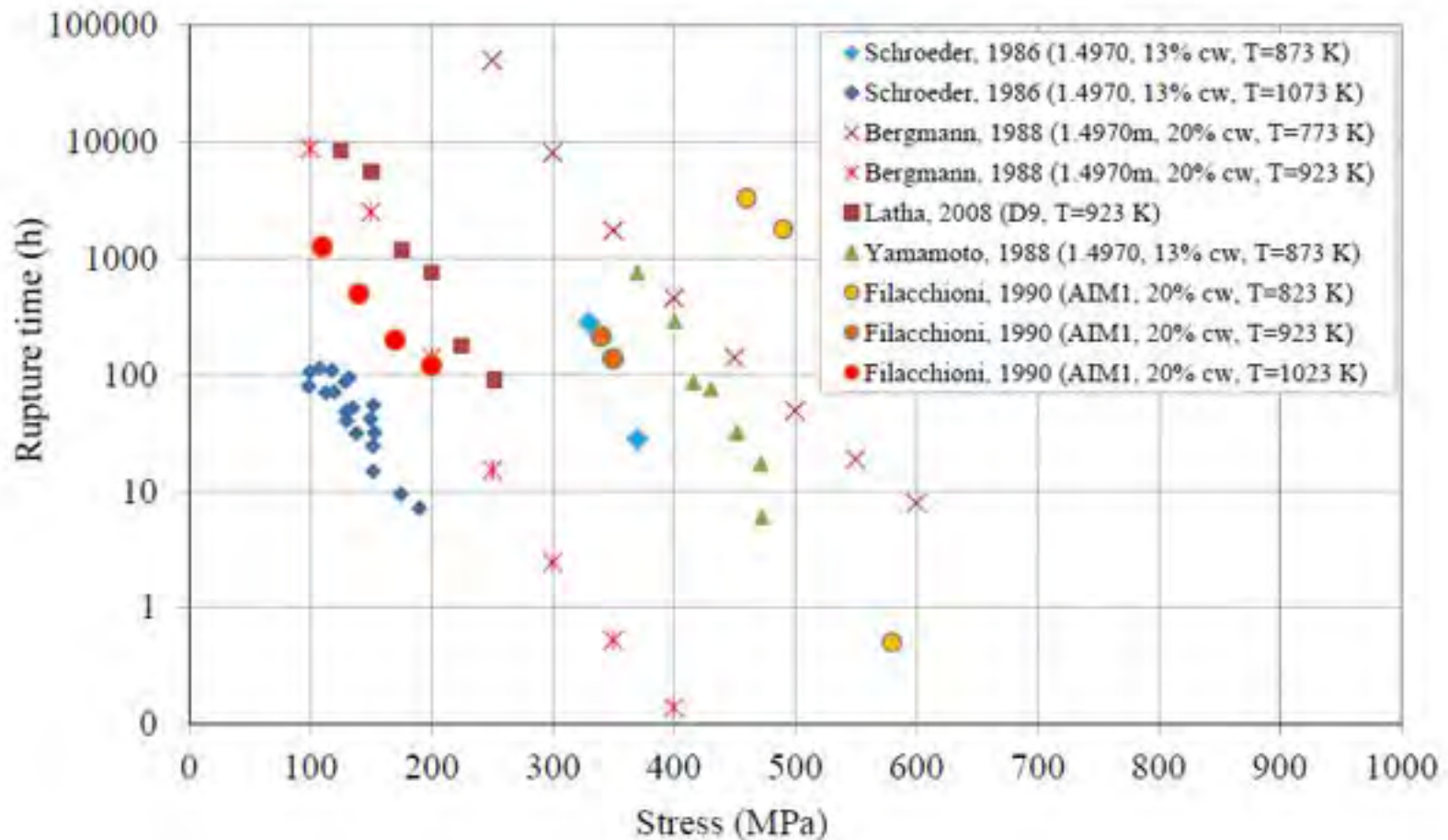


Matrice di prova proposta:

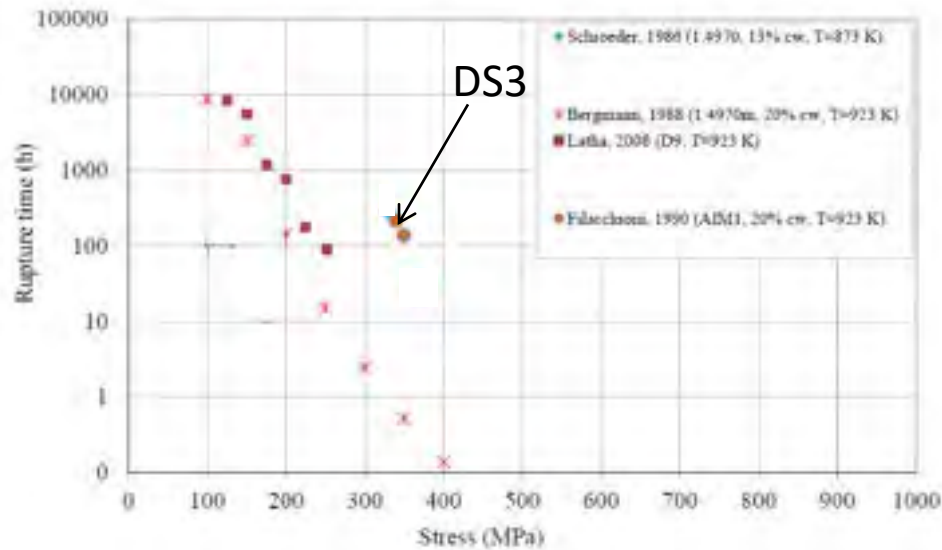
Series	Testing Temperature	Exposure (hrs)	N of samples
1	550°C	1000	8
2	550°C	2000	8

Caratterizzazione meccanica: Prove di Creep

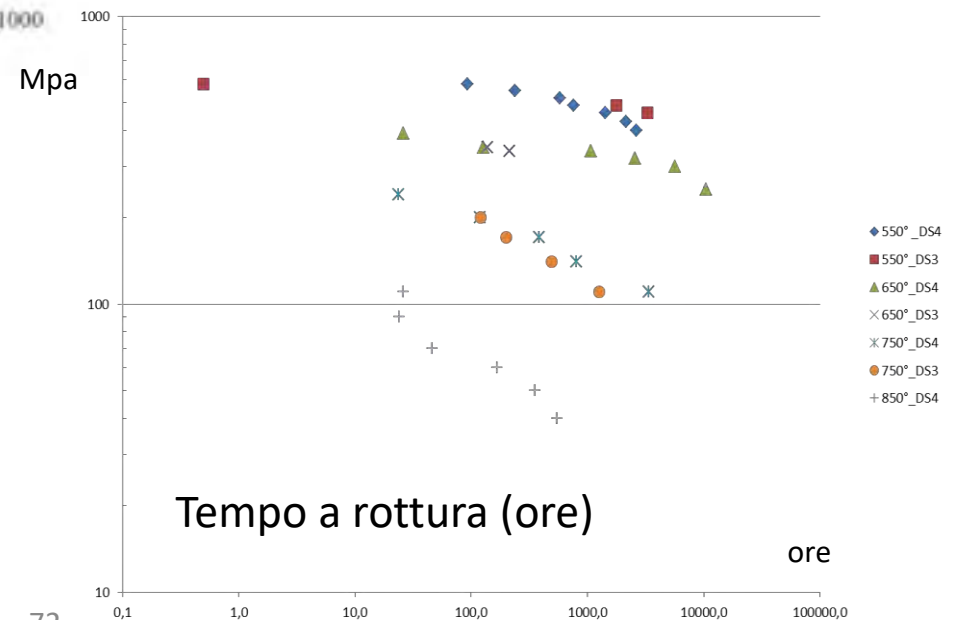
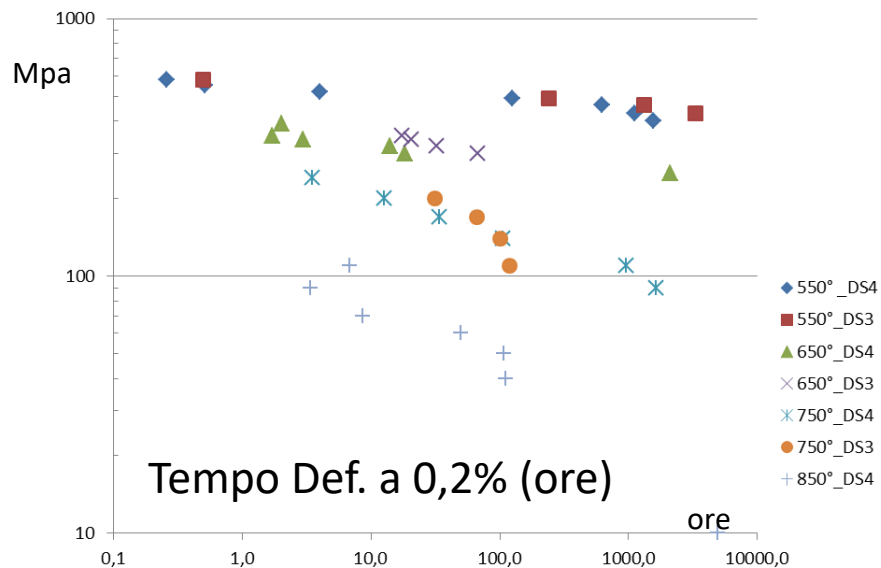
Proprietà a Creep; Confronto con altri acciai austenitici 15-15



Pregresso anni 90: Risultati a Creep dei DS



acciaio	Voto (da * a ***)
15-15 std	**
DS3 (15-15)	***
DS4 (15-25)	***
DS5 (15-25)	No dati



Attività 2015

Task 2: Prove di creep

Prove previste: 550-650 °C, fino a 8000 ore.

Necessario ripristinare il funzionamento delle macchine obsolete trasferite dai laboratori di Casaccia a quelli di Brasimone.

Matrice di prova proposta:

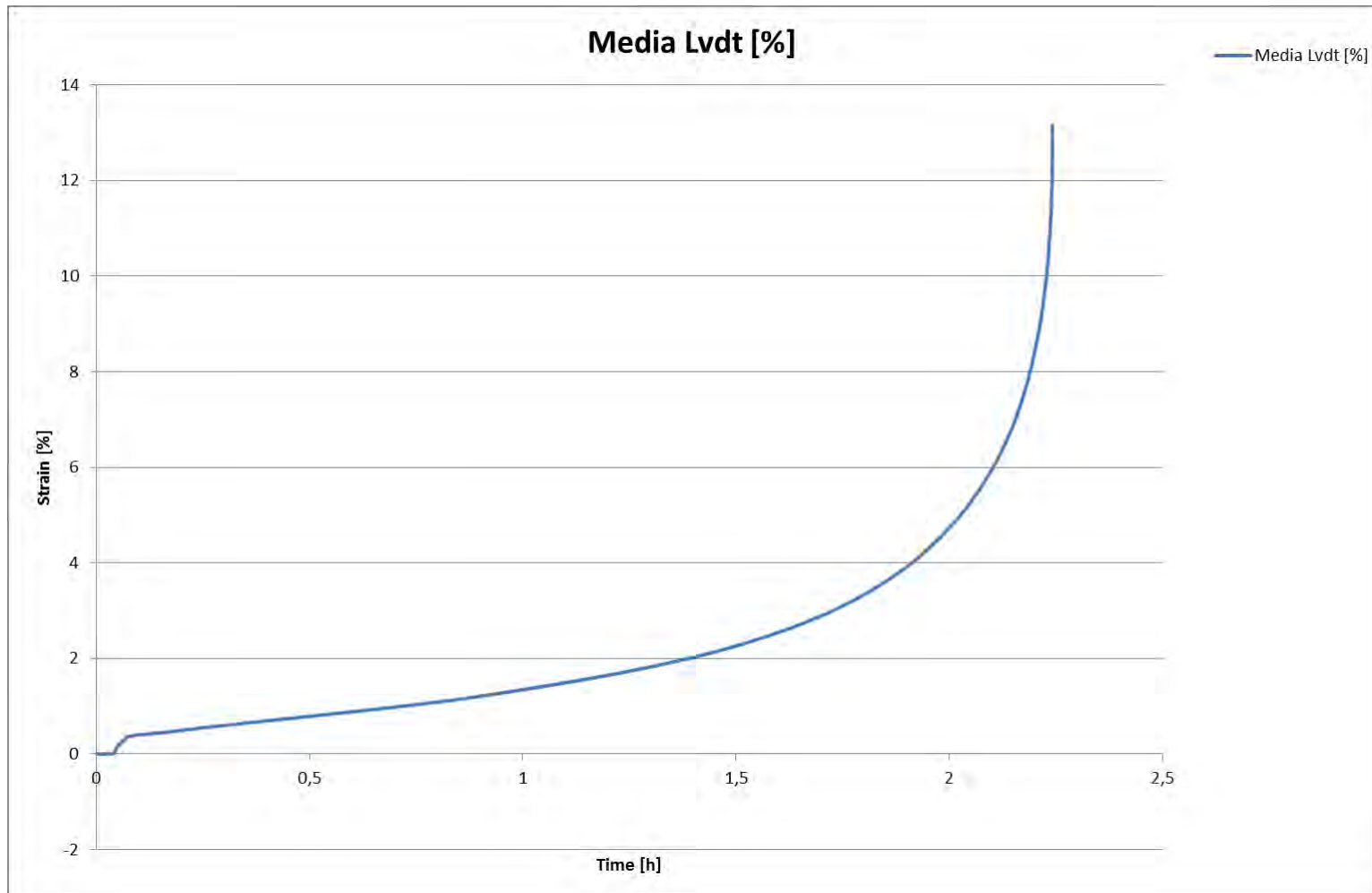
Series	Testing Temperature	Initial Stress (MPa)	N of samples
1	550°C	400	2
2	550°C	430	2
3	550°C	460	2
4	550°C	490	2
5	550°C	520	2
6	550°C	550	2
7	550°C	580	2
8	650°C	250	2
9	650°C	300	2
10	650°C	320	2
11	650°C	340	2
12	650°C	350	2
13	650°C	390	2
14	650°C	73415	2

Prove già eseguite



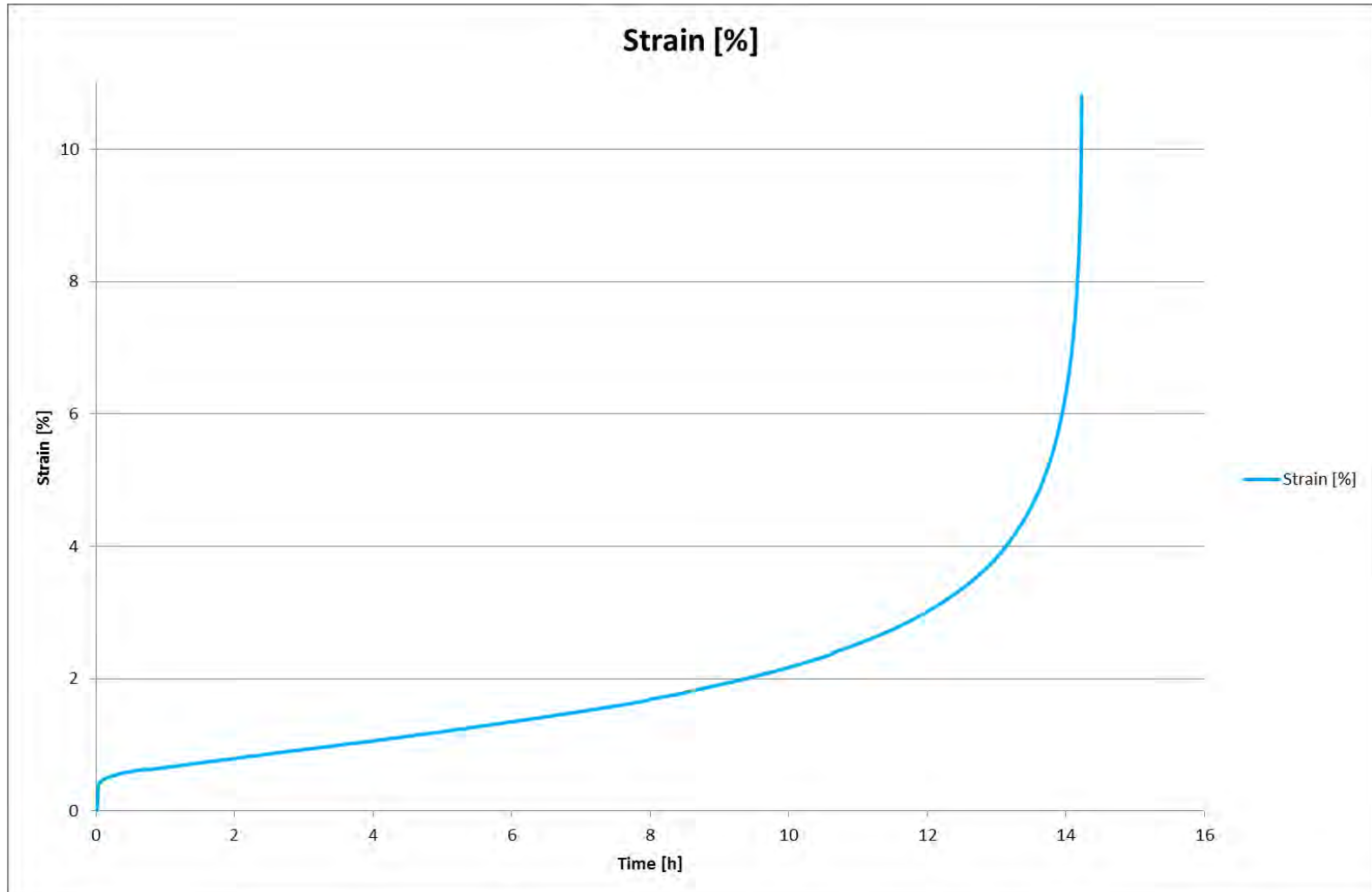
Attività 2015

Prova 650°C – 415 Mpa (Yield Stress)



Attività 2015

Prova 650°C – 390 Mpa

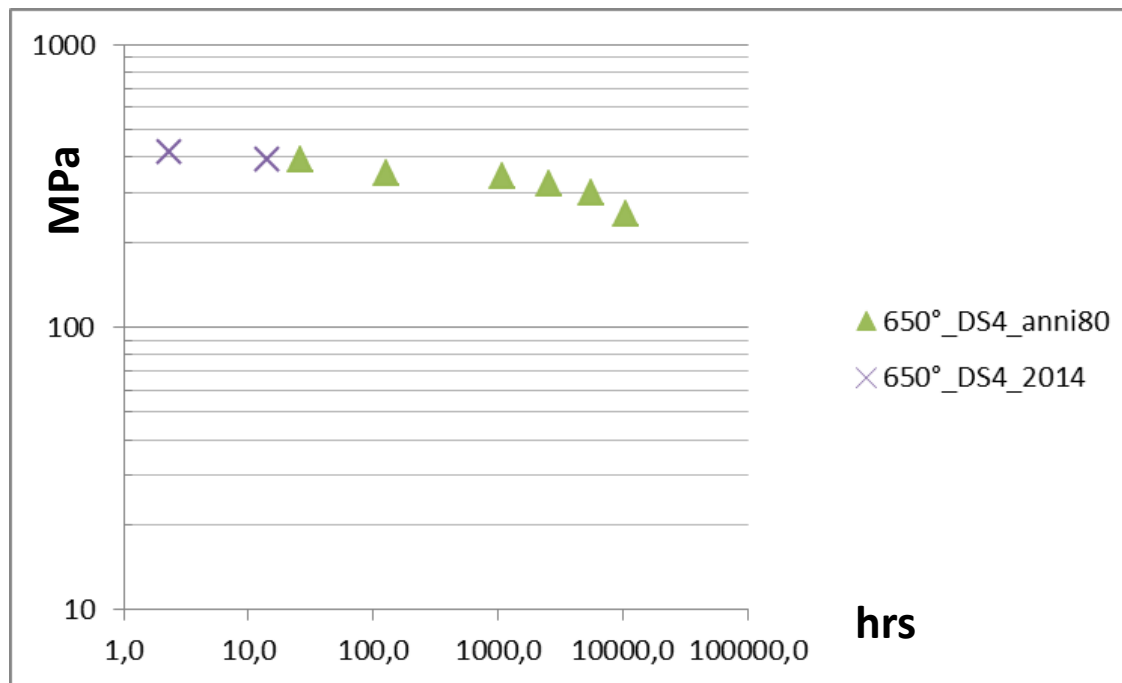


Attività 2015

Task 2: Prove di creep eseguite in modalità tempo a rottura

- 2 telai ripristinati su 12
- Hall non ancora termostata per l'esecuzione di prove di creep strumentato (misura del creep rate)

Confronto tra i tempi a rottura ottenuti:



Attività 2015

Task 4: Collaborazione Università di Pisa + ANL (Argonne National Laboratories) + INL (Idaho National Laboratories) + Urbana Laboratories

Task 4.1

Preparazione micro-provini tensile da irraggiare con fotoni (analisi Raggi X) al Sincrotrone di Argonne (ANL) per monitorare il movimento delle dislocazioni durante prova di trazione in temperatura.

Task 4.2

Fornitura di materiale per fabbricazione di provini cilindrici per prove di creep biassiale. Matrice di prova dipendente dal sistema di pressurizzazione dei cilindretti (massima pressione interna che si riesce a raggiungere) e dal rapporto spessore/diametro che la tecnologia adottata ci consente (lavorazione di macchina o elettroerosione). Condizioni operative (550°C) o incidentali (fino a 850°C).

Task 4.3

Fornitura di materiale per caratterizzazione microstrutturale dell'adesione di coatings prodotti da ANL ed IIT sul substrato DS4. Ricoperti micro-provini tensile con allumina amorfa (Pulsed Laser Deposition, IIT) per poter essere inseriti in una campagna di irraggiamento con neutroni.

Produzione lamiera DS4; conclusioni

- Prodotti 80 Kg di acciaio DS4; eseguite le laminazioni a caldo e a freddo (incrudimento 20%);
- Sui laminati (sia allo stato solubilizzato che incrudito) eseguite analisi ottiche, prove di durezza HV, prove di trazione. I Risultati mostrano un affinamento della dimensione del grano austenitico a seguito del processo di deformazione a freddo. Tale affinamento è più evidente in prossimità delle superfici esterne e giustifica la maggior durezza lì registrata. La dimensione del grano nel solubilizzato varia da 35 a circa 50 micron e nel laminato a freddo varia da 30 a 35 micron. Tali caratteristiche hanno influito sulle variazioni delle proprietà meccaniche registrate sul materiale prima e dopo la laminazione a freddo.
- Si rileva consistente anisotropia delle proprietà tra i provini estratti nella direzione di laminazione e quelli estratti dal trasverso di lamiera.
- Le proprietà meccaniche della nuova colata corrispondono a quelle del lotto di fine anni '80.

Caratterizzazione del lingotto DS4; conclusioni

- **Task 1, Prove di Corrosione Pb fluente**, in attesa del funzionamento dell'impianto a piombo fluente LECOR;
- **Task 2, Irraggiamento con Ioni**; in corso...primo turno di irraggiamento già svolto a giugno (secondo turno a dicembre);
- **Task 3, Prove di Creep**; fabbricazione provini e ripristino funzionamento macchine trasferite da Casaccia a Brasimone ; prove «tempi a rottura» in corso; termostatazione della hall per l'esecuzione delle prove di creep strumentato.
- **Task 4, Collaborazione Università di Pisa e laboratori USA**; fornitura materiale e fabbricazione provini.

Grazie dell'attenzione

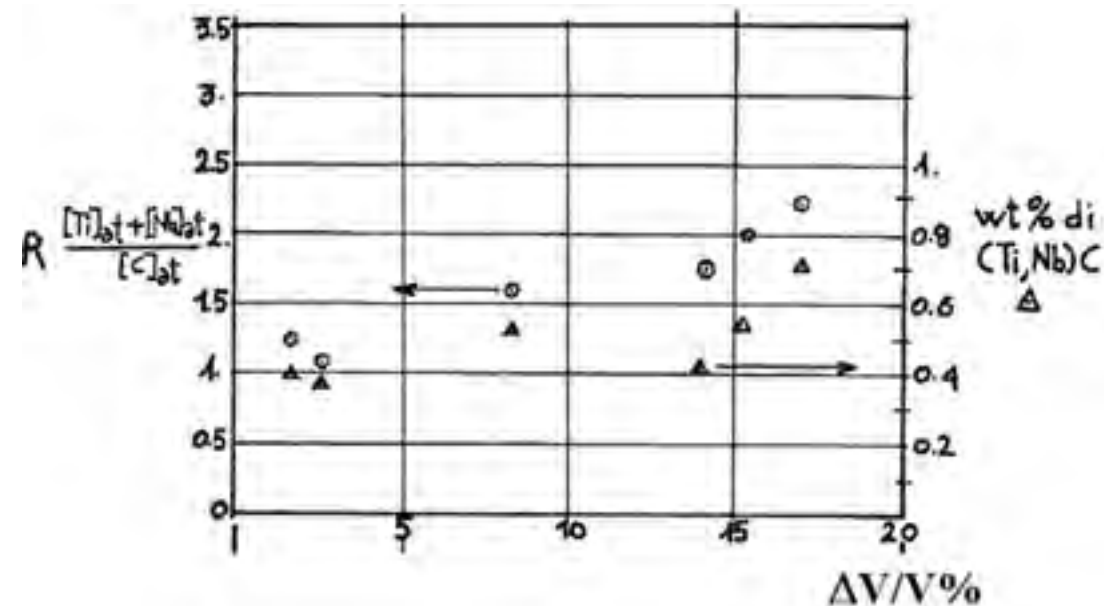
Diapositive di riserva

Introduzione

Concetto chiave 2 : Precipitazione primaria e secondaria dei carburi:

Una buona resistenza a creep alle alte temperature per un acciaio austenitico è essenzialmente dovuta alla microprecipitazione dei carburi, i quali vanno a formare una fine dispersione sul reticolo dislocativo;

- Precipitazione primaria, quella che ha luogo durante il trattamento termico dell'acciaio. Bassa precipitazione primaria significa sufficiente contenuto "libero" di Carbonio, Ti e Nb in soluzione solida per garantire una benefica precipitazione secondaria (in esercizio).
- Precipitazione secondaria, cosiddetta "in-service", che ha luogo per effetto dell'esposizione ad alta temperatura all'interno del reattore. Questa sorta di precipitazione "in esercizio" risulta altamente efficace come inibitore di movimento per i difetti lineari.



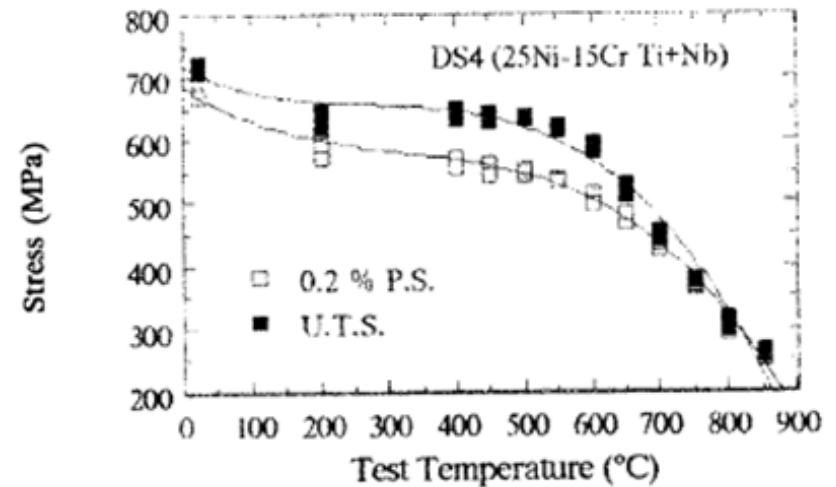
La precipitazione dei carburi non agisce solo sulla resistenza a creep del materiale; influenza anche positivamente la stabilità sotto irraggiamento. E' qui riportato il risultato grafico di un'analisi condotta nei primi anni 90 riguardante la dipendenza del comportamento a swelling dalla precipitazione primaria e dal rapporto di stabilizzazione per una matrice 15Cr-15Ni. Tanto la precipitazione primaria risulta bassa (tenendo il rapporto di stabilizzazione vicino a 1) tanto più quella secondaria (altamente desiderabile) verrà favorita mantenendo basso lo swelling.

15-15DS; 105dpa, T_{irr}=450°C

Mechanical Characterization: Tensile tests

Results; DS4

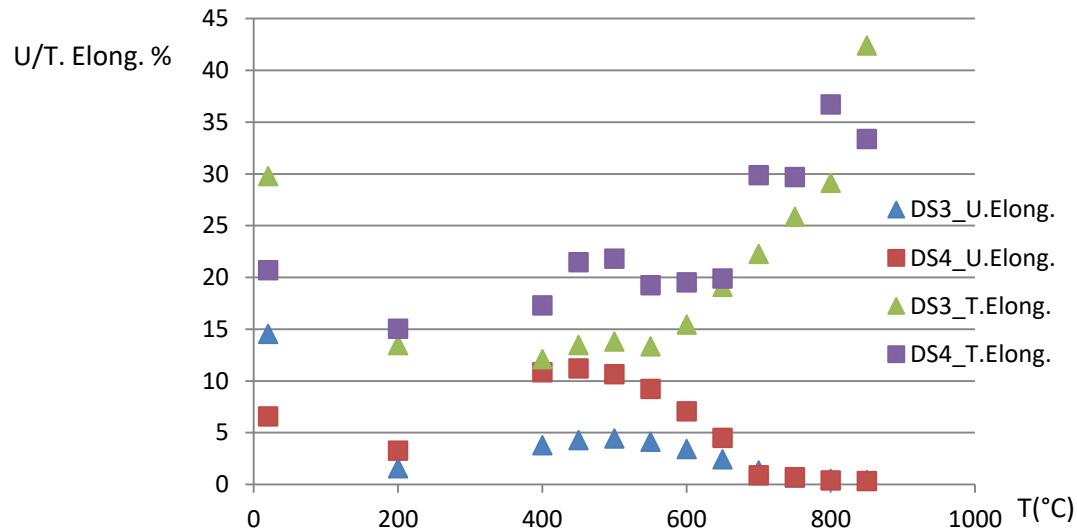
T °C	0.2% PS MPa	U.T.S. MPa	U.Elon. %	T.Elon. %	R.A. %
20	673	708	6.55	20.69	70.68
200	601	666	3.26	15.01	64.23
400	570	650	10.82	17.28	55.5
450	560	639	11.2	21.44	56.67
500	548	624	10.64	21.79	54.79
550	530	601	9.2	19.22	54.16
600	506	570	7.05	19.51	56.66
650	474	529	4.49	19.87	60.64
700	434	476	0.86	29.85	70.53
750	383	410	0.67	29.69	78.39
800	320	329	0.36	36.68	84.62
850	245	263	0.32	33.36	86.04



No relevant differences in UTS and 0,2% PS in the two DS steels

Mechanical Characterization: Tensile tests

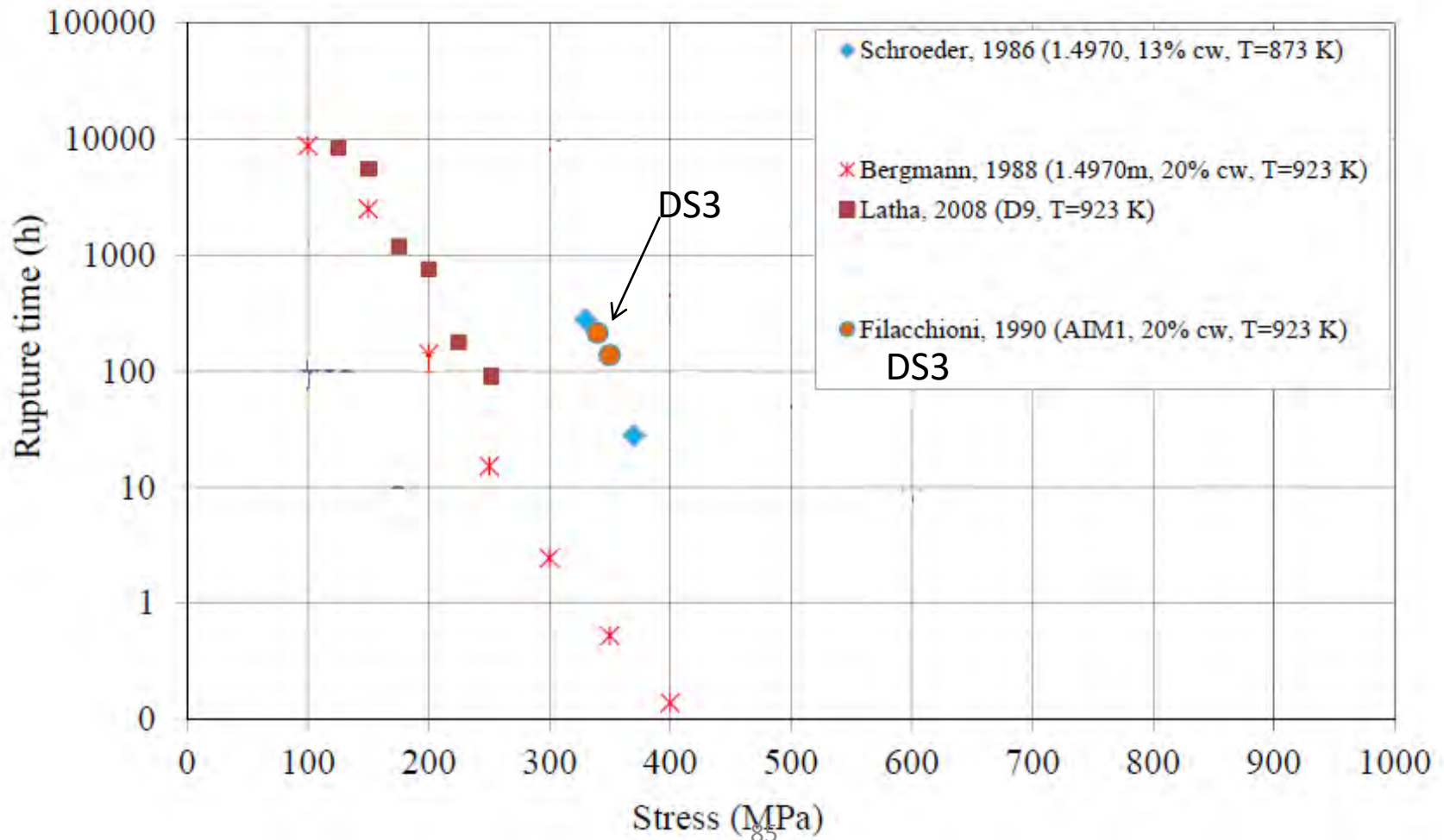
Comparison Total and Uniform Elongation



At room temperature and at higher test temperature (850°C), the total elongation of the lower Nickel content steel (DS3) is higher than that of DS4 (25% Ni), in the intermediate range DS4 shows a higher total toughness. Concerning the uniform elongation DS4 behaviour is excellent. In the interval between 400 and 600-650°C the steel performs values that are almost twice respect to those of the other steel. This behavior, similar to the best ones for the stainless steels with high yield strength, is symptomatic of good characteristics of stretchiness, performing delayed onset of mechanical instability.

Caratterizzazione meccanica: Prove di Creep

Proprietà a Creep; Confronto con altri acciai austenitici 15-15



Mechanical Characterization: Creep tests

Results; DS4

T (°C)	σ(MPa)	ε _m [•] (1/h)	t _{0.2} (h)	t _R (h)	ε _f (%)	Z _f (%)
550	400	0.394	1560	2628	1.56	4.25
	430	0.568	1111	2140	1.67	3.74
	460	1.753	620	1424	2.25	5.97
	490	3.582	125	765	7.79	10.88
	520	6.041	4	575	6.07	18.35
	550	42.436	0.52	238	9.47	26
	580	331.73	0.26	93.4	14.89	44.66
650	250	0.386	2096	10507	16.58	68.76
	300	0.949	18.5	5637	19.34	57.54
	320	2.691	14	2570	12.96	63.2
	340	10.393	3	1067	12.97	54.94
	350	131.188	1.71	126.2	10.68	41.61
	390	572.69	2.02	26	12.52	44.49
750	90	1.212	1633			
	110	1.356	955	3358	36.58	85.11
	140	10.312	106	802	28.88	83.34
	170	16.206	34	384	32.29	79.32
	200	64.209	12.8	119	29.19	77.15
	240	356.75	3.5	23.6	19.01	70.75
850	10	0.252	4962			
	40	16.601	112	544	52.69	91.07
	50	17.856	108	354	49.89	90.59
	60	31.42	50.3	167	63.62	92.49
	70	173.07	8.7	46.2	37.35	89.91
	90	285.87	3.4	24.1	44.89	93.08
	110	471.76	6.9	26.1	37.84	86.41

Creep laws

To correlate secondary creep speed to the applied stress

Norton Bailey (low/intermediate stresses)

$$\dot{\varepsilon}_{ss} = A\sigma^n$$

Sherby-Burke (high stresses)

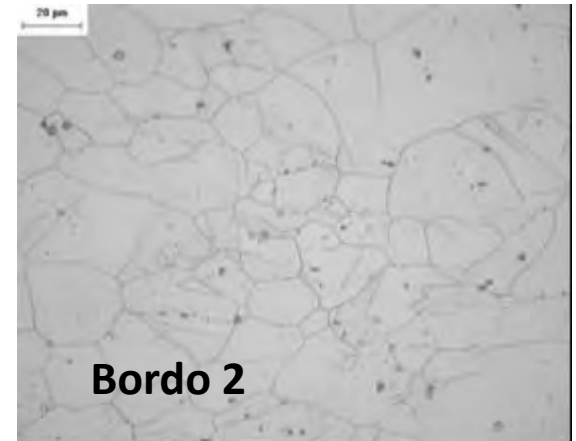
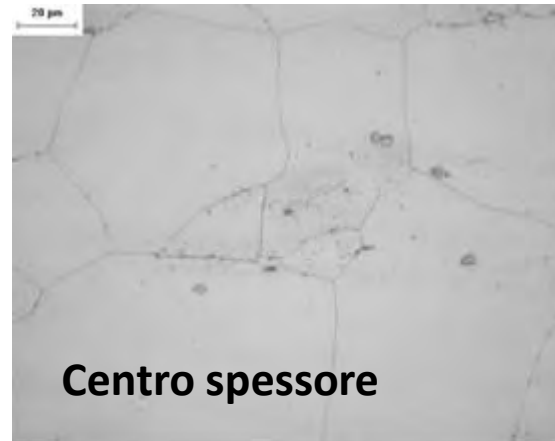
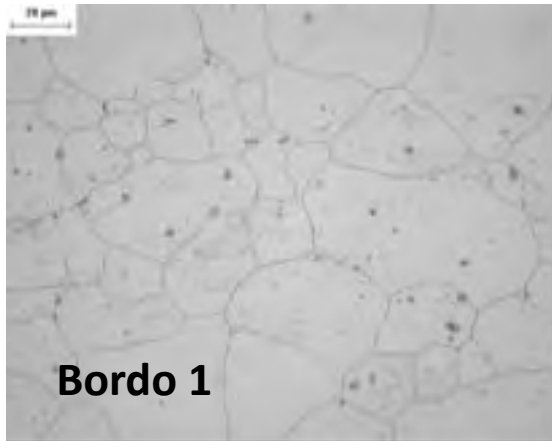
$$\dot{\varepsilon}_m = A \cdot \exp(\beta \cdot \sigma)$$

Garofalo (comprehensive)

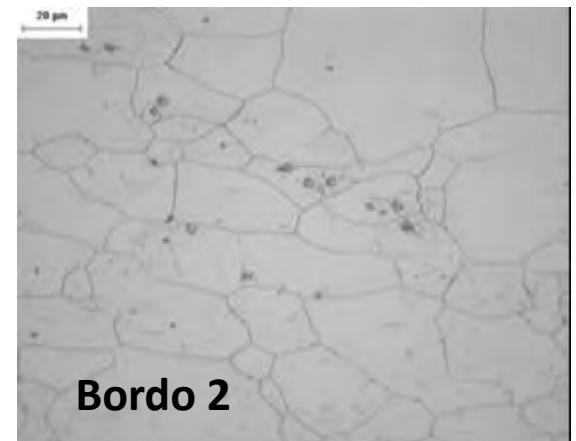
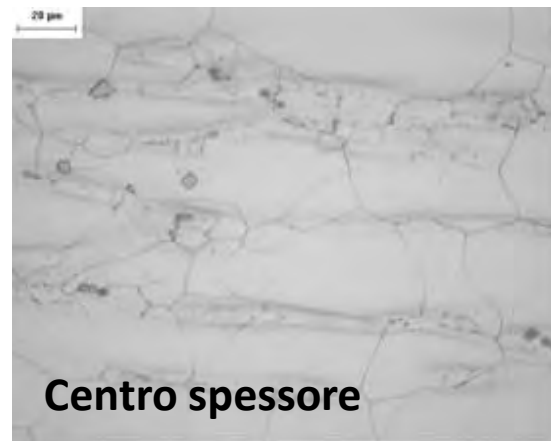
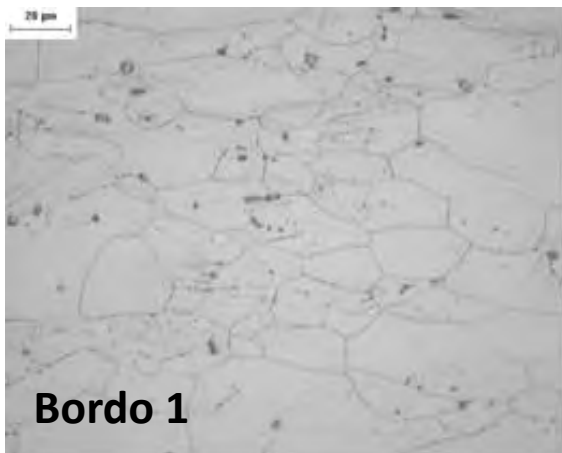
$$\dot{\varepsilon}_m = A^{II} \cdot [\sinh(\alpha \cdot \sigma)]^n$$

Grain Size sezione longitudinale

Materiale solubilizzato



Materiale incrudito al 20%



Attività 2015

Task 3: Ion-Irradiation

Proposta all'LNL:

In data 12/12/2014 è stata inviata la Proposta a LNL (Laboratori Nazionali di Legnaro) per ottenere un irraggiamento a 100 dpa con ioni pesanti (58 Ni, 110 MeV).

Risposta dell'LNL:

Ci sono stati concessi 3 turni da due giorni l'uno; a luglio, a dicembre e il primo semestre dell'anno prossimo.

Irraggeremo due campioncini 0,5x2 cm per tre sessioni per sei giorni totali per ottenere il danneggiamento a 100 dpa.

Campagna di test per verificare l'adesione coating-substrato. Proveni pronti a inizio giugno per poter essere inviati a IIT per ricoprimento.

Materiali e fabbricazioni

Qualifica, modellizzazione e analisi di coating e materiali strutturali
per sistemi LFR

*LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti
per applicazioni in sistemi refrigerati a metallo liquido pesante”*

Brasimone 19 Novembre 2015

A. Coglitore, A. Strafella

ENEA – SSPT-PROMAS-TEMAF

Dipartimento Sostenibilità dei sistemi produttivi e territoriali (SSPT)

Divisione Tecnologie e processi dei materiali per la sostenibilità (PROMAS)

Laboratorio tecnologie di materiali Faenza (TEMAF)



- 1. Ricerca e Sviluppo Tecnologie e Nuovi Materiali**
- 2. Qualificazione di Materiali e Componenti**
- 3. Servizi**

ENEA – SSPT-PROMAS-TEMAF:

2. Laboratorio termomeccanico

Strumenti

- Tre macchine universali MTS per prove materiali fino a 500 kN e 1500°C
- Dieci macchine per prove di creep a trazione fino a 1000°C
- Tre macchine per prove di creep in flessione fino a 1500°C
- Impianto di pressurizzazione per prove di scoppio/tenuta fino a 200 bar.



LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

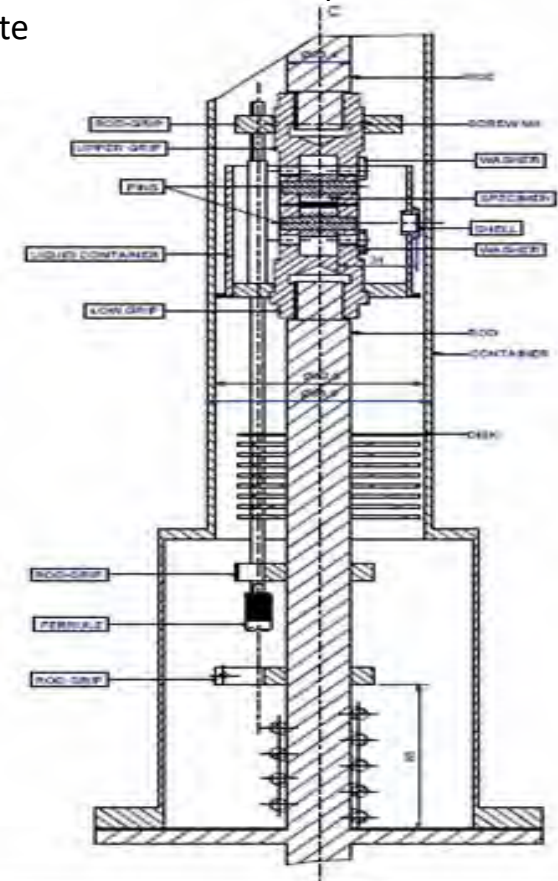
PAR2012 LP2 B1: Messa a punto di prove meccaniche in piombo liquido stagnante per la caratterizzazione di materiali strutturali ricoperti per applicazioni nucleari

Nell’ambito della campagna sperimentale di caratterizzazione dei rivestimenti realizzati nella precedente annualità sono state avviate le prove di creep-rupture in piombo liquido stagnante

- **Substrati** : AISI 316L , T91, 15-15 Ti (mod. Si, 20% CW)
- **Rivestimenti**: TiN (PVD), Fe(67wt%)Al(33wt%) (PVD),
Fe Cr (18-20 wt%)Al(8-10 wt%) (PVD), Ta (CVD))
- **Test preventivati** : 96

Questa attività ha richiesto modifiche ed implementazioni alla strumentazione presente presso i laboratori di caratterizzazione termomeccanica “Creep” presenti nei Laboratori ENEA di Faenza

- Realizzazione di una linea di gas inerte/riducente dedicata ad ogni singola macchina di prova
- Modifiche alla linea di carico del campione per il contenimento del piombo liquido per poter utilizzare le termo-camere da vuoto in dotazione
- Progettazione e realizzazione di un nuovo sistema di acquisizione (Hardware/Software)



Disegno complessivo della facility di prova

LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

PAR2013 LP2.b1_h: “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

- Sono stati realizzati i particolari dei disegni CAD per la progettazione finale dell’attrezzatura di prova per i test in metallo liquido
- È stato individuato come materiale prioritario il [15-15 Ti(Si)]
- Sono state eseguite delle prove preliminari nelle seguenti condizioni:
 - 550°C; 300MPa; in aria
 - 550°C; 400MPa; in aria
- Sono stati elaborati risultati delle prove
- I risultati sono stati confrontati con quelli di un acciaio austenitico analogo, disponibili in letteratura.
- Si è provveduto a identificare un adeguato sistema di aspirazione (come richiesto da normativa vigente, a causa della presenza di vapori di Pb durante i test)

LP2.B1_14 *“Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”*

Risultati:

Nell'ambito del ADP ENEA-MSE PAR2014 (attività LP2.B1_14):

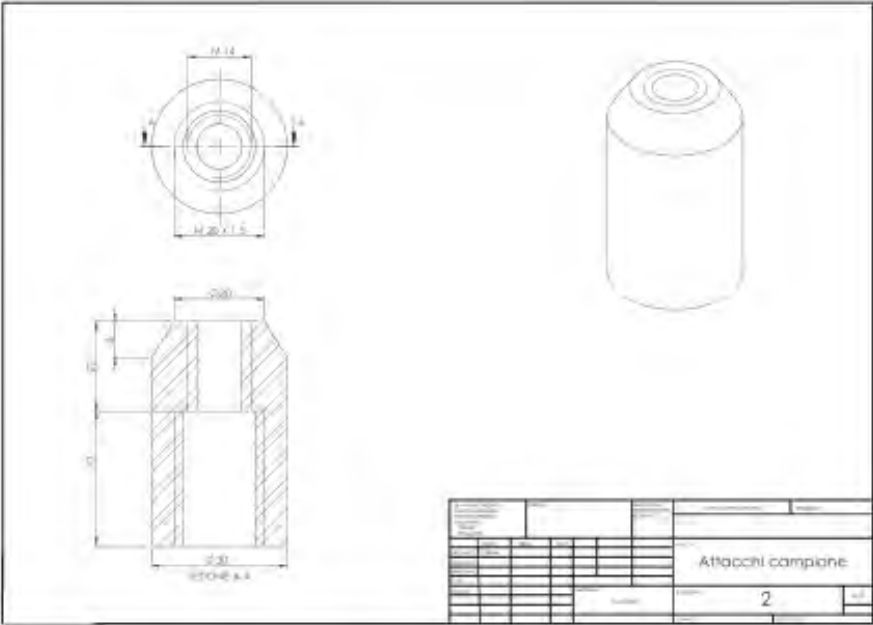
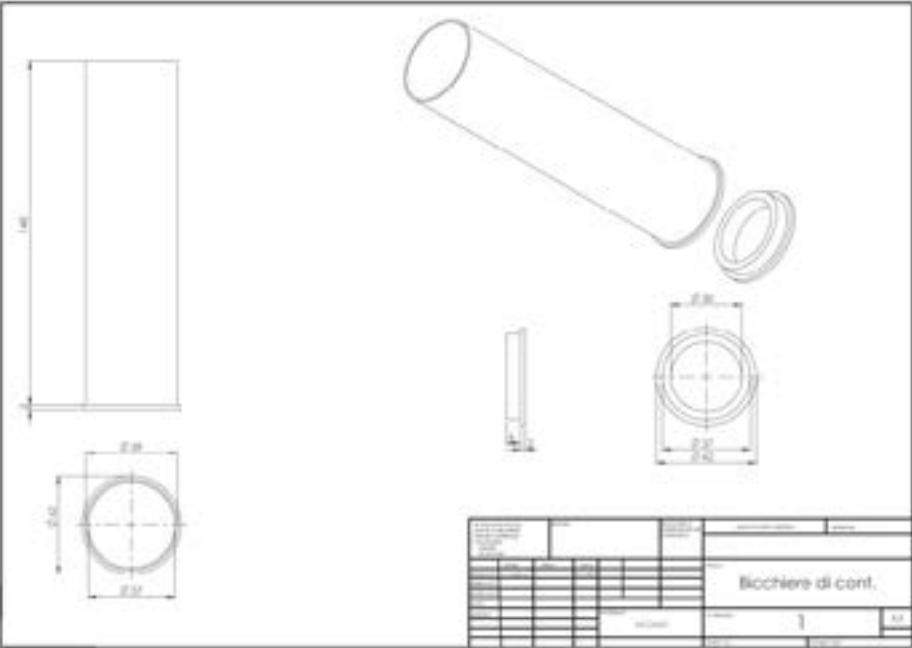
- Realizzazione dell'attrezzatura di prova per i test in metallo liquido

- Sono state eseguite delle prove nelle seguenti condizioni del materiale di riferimento individuato nel ADP ENEA-MSE PAR2013 LP2.b1_h (15-15 Ti (Si)):
 - 550°C; 400MPa; in aria
 - 550°C; 558MPa; in aria
 - 550°C; 576MPa; in Pb

- Sono stati elaborati risultati delle prove .

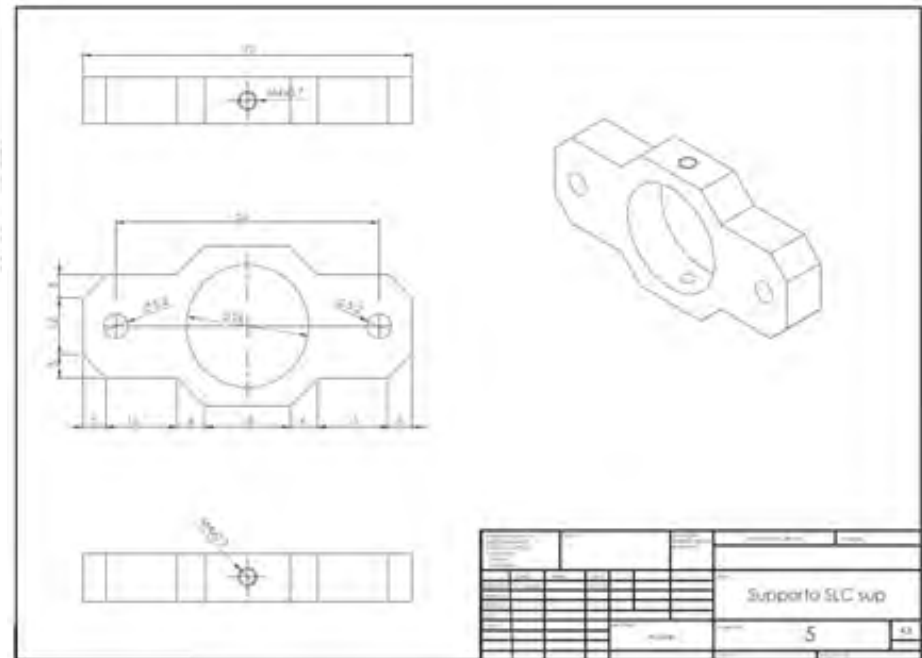
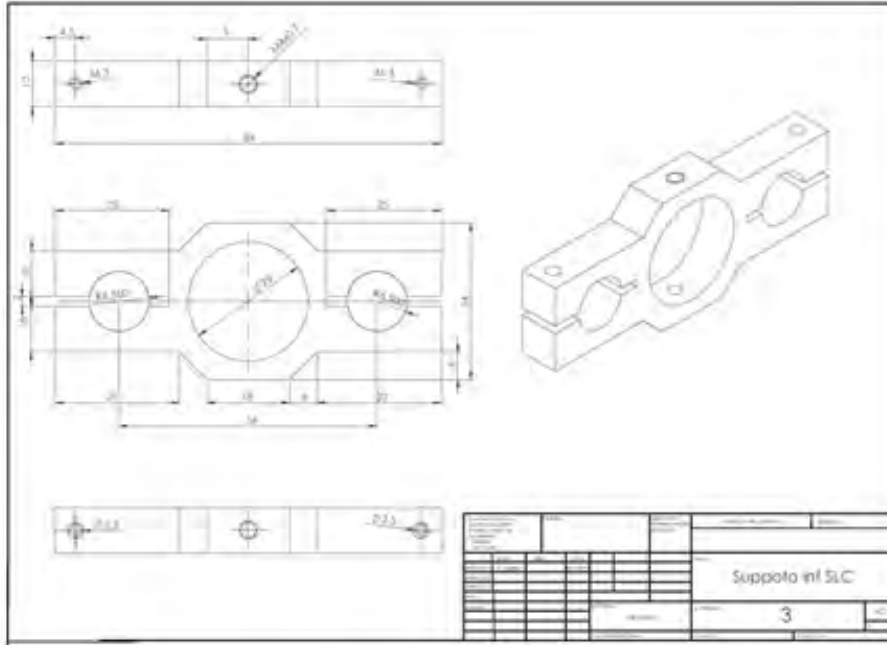
LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

Particolari disegni attrezzatura per prove in Pb



LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

Particolari disegni attrezzatura per prove in Pb



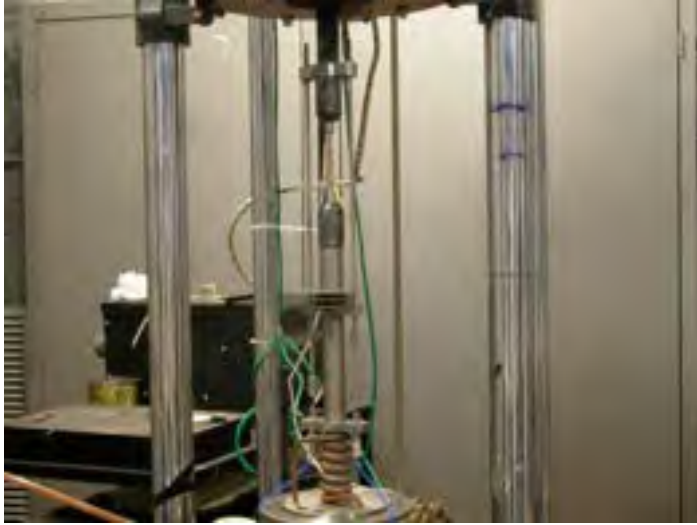
LP2.B1_14 *“Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”*

Particolari montaggio attrezzatura per prove in Pb



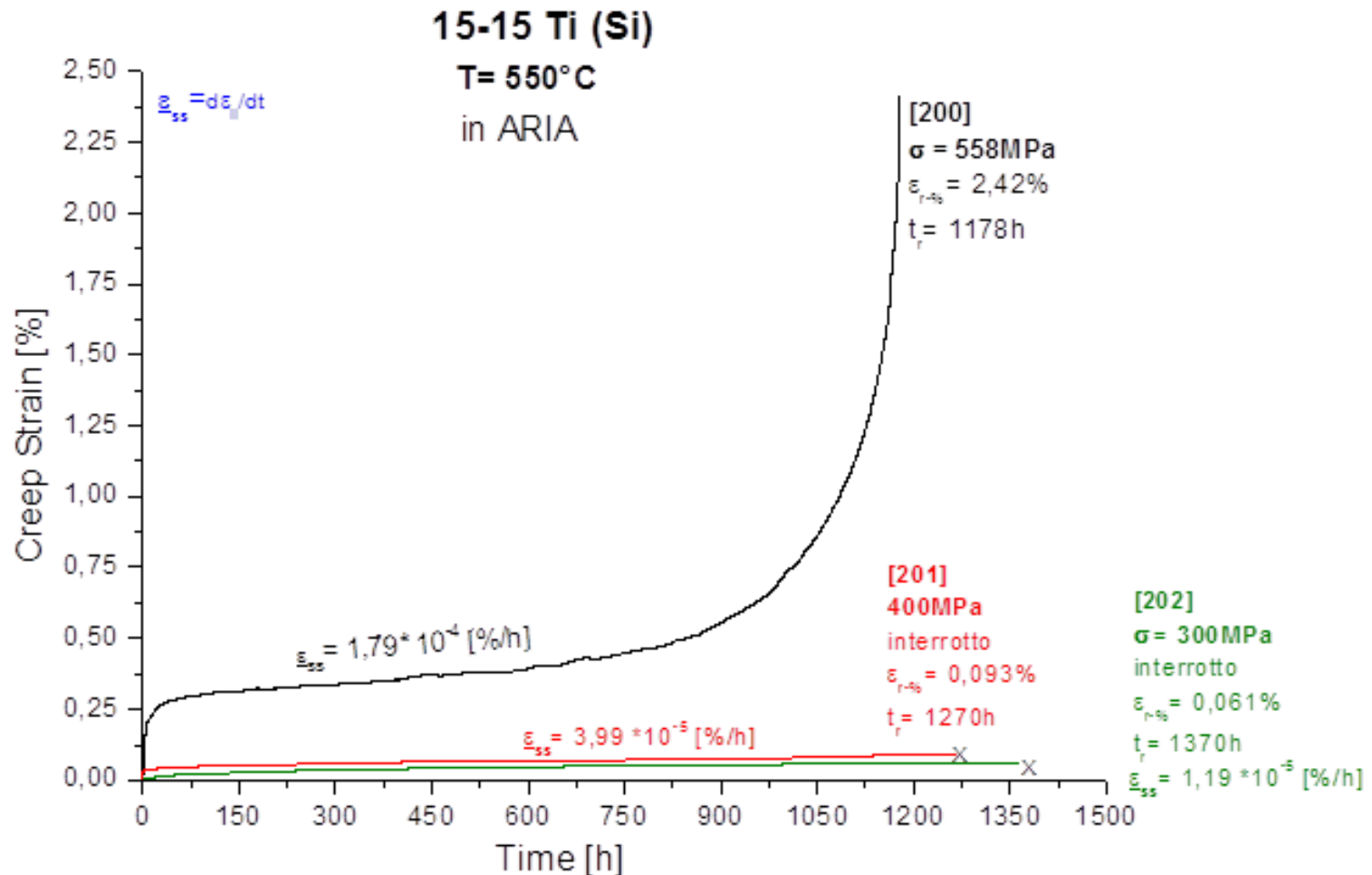
LP2.B1_14 *“Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”*

Particolari di campioni in aria ed in Pb



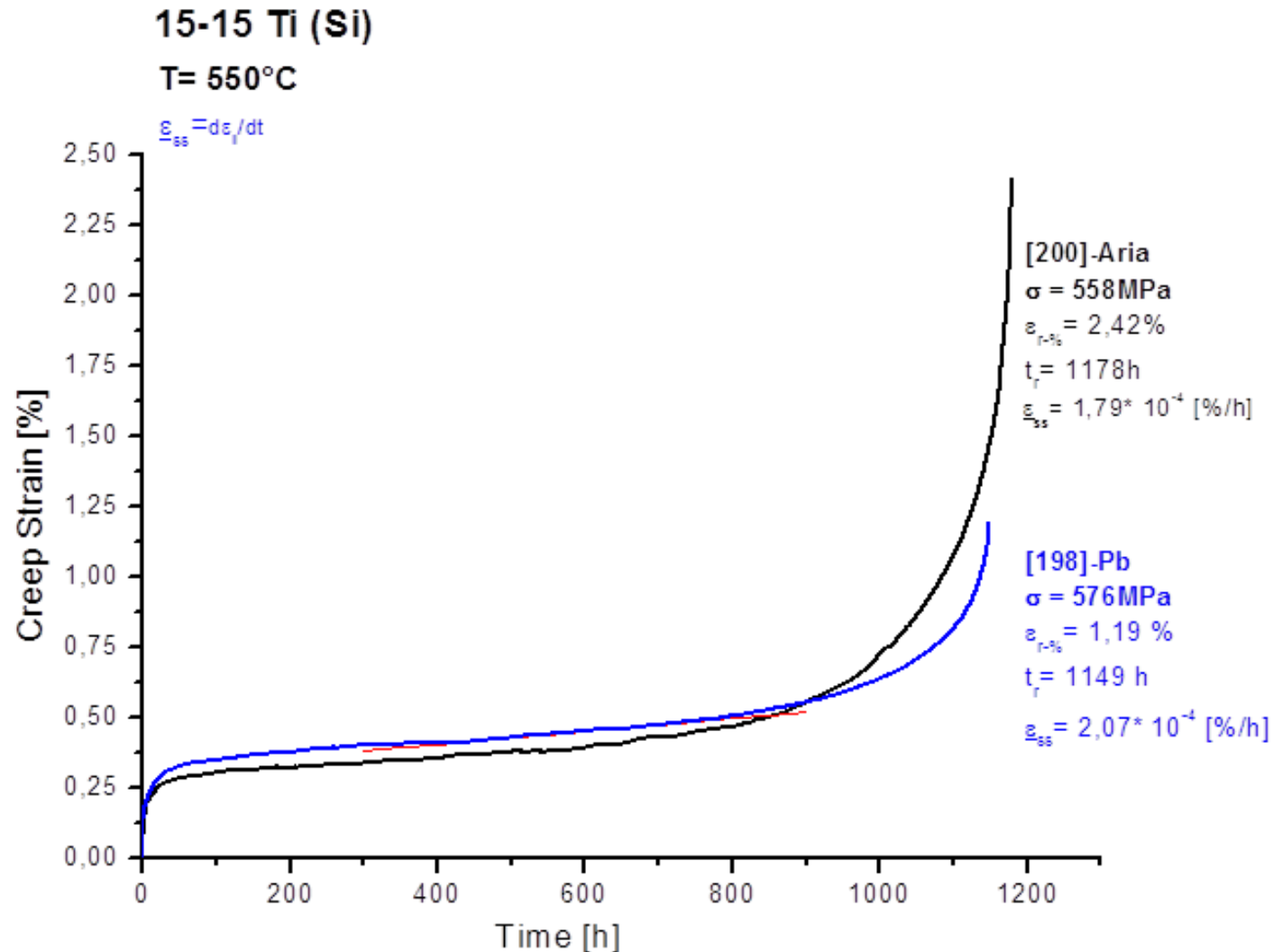
LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

Curva Creep Strain test 15-15 Ti (Si) in aria



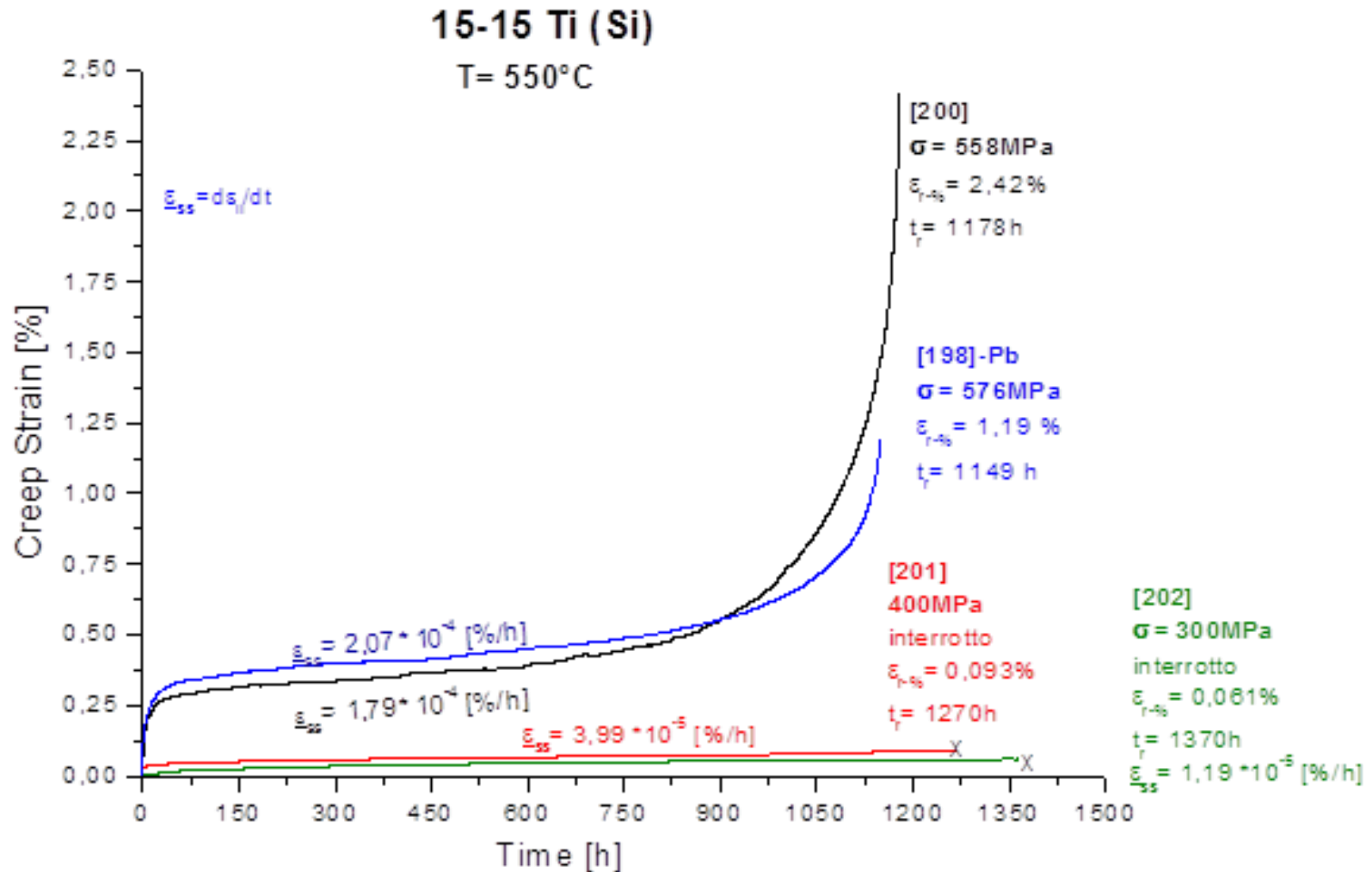
LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

Curva Creep Strain test 15-15 Ti (Si) a 558 MPa in aria ed 576 Mpa in Pb



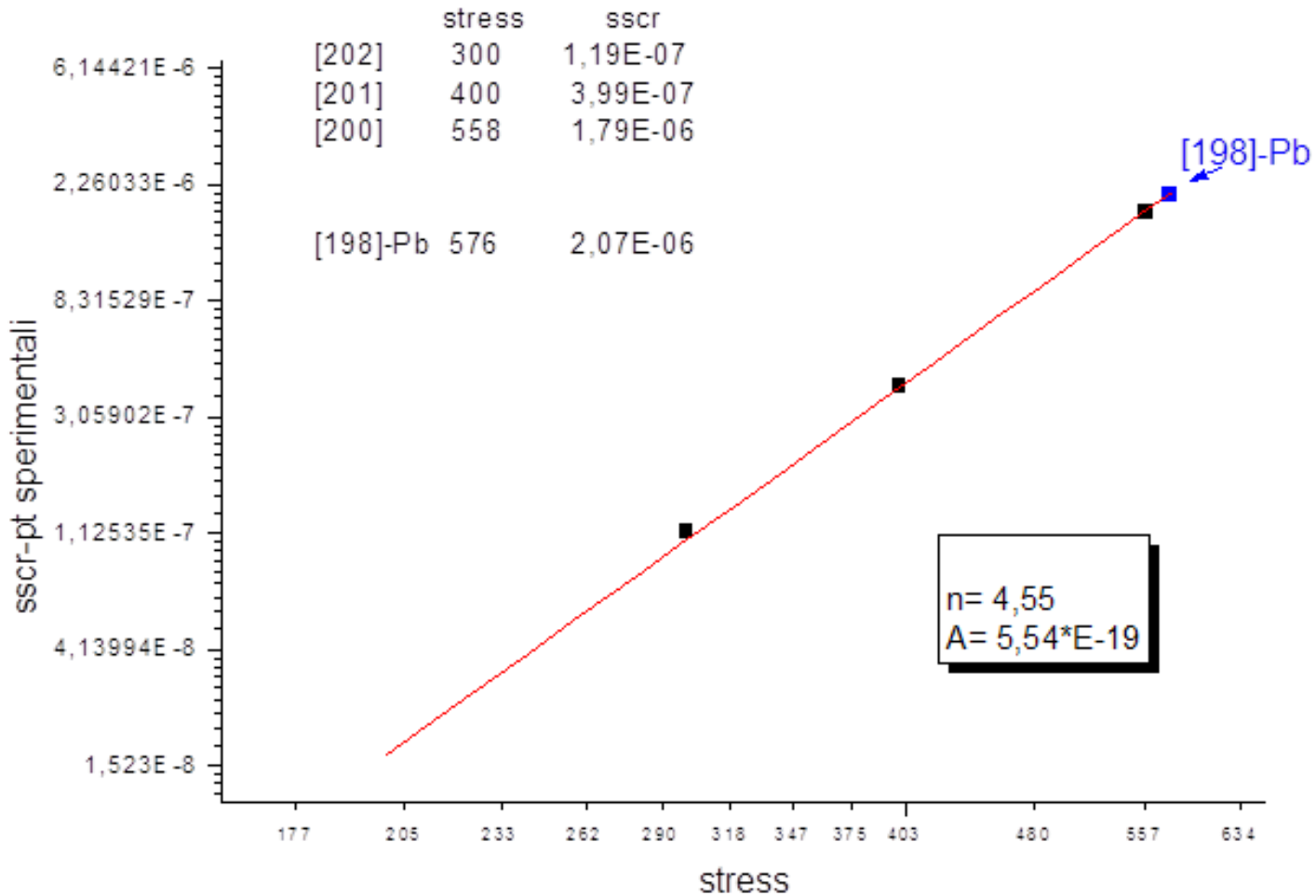
LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

Confronto curve Creep Strain test 15-15 Ti (Si) in aria ed in Pb



LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

Analisi delle steady-state creep rate (sscr)



LP2.B1_14 “Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”

CONCLUSIONI

Nell'ambito del ADP ENEA-MSE PAR2014 LP2.b1 sono state svolte le seguenti attività:

- realizzazione ed ultimazione dell'attrezzatura necessaria per la realizzazione della facility di prova per poter effettuare i test di creep-rupture in piombo;
- test di CREEP in aria di un acciaio austenitico 15-15 Ti (Si) a due differenti livelli di carico (400 e 558MPa) ;
- test di CREEP in piombo di un acciaio austenitico 15-15 Ti (Si) a 576MPa
- confronto dei risultati ottenuti
- determinazione dei parametri del secondario per i test in aria, in accordo con la legge di Norton

LP2.B1_14 *“Prove di CREEP-RUPTURE su materiali strutturali ricoperti per applicazioni in sistemi refrigerati a metallo liquido pesante”*

FINE

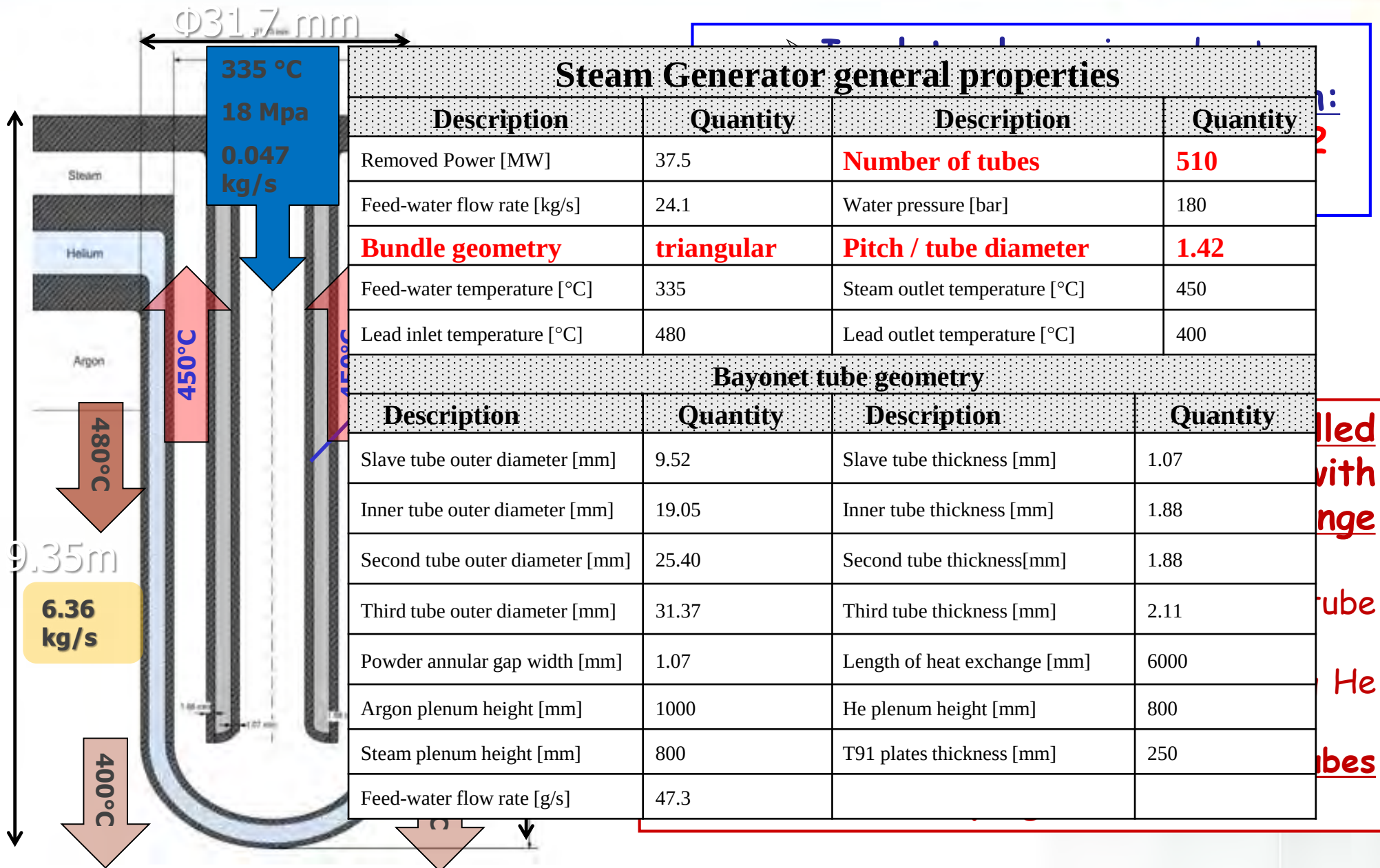
ALFRED-SGBT. HERO Test Section on CIRCE facility

ADP-WORKSHOP: LFR-Gen IV: Stato attuale della tecnologia e prospettive di sviluppo

Brasimone , 19th - 20th November 2015

Del Nevo A., Rozzia D., Tarantino M, Sermenghi V.,

INTRODUCTION



INTRODUCTION

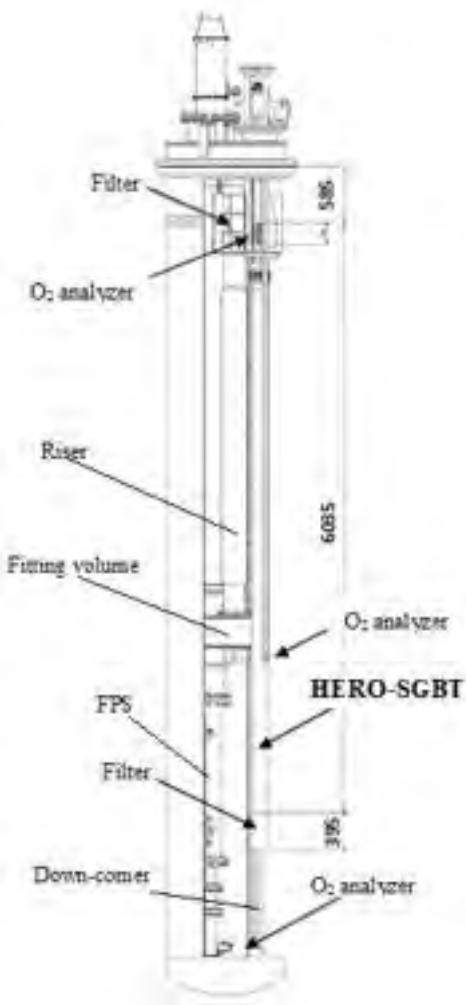


Reactor	Classification	Th. Power	SG type	Operation
RAPSODIE (France)	Exp. reactor	40 MWth	No SG	1967 - 1983
KNK-II (Germany)	Exp. reactor	58 MWth	Once-through evaporator, twin tubes	1971 - 1991
FBTR (India)	Exp. reactor	40 MWth	Once through; triple S shaped tubes	1985 -
PEC (Italy)	Exp. reactor	120 MWth	No SG	Never operated
JOYO (Japan)	Exp. reactor	140 MWth	No SG	1977 -
DFR (UK)	Exp. reactor	60 MWth	Parallel tubes in copper heat transfer block	1959 - 1977
BOR-60 (Russia)	Exp. reactor	55 MWth	7 types of once through SGs	1968 -
EBR-I (USA)	Exp. reactor	4 MWth	<u>Once through; straight double wall tubes</u>	1951 - 1970
EBR-II (USA)	Exp. reactor	62.5 MWth	<u>Once through; straight double wall tubes</u>	1964 - 1994
FFTF (USA)	Exp. reactor	200 MWth	No SG	1980 - 1996
BR-10 (Russia)	Exp. reactor	8 MWth	No SG	1958 - 2003
CEFR (China)	Exp. reactor	65 MWth	Once through; straight tubes, evaporator and super-heater	2011 -
Phenix (France)	DEMO	350 MWth	Once-through, vertical bank of large S-shaped tubes, each containing small pipes for water	1973 - 2010
SNR-300 (Germany)	DEMO	762 MWth	Once-through evaporator and separate super-heater, tubes straight in 2 loops, helical in 3rd	Never operated
MONJU (Japan)	DEMO	714 MWth	Once-through evaporator and separate super-heater; helical coiled; intermediate coolant on shell side	1994 - ?
PFR (UK)	DEMO	650 MWth	Forced recirculation evaporator and drum separate super-heater; separate re-heater	1974 - 1994
BN-350 (Kazakhstan)	DEMO	750 MWth	Shell and tubes, Fild's tubes in evaporator, U-tubes in super-heater	1972 - 1999
BN-600 (Russia)	DEMO	1470 MWth	Shell and straight tubes, module type	1980 -
Super-Phenix	Commercial	2990 MWth	Once-through evaporator and super-heater with helical tubes	1985 - 1998
BN-800 (Russia)	Commercial	2100 MWth	Shell-and straight tubes, module type	2012 -

HERO CIRCE TEST SECTION

The **Heavy liquid mEtal – pRessurized water cOoled tube (HERO)** aims

- To investigate a bundle of seven 1:1 double wall bayonet tubes under conditions that represent, as much as possible, the ALFRED SG.
- To provide suitable experimental data to support the validation process of TH-Sy codes and CFD codes coupled simulations.



The primary circuit flow path includes

Feeding Conduit

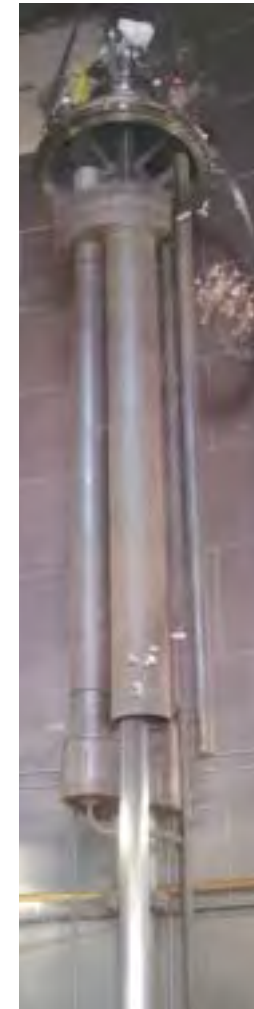
Fuel Pin Simulator: it corresponds to the heat source

Riser: it is an insulated pipe connecting the fitting volume with the separator. A nozzle is installed in the lower section to allow the argon injection inside this pipe.

Separator: it connects the riser to the HERO-SGBT. It allows the separation of the LBE flowing downward into the HX from the Argon flowing in the test section cover gas through the free surface. It works as an expansion vessel.

HERO-SGBT: it corresponds to the heat sink of the system. It consists in **seven double-walls bayonet tubes** (with stainless steel powder +He filling the gap) fed by pressurized water (180 bar). It has a thermal duty of about **500 kW**.

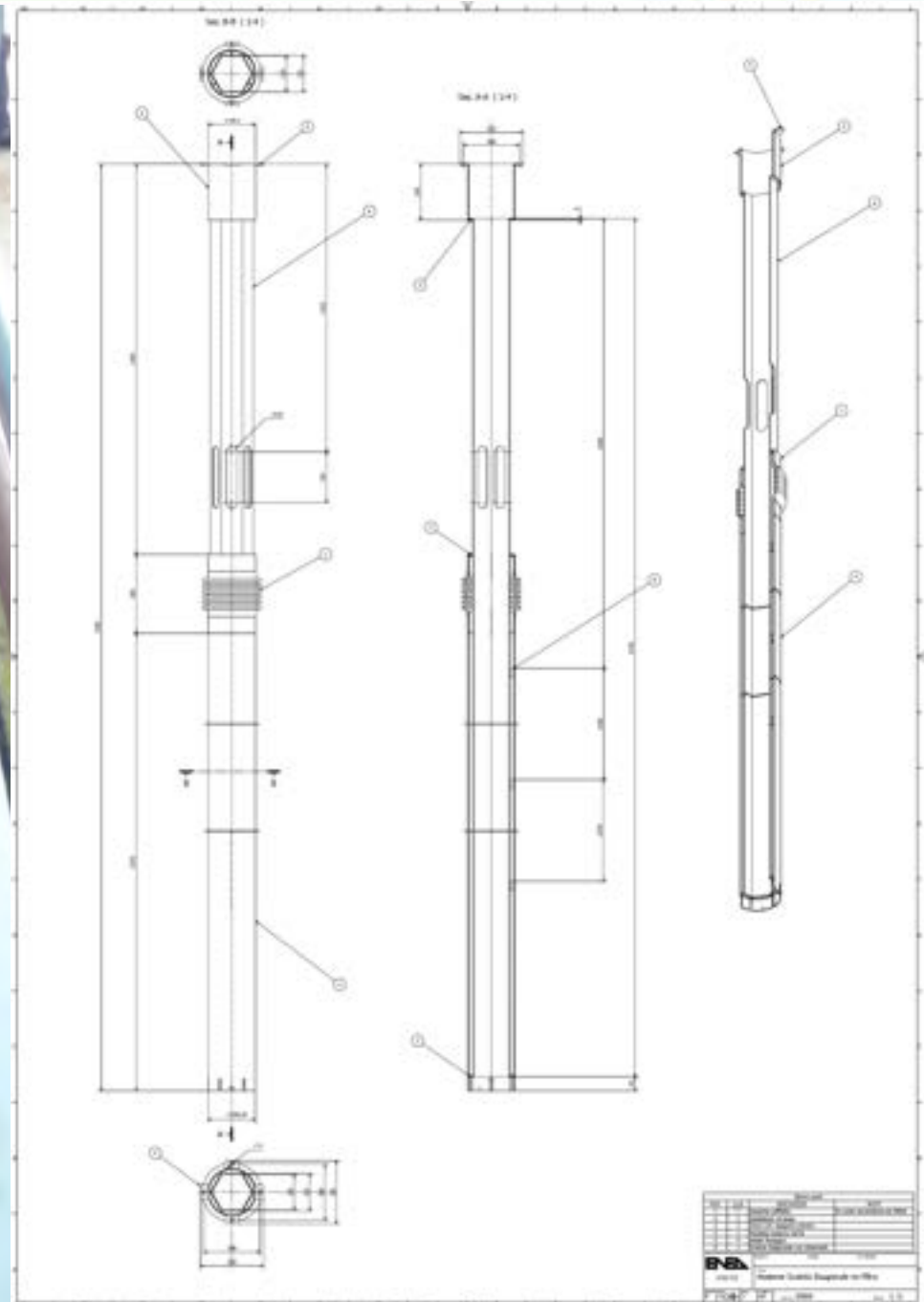
Down-comer: It is the volume between the test section and the main vessel





Description	Unit	Water-Steam side	He side	LBE side
Fluid	--	Water – steam	Helium	LBE
Circulation mechanism	--	Axial pump + accumulator	leakage accommodation	Gas enhanced
Main components	--	bayonet tubes, steam chamber	Helium chamber	SGBT unit shell
Bundle type and P/D	-	Triangular / 1.42	--	Shell
Inlet temp.	°C	335	--	480
Mass flow	kg/s	0.330785	stagnant	44.573529
Design pressure	bar	180	5.0	As CIRCE
Operating pressure	bar	172	4.5	Hydraulic head
Design temp.	°C	432	432	As CIRCE

HERO SGBT UNIT

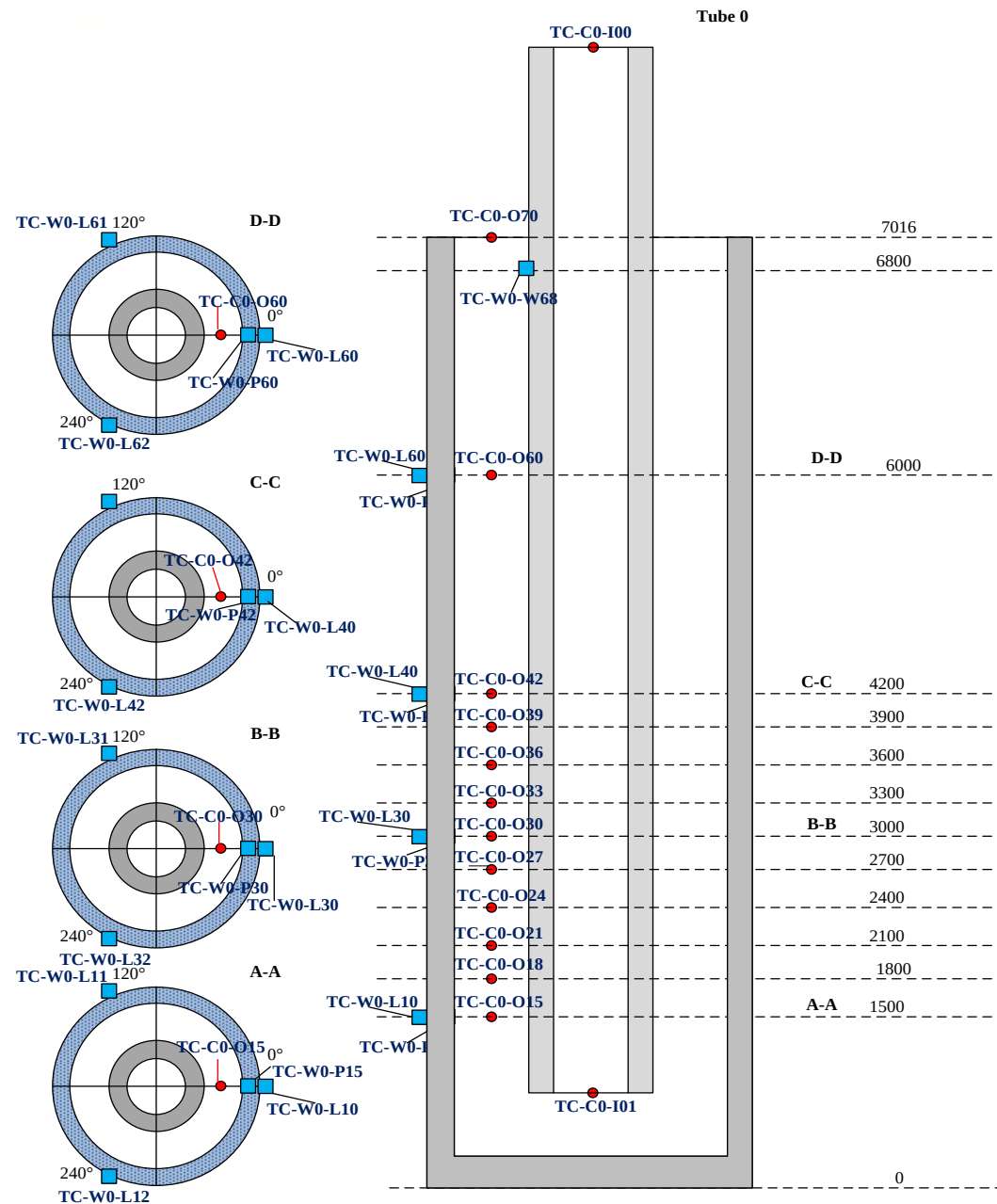


Rev.	Descr.	Aut.	Ver.
01	Disegno	...	...
02	...	...	...
03	...	...	...
04	...	...	...
05	...	...	...
06	...	...	...
07	...	...	...
08	...	...	...
09	...	...	...
10	...	...	...

ENEA
Progetto: ...
Disegnato: ...
Verificato: ...
Data: ...

HERO SGBT UNIT

Central byonet tube

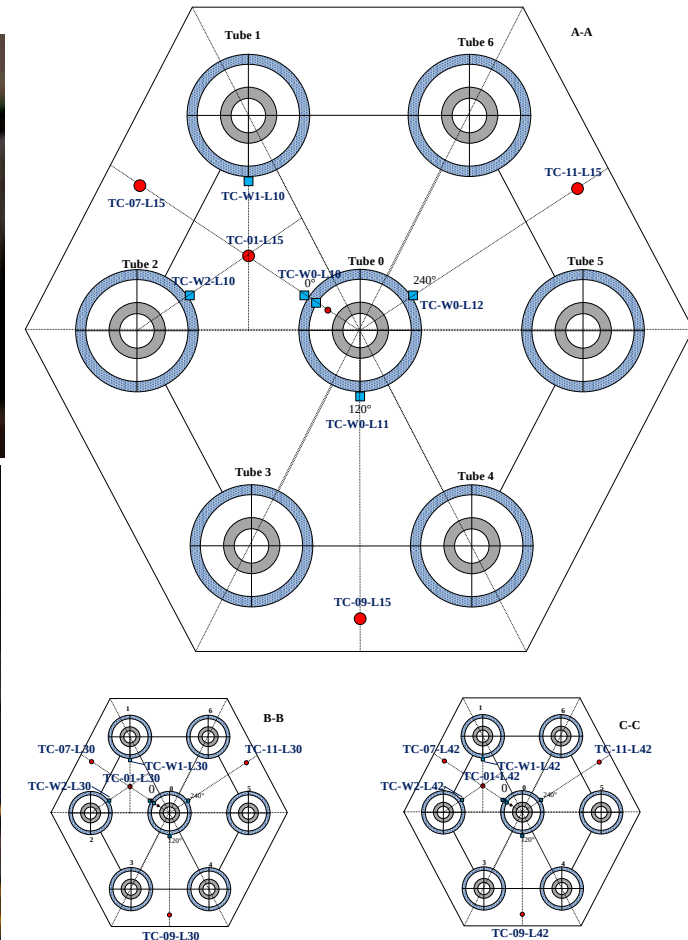


Central tube TCs

- **Fluid flow:** 1 TC at inlet, 1 TC at the end of the descendent tube, 1 TC at the end of the active height and 1 TC its outlet. These TC are located at the center of the channel.
- **Boiling height:** 10 TC in the center of the riser (pitch 300mm).
- **Condensation?:** 1 TC at the riser outlet located in the descendent tube outer surface.
- **Lead side:** 12 TC at four heights and 3 azimuth.
- **In total 27 TH (15 TC-0.25mm, 12-1mm)**
- 4 TCs initially planned to be inserted in the AISI powder gap were not installed due to technological feasibility.

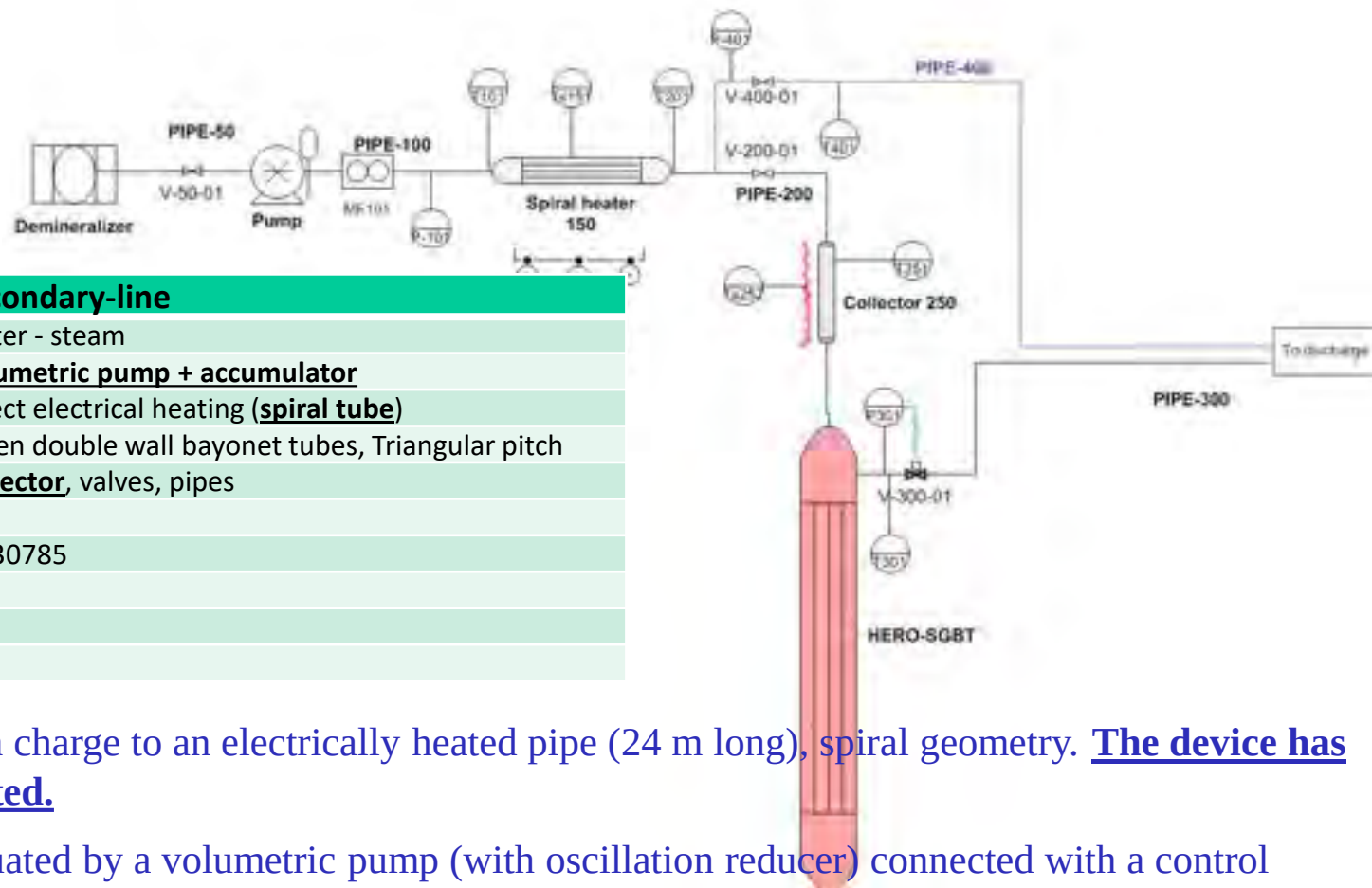
Lead channel

- **Sub-Channel monitoring:** Two TC at 120° respect to the central tube and 1 TC at the center of the triangle.
- **Boundary effects:** three TC at the center of the outer sub-channels
- **This is repeated for three elevation in the active length**
- **In total 18 TCs (1mm)**



HERO CIRCE SECONDARY LOOP

- ❑ The commissioning of the secondary loop is presently ongoing. It is based on an open loop circuit fed by water. The water should be pressurized at 172 bar and preheated at 335°C before entering the SGBT unit (approximately 500kW required).



Description	Unit	Secondary-line
Fluid	--	Water - steam
Circulation mechanism	--	Volumetric pump + accumulator
Pre-heating mechanism	--	Direct electrical heating (spiral tube)
SGBT Bundle type	-	Seven double wall bayonet tubes, Triangular pitch
Other components	--	Collector , valves, pipes
Operating inlet Temp.	°C	335
Operating mass flow	kg/s	0.330785
Design pressure	bar	180
Operating pressure	bar	172
Design temperature	°C	432

- The preheating function is in charge to an electrically heated pipe (24 m long), spiral geometry. **The device has been designed and constructed.**
- Pressurization function is actuated by a volumetric pump (with oscillation reducer) connected with a control valve. **Both these devices have been acquired.**
- The collector has been **designed and manufactured.**
- Secondary loop TC instrumentation **has been investigated.**



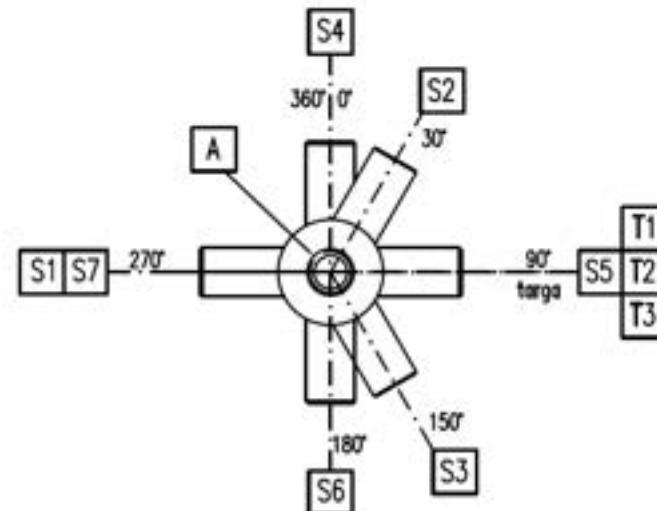
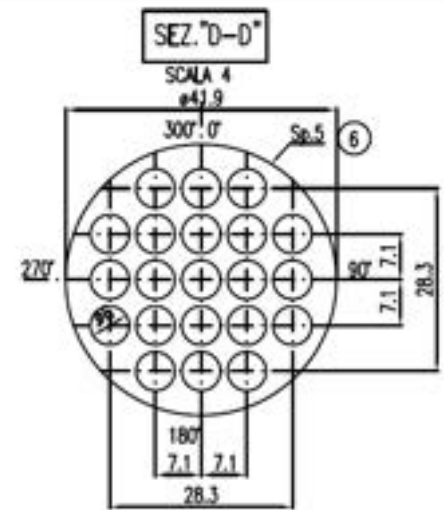
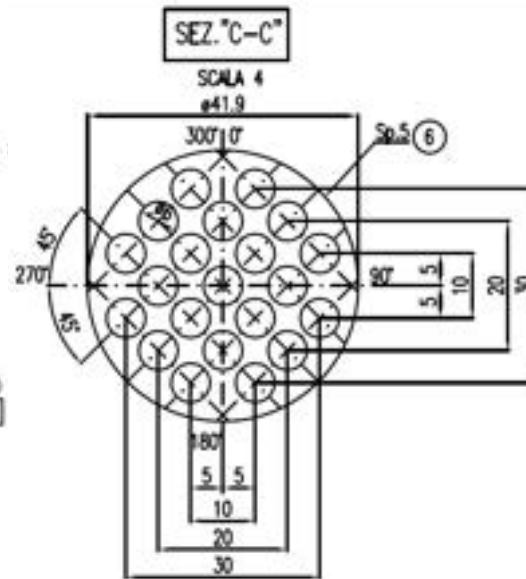
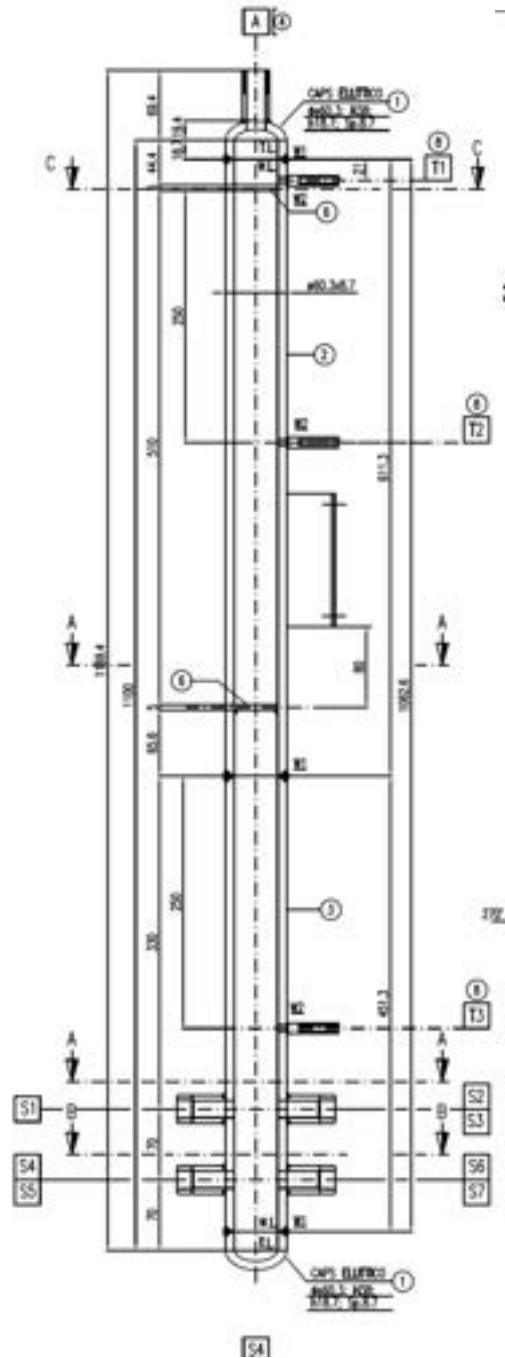
HERO CIRCE SECONDARY LOOP

Collector

The component is designed in order to achieve as uniform as possible distribution of the feed-water to the seven bayonet tubes.

water at 335°C,
170 bar,
0.33 kg/s.

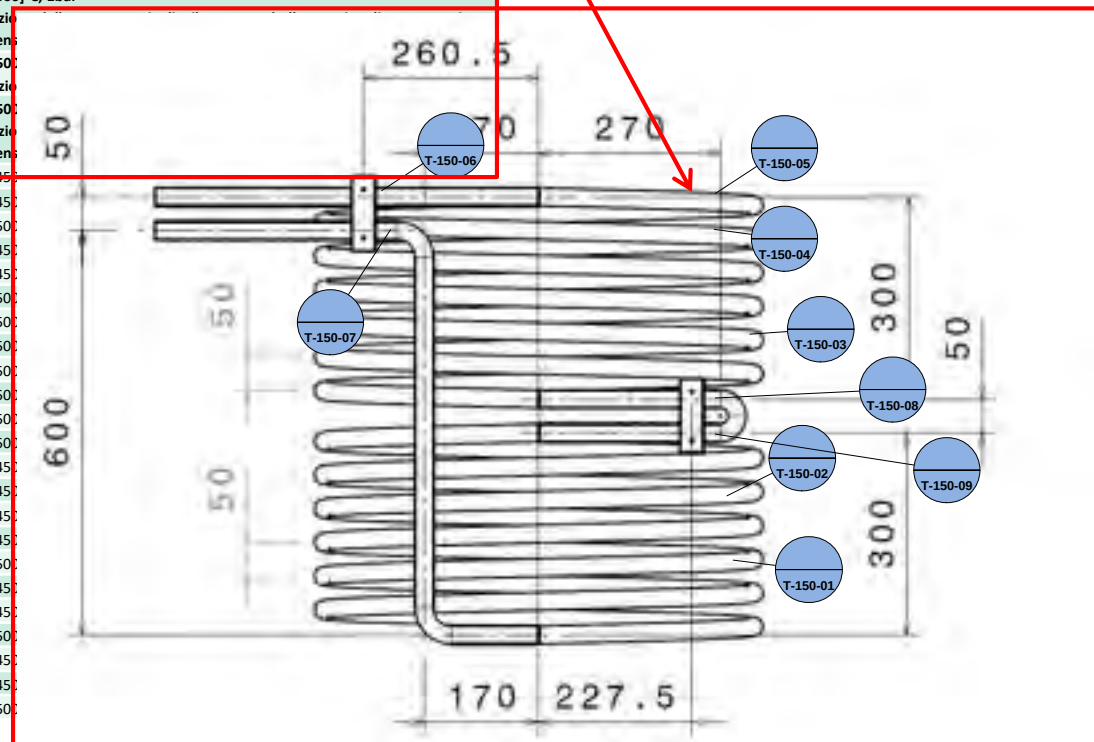
Φ 60.3mm x 8.7 mm
L 1100 mm



HERO CIRCE SECONDARY LOOP

#	ID	Location	Elev /Position	Type	Diameter	Length	Operating range
1	TF-100-01	PIPE-100	After the pump	K-type	3 mm	0.5 m	[5-50]°C, [1-200] bar
2	TF-100-02	PIPE-100	Twin to TF-100-01	K-type	3 mm	0.5 m	[5-50]°C, [1-200] bar
3	TF-100-03	PIPE-100	Spiral pipe inlet	K-type	3 mm	0.5 m	[5-50]°C, [1-200] bar
4	TF-100-04	PIPE-100	Twin to TF-100-03	K-type	3 mm	0.5 m	[5-50]°C, [1-200] bar
5	TW-100-05	PIPE-100	Spiral pipe inlet- tube surface	K-type	1 mm	0.5 m	[50-500]°C, [1] bar
6	TW-150-01	SPIRAL-PIPE-150	3 rd spire from the inlet, outer surface	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
7	TW-150-02	SPIRAL-PIPE-150	5 th spire from the inlet, outer surface	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
8	TW-150-03	SPIRAL-PIPE-150	8 th spire from the inlet, outer surface	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
9	TW-150-04	SPIRAL-PIPE-150	11 th spire from the inlet, outer surface	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
10	TW-150-05	SPIRAL-PIPE-150	12 th spire from the inlet, outer surface	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
11	TW-150-06	SPIRAL-PIPE-150	Electric joints	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
12	TW-150-07	SPIRAL-PIPE-150	Electric joints	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
13	TW-150-08	SPIRAL-PIPE-150	Electric joints	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
14	TW-150-09	SPIRAL-PIPE-150	Electric joints	K-type	1 mm	2m	[50-500]°C, 1bar giunzione della termocoppia di stile a terra a bullone, spina di termocoppia a dimensioni standard OSTW. Lunghezza 1 metro
15	TF-200-01	PIPE-200	Spiral pipe outlet	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
16	TF-200-02	PIPE-200	Twin to TF-200-01	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
17	TW-200-03	PIPE-200	Spiral pipe outlet, outer surface	K-type	1 mm	0.5 m	[50-500]°C, [1] bar
18	TF-200-04	PIPE-200	Collector inlet	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
19	TF-200-05	PIPE-200	Twin to TF-200-04	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
20	TW-200-06	PIPE-200	Collector inlet, outer surface	K-type	1 mm	0.5 m	[50-500]°C, [1] bar
21	TW-250-01	Collector-250	Outer surface top	K-type	1 mm	1 m	[50-500]°C, [1] bar
22	TC-250-02	Collector-250	Heating cable top	K-type	1 mm	1 m	[50-500]°C, [1] bar
23	TW-250-03	Collector-250	Outer surface middle	K-type	1 mm	1 m	[50-500]°C, [1] bar
24	TC-250-04	Collector-250	Heating cable middle	K-type	1 mm	1 m	[50-500]°C, [1] bar
25	TW-250-05	Collector-250	Outer surface bottom	K-type	1 mm	1 m	[50-500]°C, [1] bar
26	TC-250-06	Collector-250	Heating cable bottom	K-type	1 mm	1 m	[50-500]°C, [1] bar
27	TF-250-07	Collector-250	After the last grid	K-type	3 mm	1 m	[50-450]°C, [1-200] bar
28	TF-SGT-01	HERO-SGBT	Steam plenum outlet nozzle	K-type	1 mm	1 m	[50-450]°C, [1-200] bar
29	TF-SGT-02	HERO-SGBT	120° to TF-SGT-01	K-type	1 mm	1 m	[50-450]°C, [1-200] bar
30	TF-SGT-03	HERO-SGBT	240° to TF-SGT-01	K-type	1 mm	1 m	[50-450]°C, [1-200] bar
31	TW-SGT-04	HERO-SGBT	Nozzle outer surface	K-type	1 mm	1 m	[50-500]°C, [1] bar
32	TF-300-01	PIPE-300	After VC-300-01	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
33	TF-300-02	PIPE-300	Twin to TF-300-01	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
34	TF-300-03	PIPE-300	Outer surface	K-type	1 mm	0.5 m	[50-500]°C, [1] bar
35	TF-400-01	PIPE-400	After VB-400-01	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
36	TF-400-02	PIPE-400	Twin to TF-400-01	K-type	3 mm	0.5 m	[50-450]°C, [1-200] bar
37	TW-400-03	PIPE-400	Outer surface	K-type	1 mm	0.5 m	[50-500]°C, [1] bar

TC instrumentation
The secondary loop has been mapped with 37 thermocouples



HERO-CIRCE MODELING

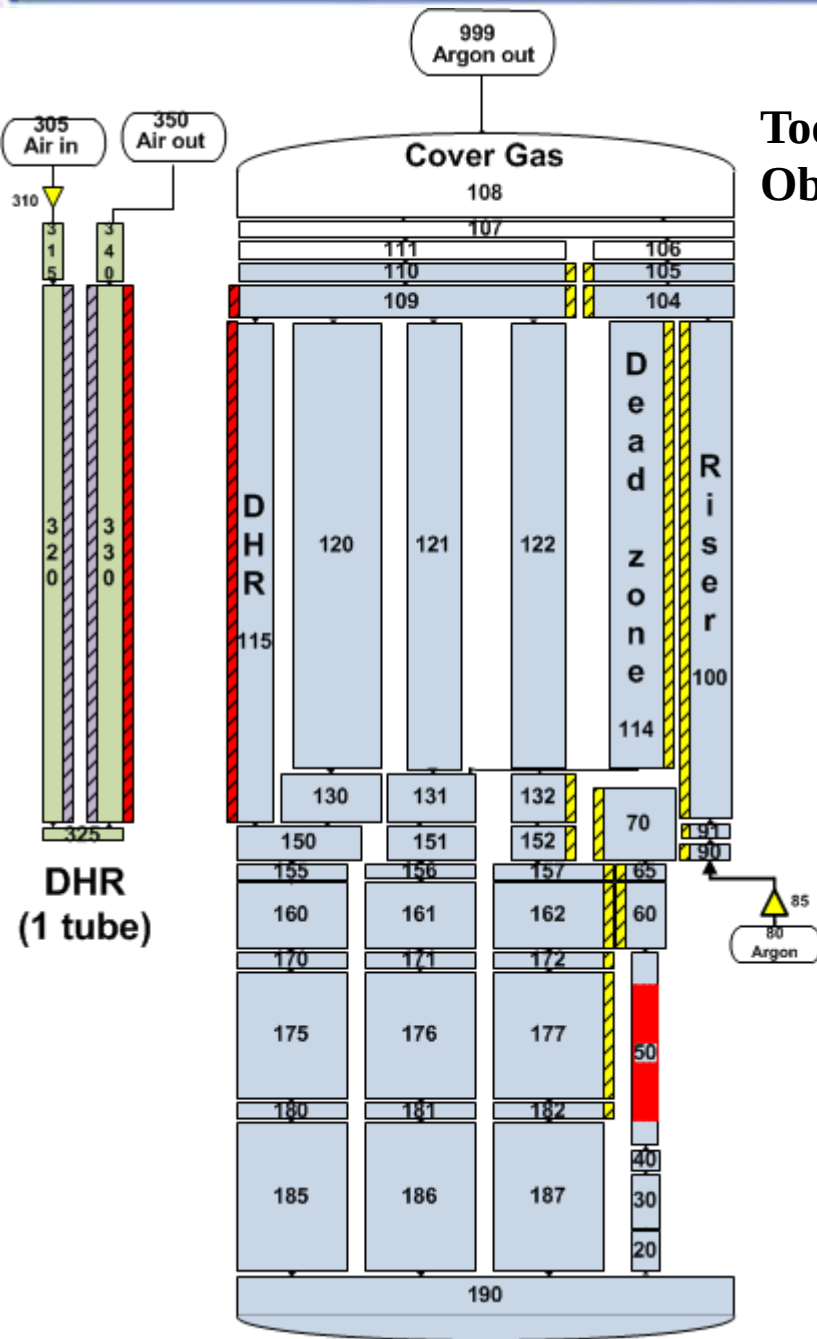
HERO-CIRCE facility model

Tool: RELAP5-3.3

Objectives: Development of the test matrix

Pre-test calculations

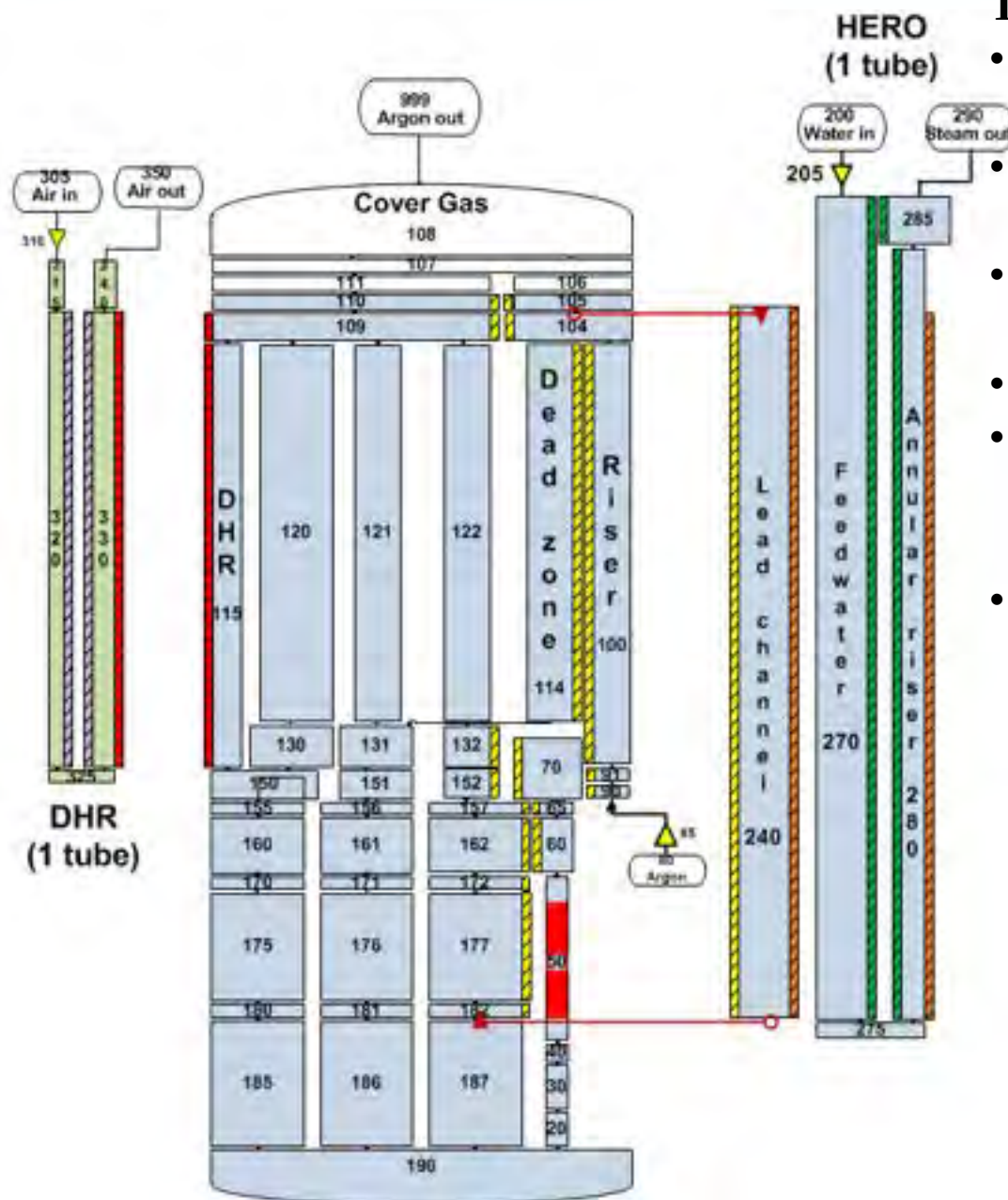
Development of CFD/RELAP5 coupled simulations



The model includes

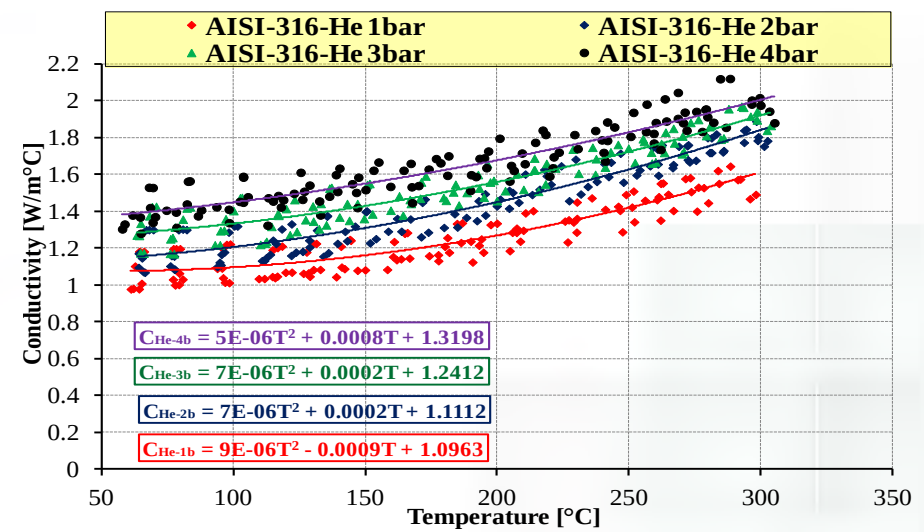
- **The Fuel Pin Simulator (FPS):** PIPE component that has axial 11 volumes including the active zone with length equal to 1 m; five spacer grids are located in the lower, middle and upper part are simulated as concentrated pressure losses.
- **The riser** PIPE component characterized by axial 25 volumes. This component is filled from the bottom with Ar in order to simulate enhanced circulation.
- **The upper plenum** modeled with 8 branch: in this part of the facility are present LBE and argon. The gas flows away into the BRANCH-999.
- **The pool** is modeled with some branches and pipes nodalized in order to simulate LBE mixing
- **The lower plenum** is the zone sliced with the conveyor (PIPE-60), the FPS and the feeding conduit (PIPE 40-30-20). It is modeled with some branches
- **The DHR-air** is modeled as a single pipe
- **The dead zone**

HERO-CIRCE MODELING



The HERO SGBT includes

- The feed-water tube, the annular steam riser and the equivalent lead channel.
- The heat exchange between the annular steam riser and the Argon zone has been neglected.
- The insulating zone in the feed-water tube has been considered.
- The material adopted for the tubes is SS
- The filling powder (AISI-316) in the double wall meatus is according to the experimental findings achieved in TxP Facility.
- The heat transfer between the lead side and the annular riser is modeled according to the Mikityuk correlation.



HERO-CIRCE ISOTHERMAL TESTS

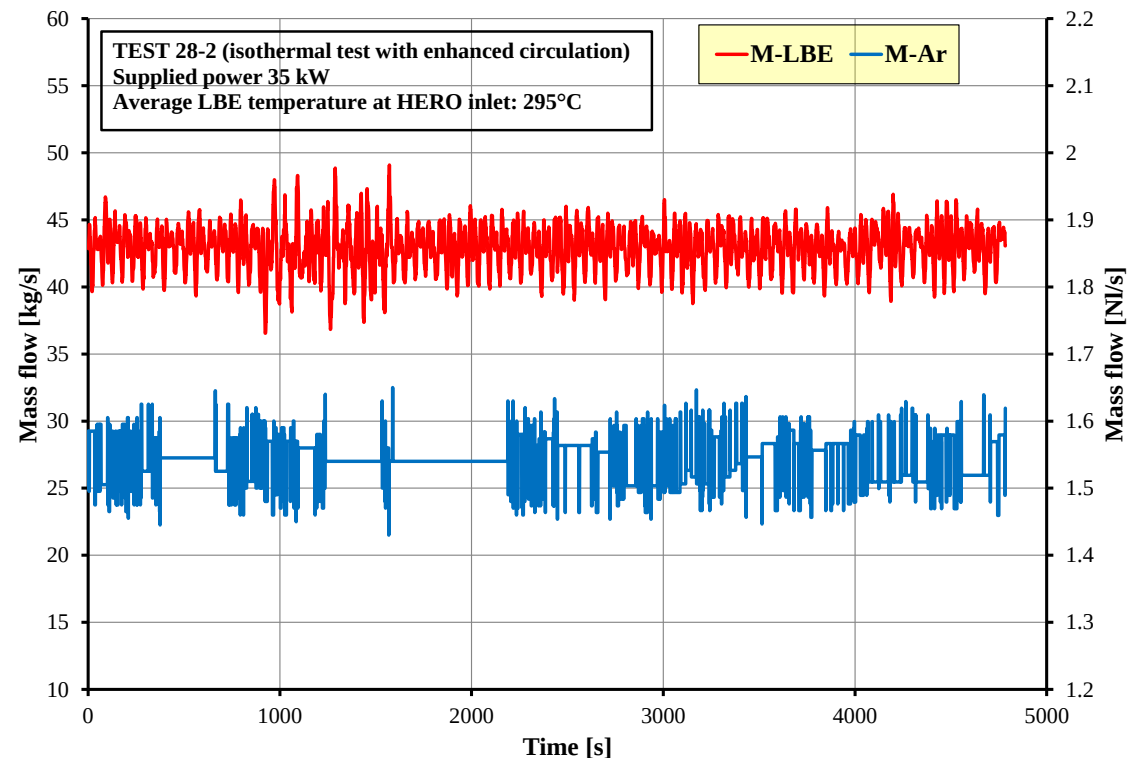


Data from	TEST 28-2 h 9.50 to 11.10, 9-12-2014
Average fuel bundle power	35 kW
Average LBE temperature at HERO inlet	295 °C
Ar mass flow rate	1.51 – 1.58 NI/s
LBE mass flow rate at HERO inlet	40 – 46 kg/s
Average power removed by DHR	5 kW

**HERO-CIRCE facility
model
Check is ongoing
against 28.2 TEST**

The preliminary experimental campaigns consisted of eight different tests aimed to assess the thermal hydraulic performance of CIRCE – HERO test section.

TEST 28-2 proved that the LBE mass flow rate at the fissure inlet is consistent with the requirements of HERO (about 44 kg/s) by using gas enhanced circulation inside the capabilities of the facility (1.55 NI/s of Argon).



CONCLUSIONS AND PERSPECTIVES



- The SGBT unit has been instrumented, installed in CIRCE and subjected to isothermal tests
- The secondary loop system has been designed and is presently under commissioning
 - The spiral heater, its supporting system and its containment have been constructed. **The supporting requires minor modifications**
 - The pump has been identified acquired
 - The collector has been designed and constructed
 - Water-steam control valves have been acquired
 - Instrumentation have been identified and partially acquired
 - **The commissioning is expected to end on April 2016**
 - **The first experimental campaign is expected on June-September 2016**
- HERO-CIRCE RELAP-5 model has been developed. It will be checked against isothermal tests and then used to develop the experimental test matrix and to perform pre-test calculations

Design dell'esperimento e specifica tecnica di fornitura relativa all'up-grade dell'impianto LIFUS5/Mod2

A. Del Nevo, M. Eboli, S. Mannori, A. Neri, S. Cati, D. Giannotti, M. Valdiserri

Workshop tematico

LFR-Gen. IV: Stato attuale della tecnologia e prospettive di sviluppo
ADP ENEA-MSE (PAR2014-LP2)

Brasimone, 19-20 Novembre, 2015

Centro Ricerche ENEA Brasimone

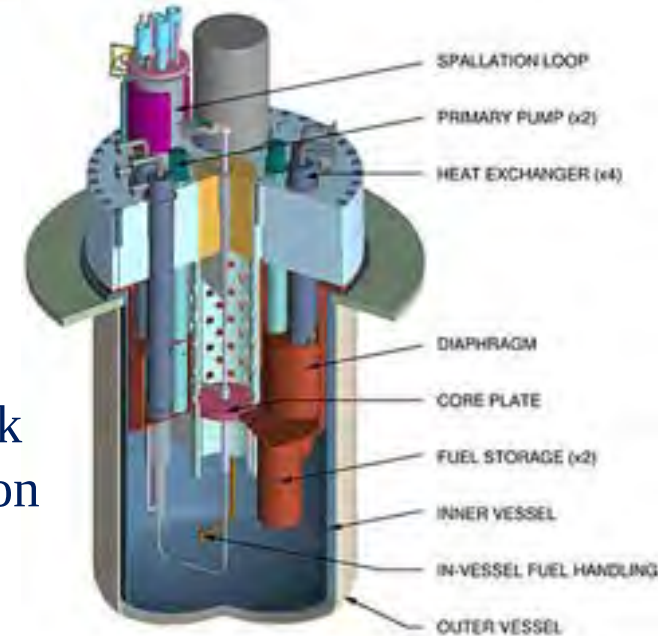
LIST OF CONTENTS



- ☐ FRAMEWORK
- ☐ OBJECTIVES OF THE ACTIVITY
- ☐ OVERVIEW OF EXP ACTIVITY
- ☐ CODE ACTIVITY IN SUPPORT OF EXP
- ☐ SUMMARY

FRAMEWORK [1]

- ❑ Steam generator tube rupture (SGTR) issue
- ❑ Besides, the safety hazards (i.e. steam bubbles dragged into the core; LBE chemistry, etc.), steam generator is the prime component having potential to reduce plant availability
- ❑ Instrumentation able to promptly detect the presence of a crack in the HX's tube may be used to prevent its further propagation which would possibly lead to a full rupture of the tube
 - Early detection might be applied, if endorsed as a technically justifiable approach, for making the consequences of a postulated accident acceptable, or even for eliminating the accident (i.e. in this case the SGTR scenario)



OBJECTIVES OF THE ACTIVITY [1]



- The goal is to implement an experimental activity, supported by the numerical simulations, that will **characterize the leak rate and bubbles sizing through typical cracks** occurring in the pressurized tubes
 - Basic tests in LIFUS5/Mod2 facility will be carried out to correlate the flow rates of the leakage through selected cracks with signals detected by proper transducers
 - Different crack sizes and geometries will be analyzed, while the injection pressure and the temperature will be kept constant
 - An acoustic device to detect the bubbles migration through the free level will be implemented

OVERVIEW OF EXP ACTIVITY [1/8]

LIFUS5/Mod2
THINS configuration 2012

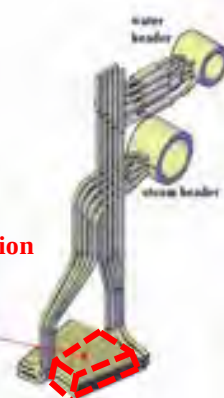
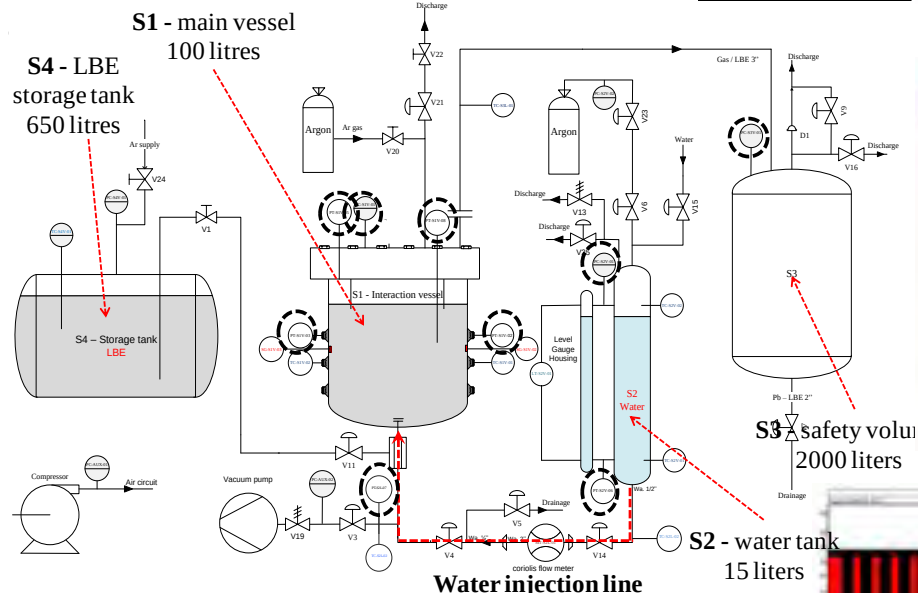
ID MST type	MST device	No. MST installed	ID MST position	Position
LC	Level gauge (control)	1	ENS	Link-section in S4-Frame Nord Sud
LT	Level gauge (acquisition)	1	FEW	Test section in S1: Frame Est West
MT	Flow meter	1	S1V	Interaction Vessel S1
PC	Absolute pressure transducer	6	S2V	Water tank S2
PT	Pressure transducer	1	S3V	Water in S3 Line
TR	Thermocouple for regulation	35	S3L	Dump system S3 Line
SG	Strain Gauge	6	AUX	Auxiliary systems

This implies a refurbishment of LIFUS5/Mod2 facility

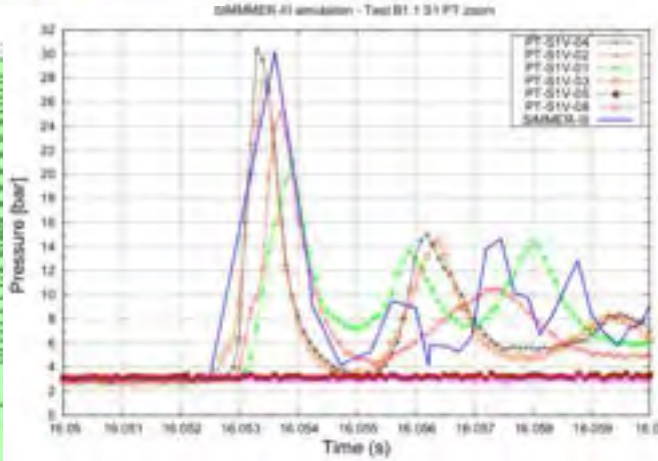
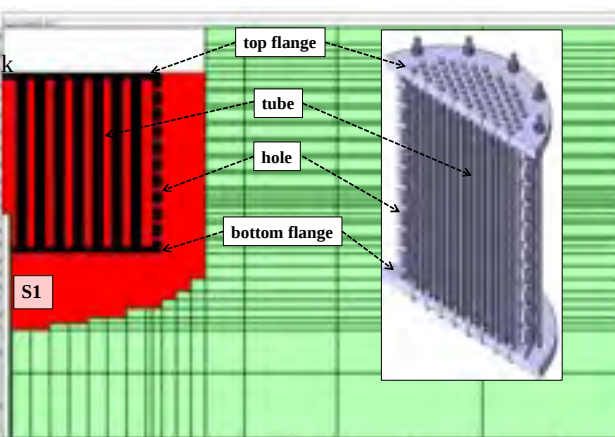
7 tests executed

ELSY Steam Generator

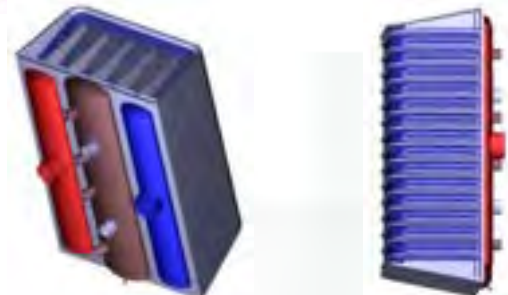
Single Tube configuration



- To recover the functionality of components (e.g. valves, instrumentation, etc...)
- To improve the safety during operation
- To allow small leakage simulation (inject. System) and the use of different HLM fluids

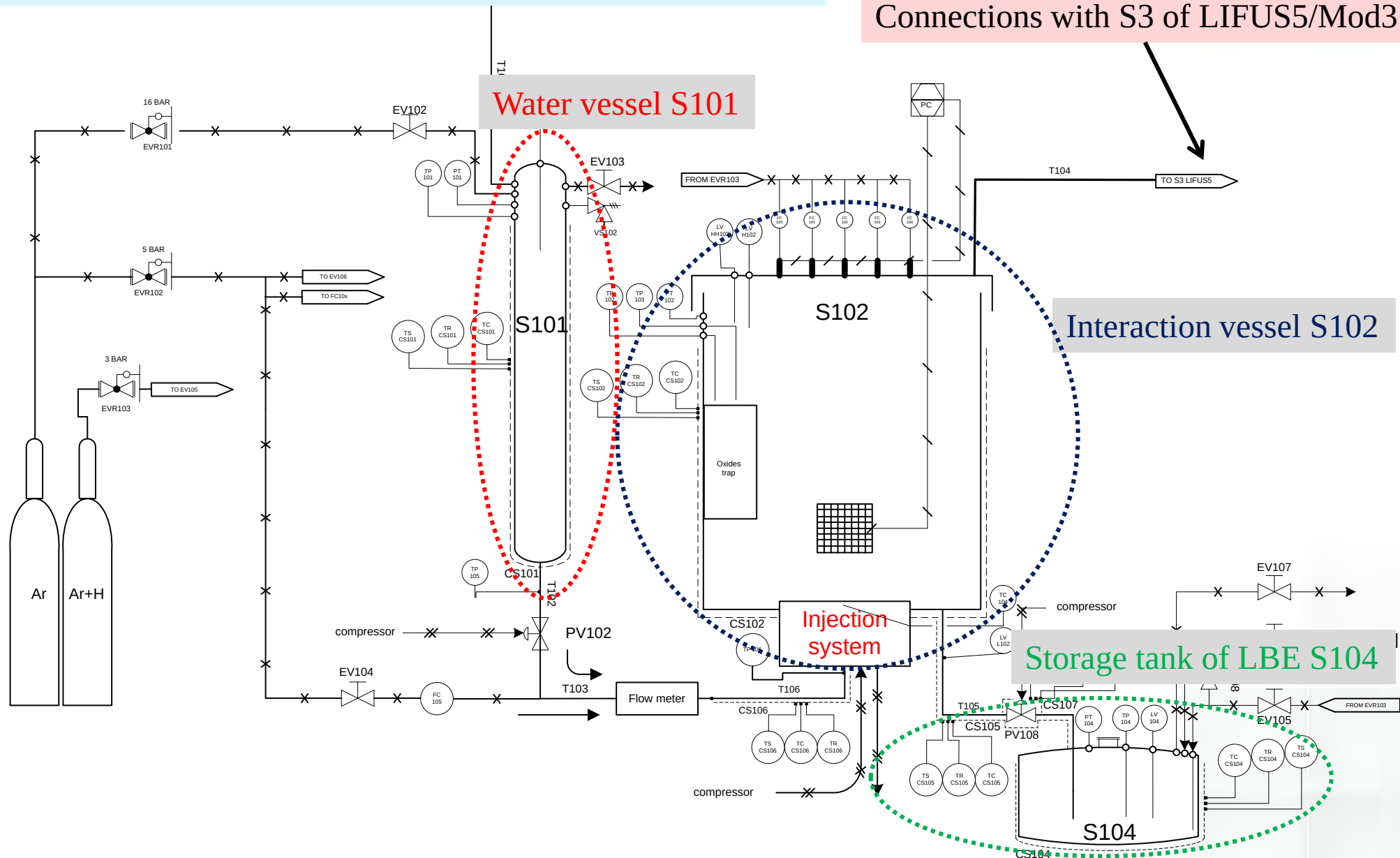


Beside this, LIFUS5 has been also involved in the 5y EUROfusion programme (DEMO), in connection with the WCLL BB design and safety, therefore...



LIFUS5/Mod3 system A

Connections with S3 of LIFUS5/Mod3

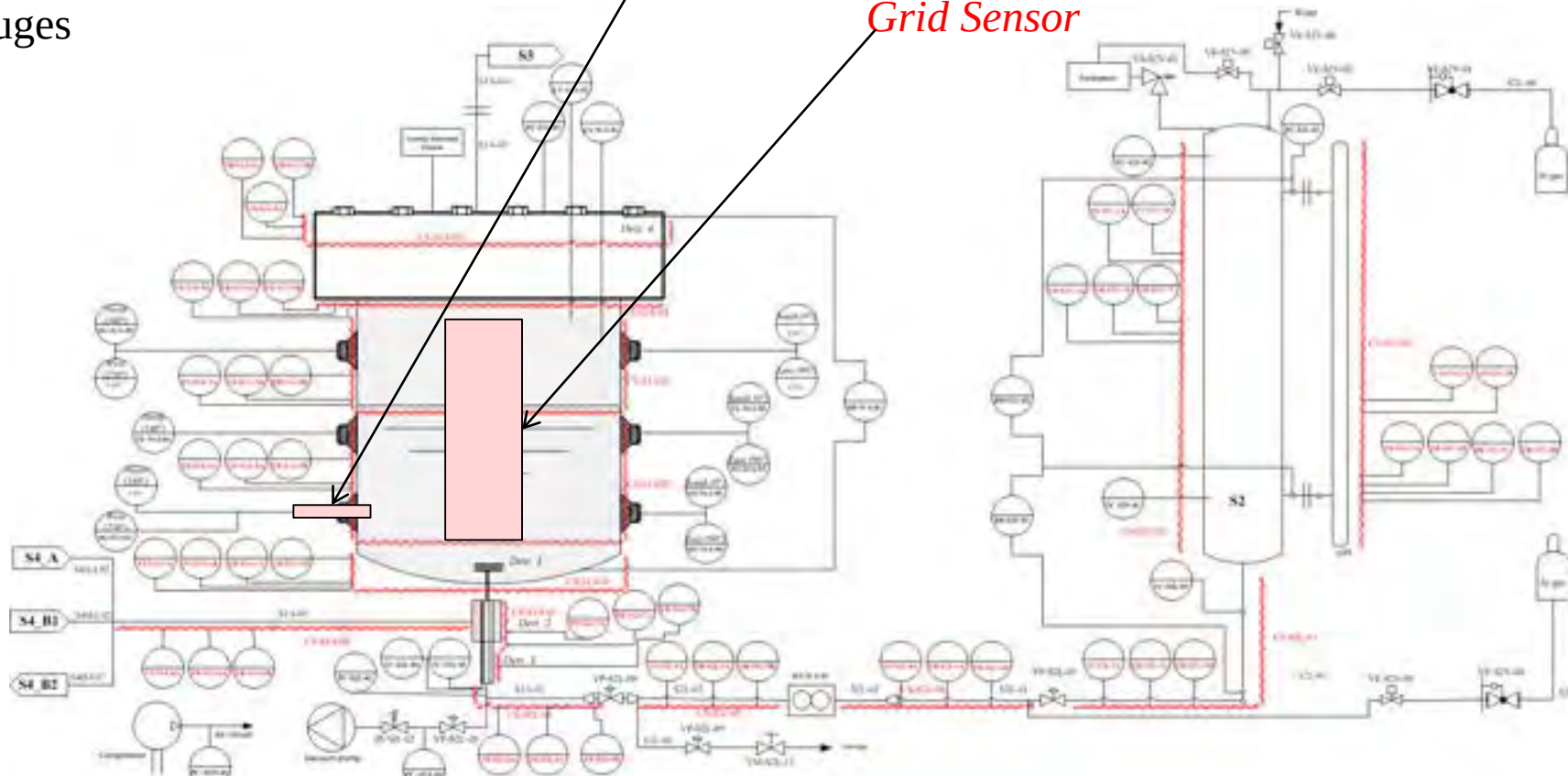


OVERVIEW OF EXP ACTIVITY [3/8]

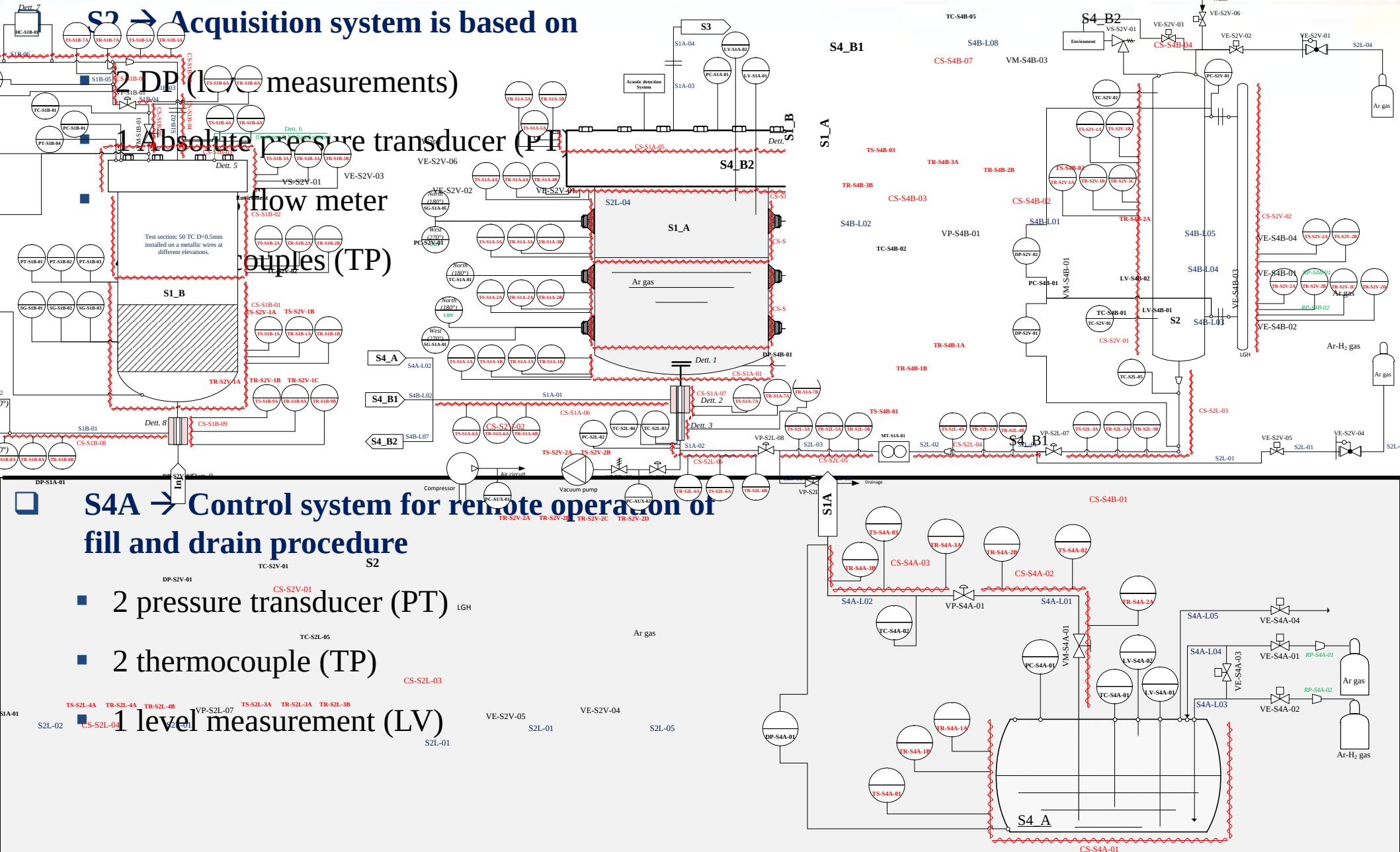
S1A → Acquisition system is based on

- 5 microphones (MPHs), installed on the top flange and 1 “acoustic sensor”, installed in the melt
- 3 level measurements (LVs)
- 2 pressure transducers (PT)
- 2 thermocouples (TP)
- 6 strain gauges

Feasibility of measuring the velocity of steam bubbles in the melt as function of the crack dimension is under evaluation using Magnetic Grid Sensor



OVERVIEW OF EXP ACTIVITY [4/8]

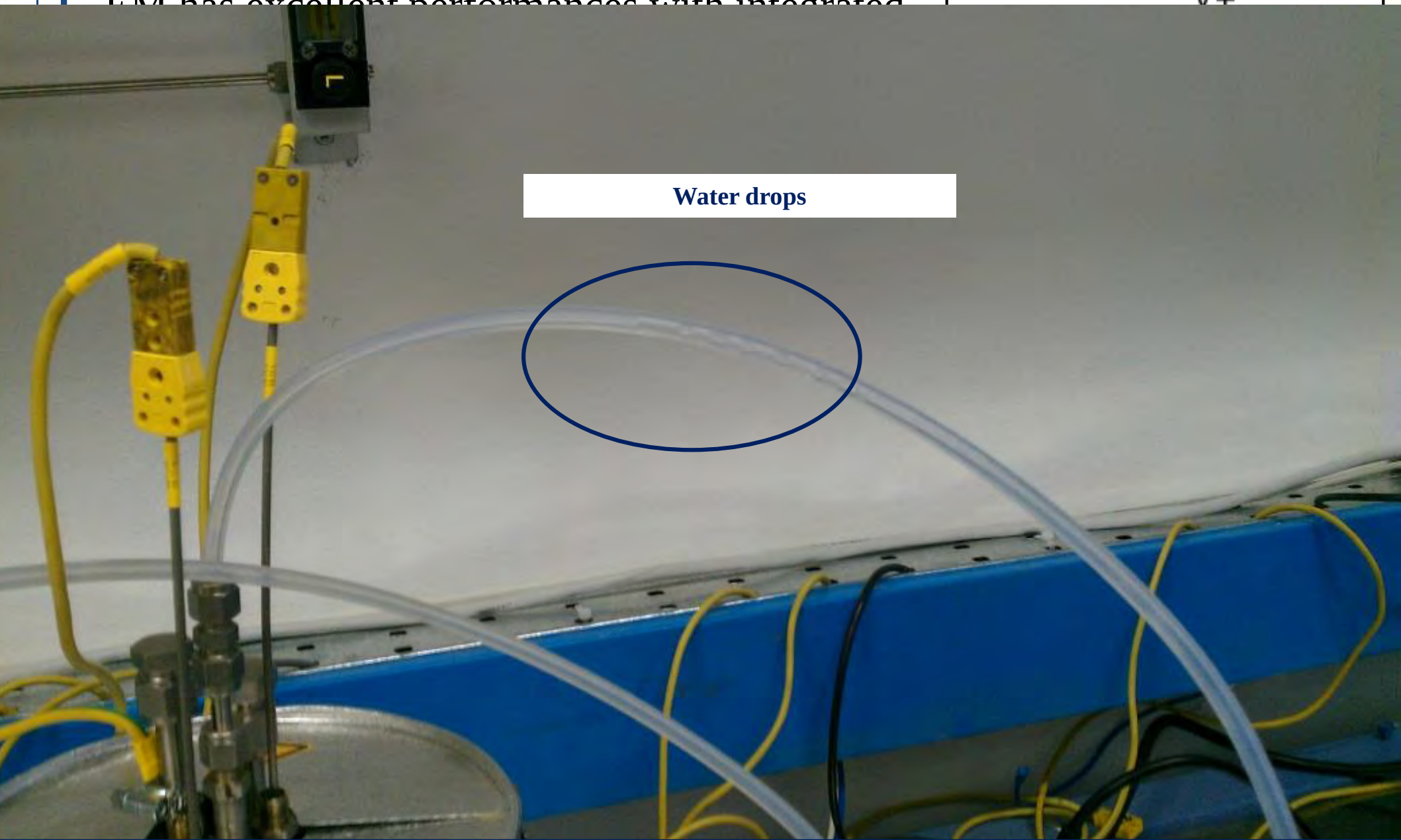


OVERVIEW OF EXP ACTIVITY [5/8]

Acoustic detection system – Feasibility tests

□ EM has excellent performances with integrated

V+

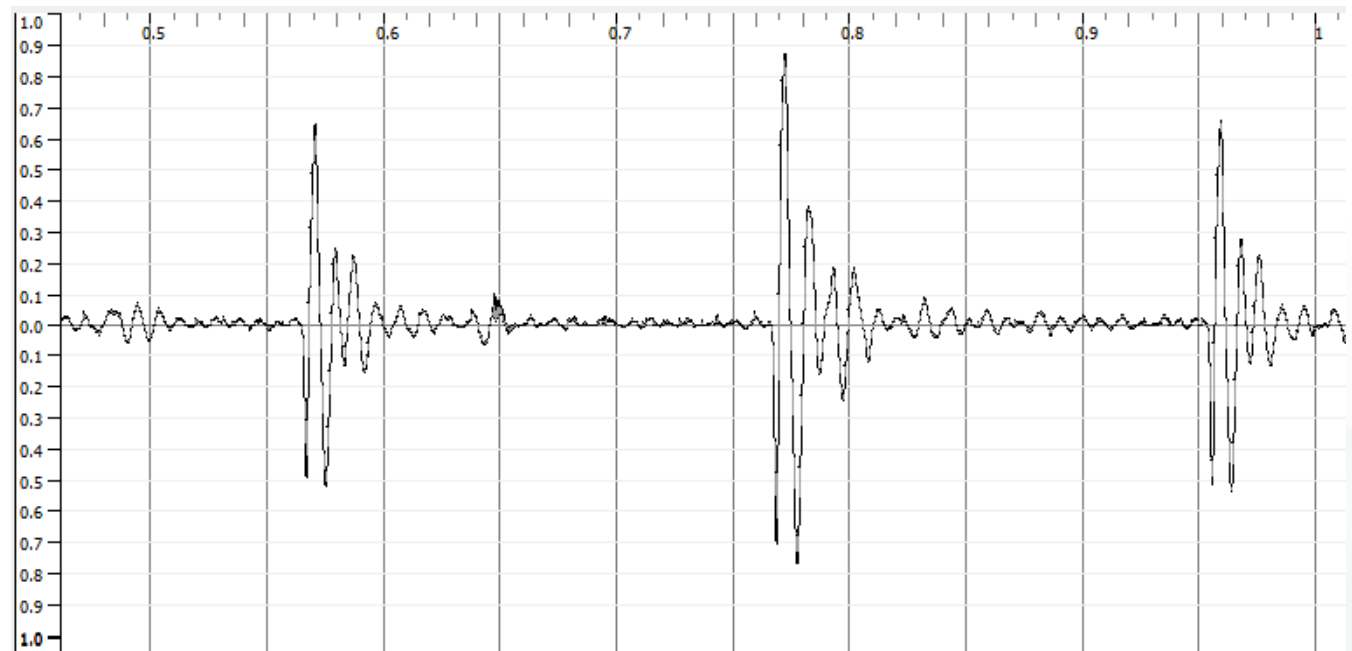


OVERVIEW OF EXP ACTIVITY [6/8]

Acoustic detection system – Feasibility tests



- ❑ Measured “1/f shaped” acoustic emission spectrum (in Ar) with 10Hz-200 Hz limits, consistent with the pulse/burst signal registered in the time domain
 - 40 tests 4mm Ar
 - 32 tests 1mm Ar
 - 3 tests 1mm H₂O → *both microphones were lost*



OVERVIEW OF EXP ACTIVITY [7/8]

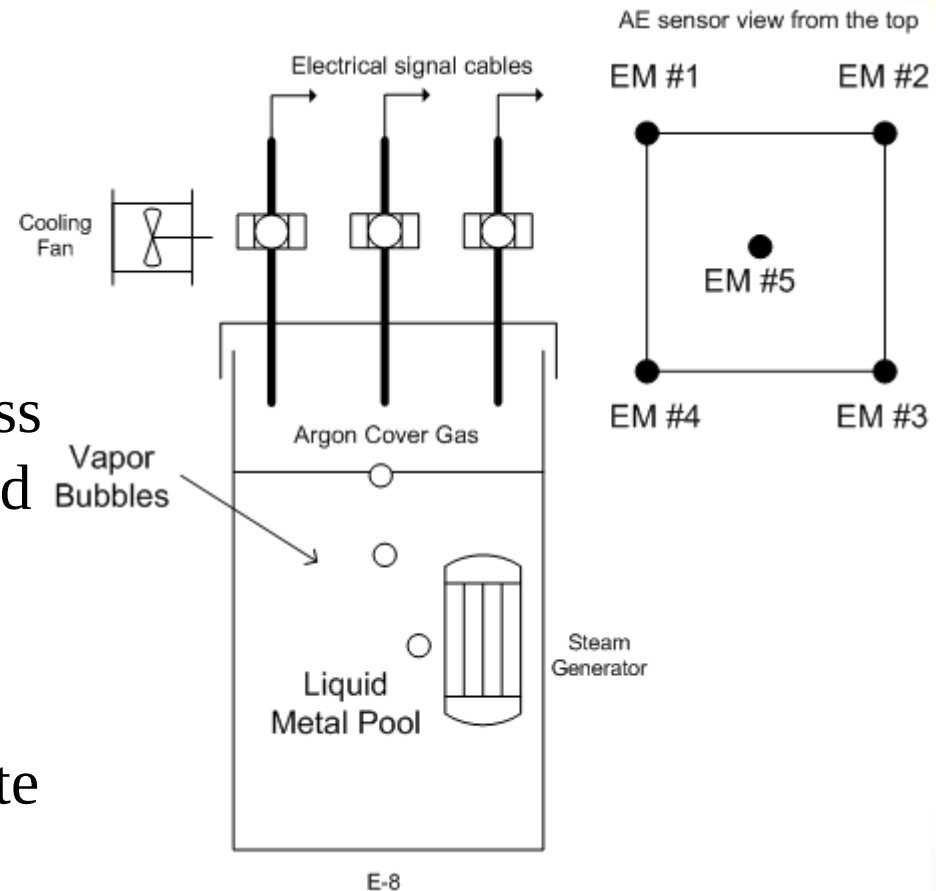
Acoustic detection system – Feasibility tests

- 5 microphone PCB piezotronics AE sensors placed:
 - 4 → square corners (side ~200mm)
 - 1 in the center

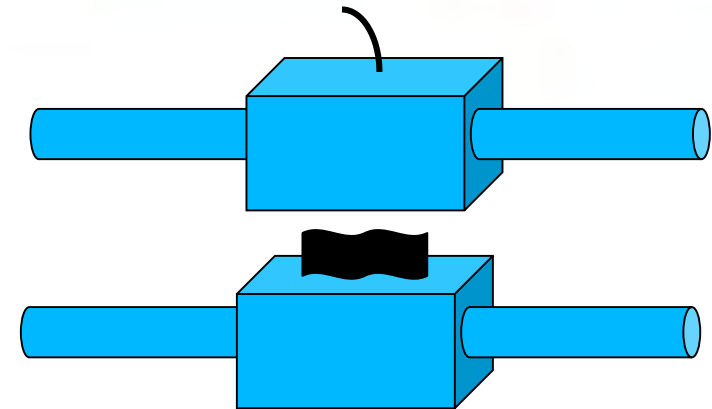
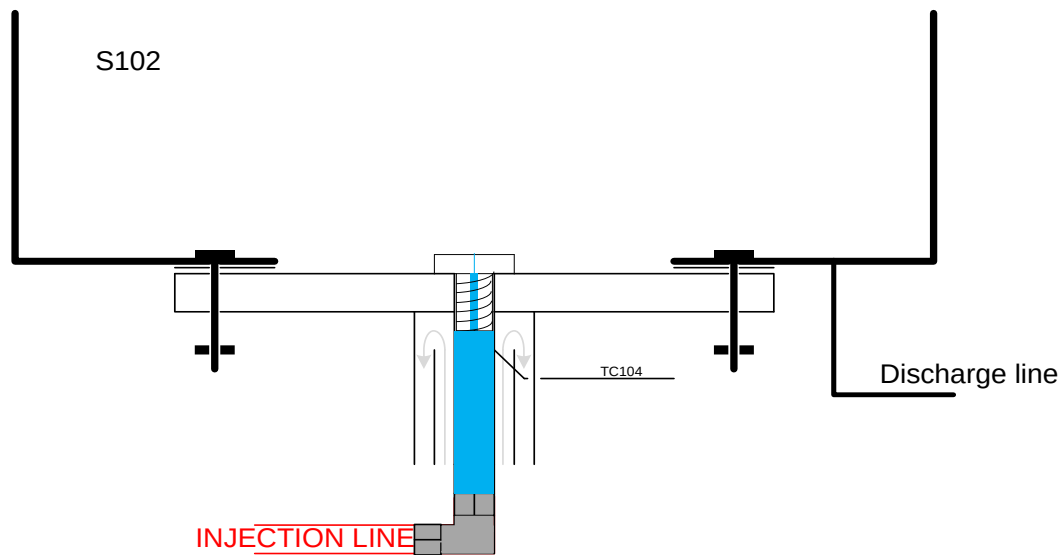
- Installed outside the S1A using stainless steel acoustic tube and cooled with cold air.

- Multi channel configuration aimed at:
 - Correlating crack size, mass flow rate (*hopefully bubble size*) and acoustic emission in MYRRHA operating conditions

- Location of bubble emersion from the surface pool: acoustic emission of bubble expansion and explosion in cover gas



- The injector orifice features:
 - diameter ranges 0.002-0.1 mm
 - different shape (cylindrical or laminar)



#	Parameter	T#1	T#2	T#3	T#4	T#5	T#6	T#7	T#8	T#9	T#10
1	Injector cylindrical orifice diameter [mm]	0.002	0.004	0.006	0.008	0.010	0.020	0.040	0.060	0.080	0.100
2	Injector laminar dimensions [--]	TBD									

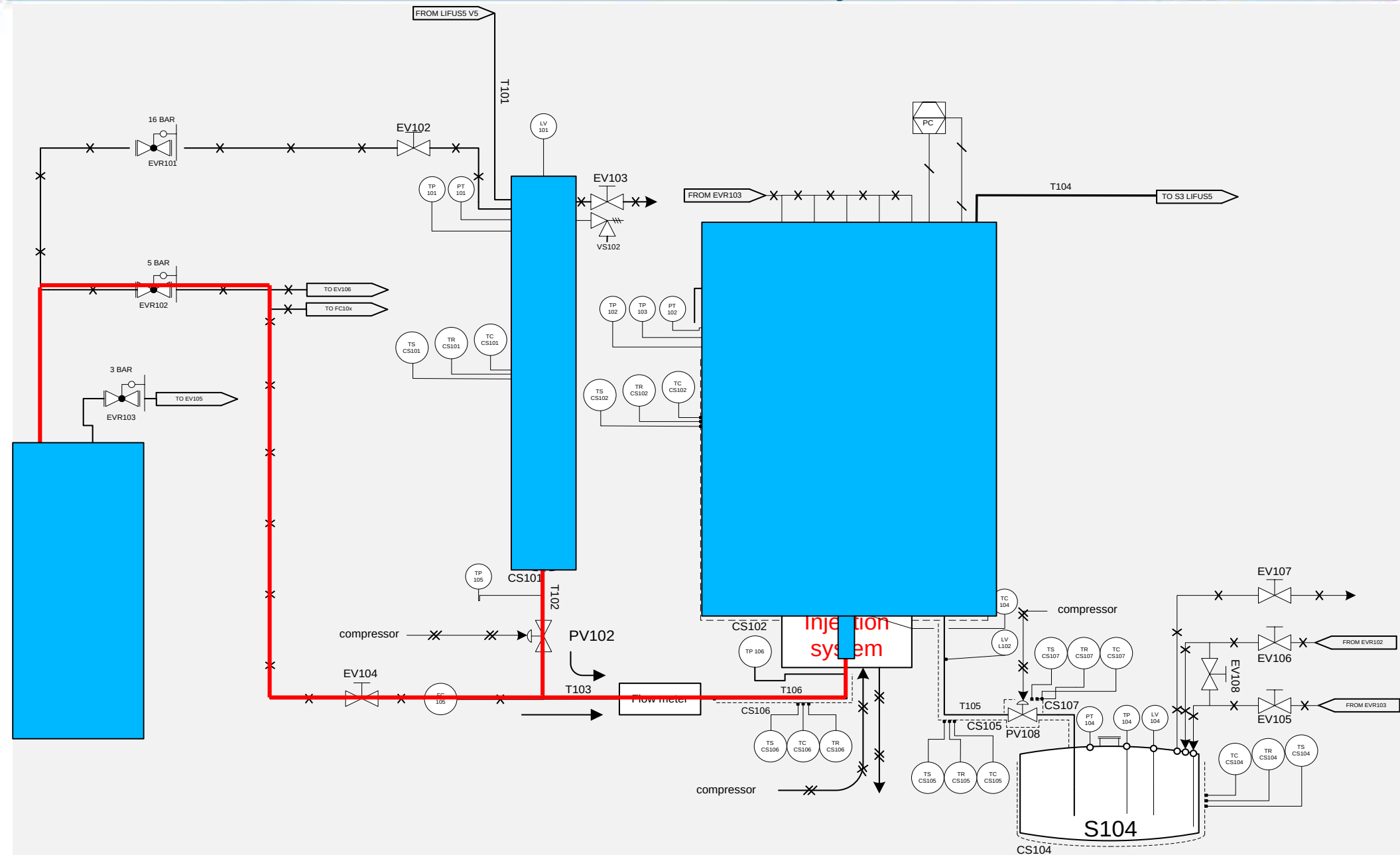
CODE ACTIVITY IN SUPPORT OF EXP [1/5]



- ☐ CODE ACTIVITY BY MEANS RELAP5/MOD3.3 AND SIMMER-III CODES
- ☐ RELAP5/MOD3.3 CALCULATIONS:
 - ☐ Supporting the design of the injection line
 - ☐ Testing the fill and drain procedure
 - ☐ Providing boundary condition to SIMMER-III calculations
- ☐ SIMMER-III CALCULATIONS:
 - ☐ Bubble characterization
 - ☐ Pre-test calculations

CODE ACTIVITY IN SUPPORT OF EXP [2/5]

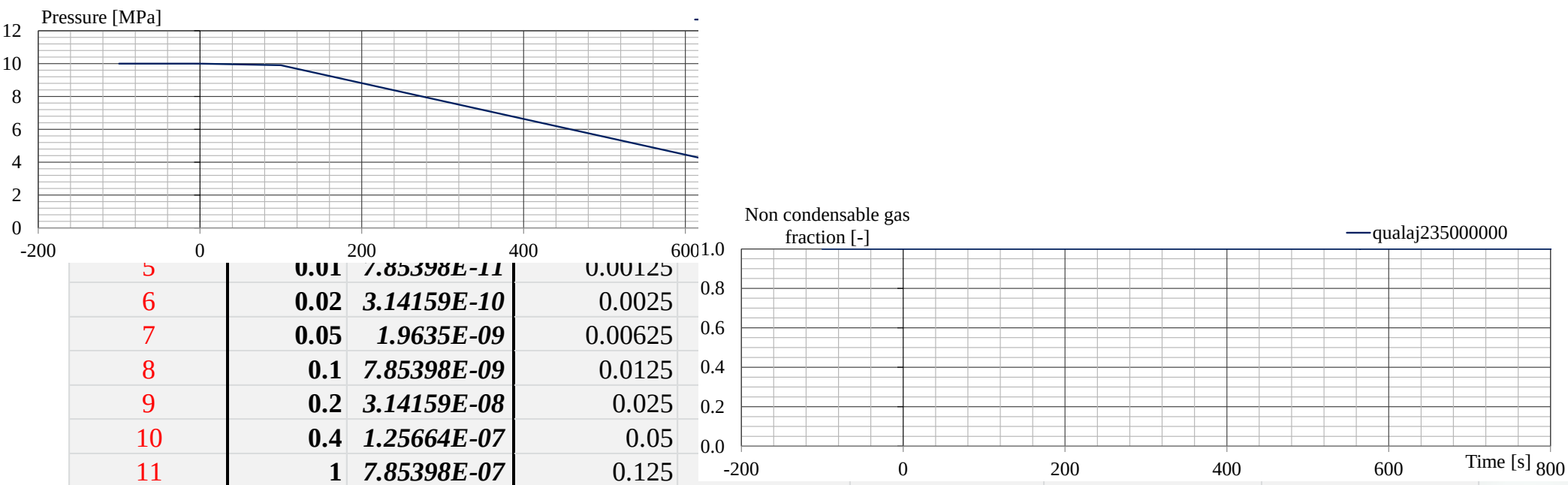
RELAP5/Mod3.3 simulation of the injection line



WATER INJECTION LINE LIFUS-5/Mod2b NODALIZATION

- Leakage diameter limited by the injection line to a diameter of about 1.5mm

- Planned tests will cover a wide range of

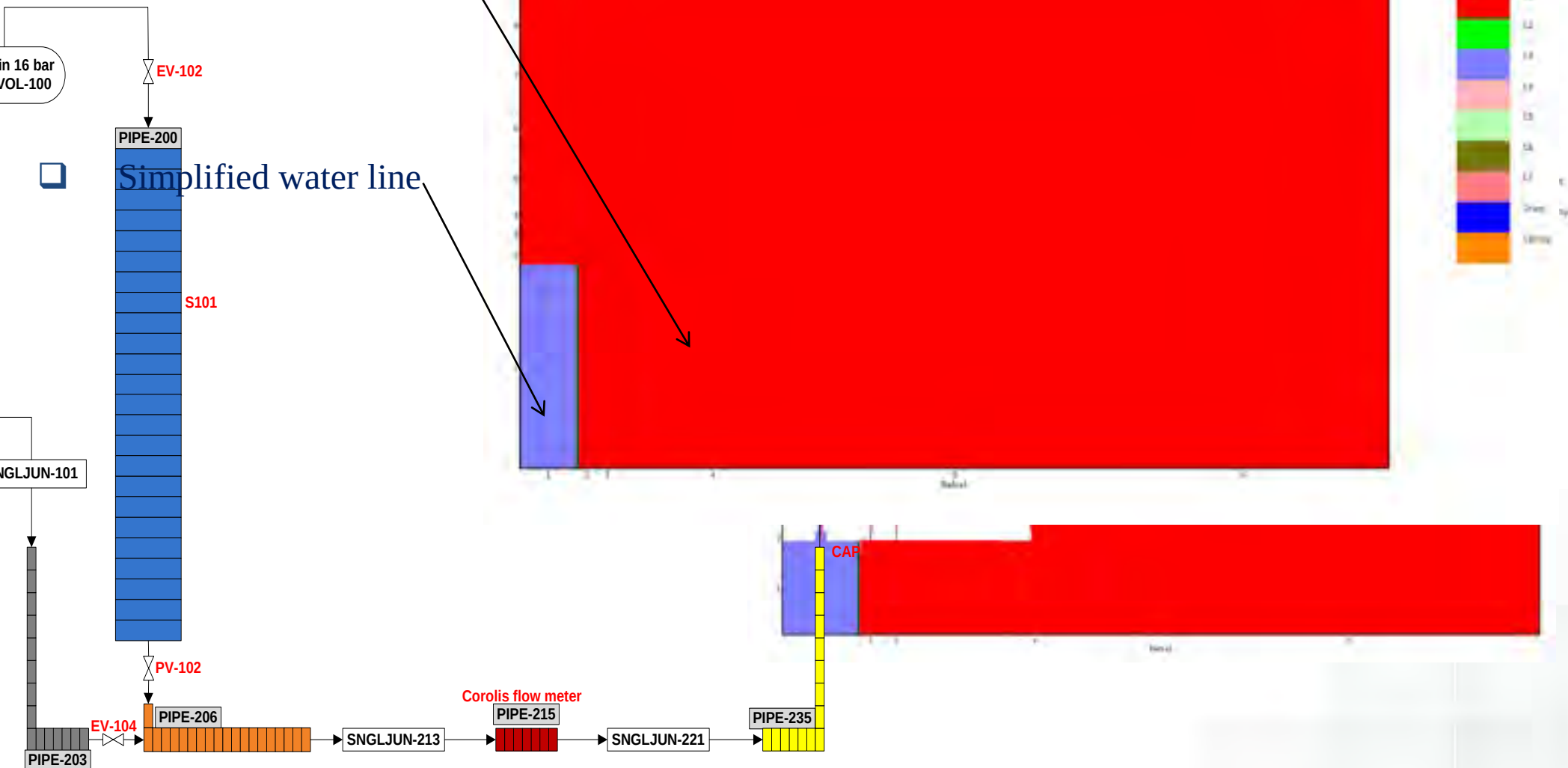


CODE ACTIVITY IN SUPPORT OF THE EXP [4/5]

SIMMER-III modeling and simulations

- ☐ LBE tank modelled

CTION LINE LIFUS-5/I



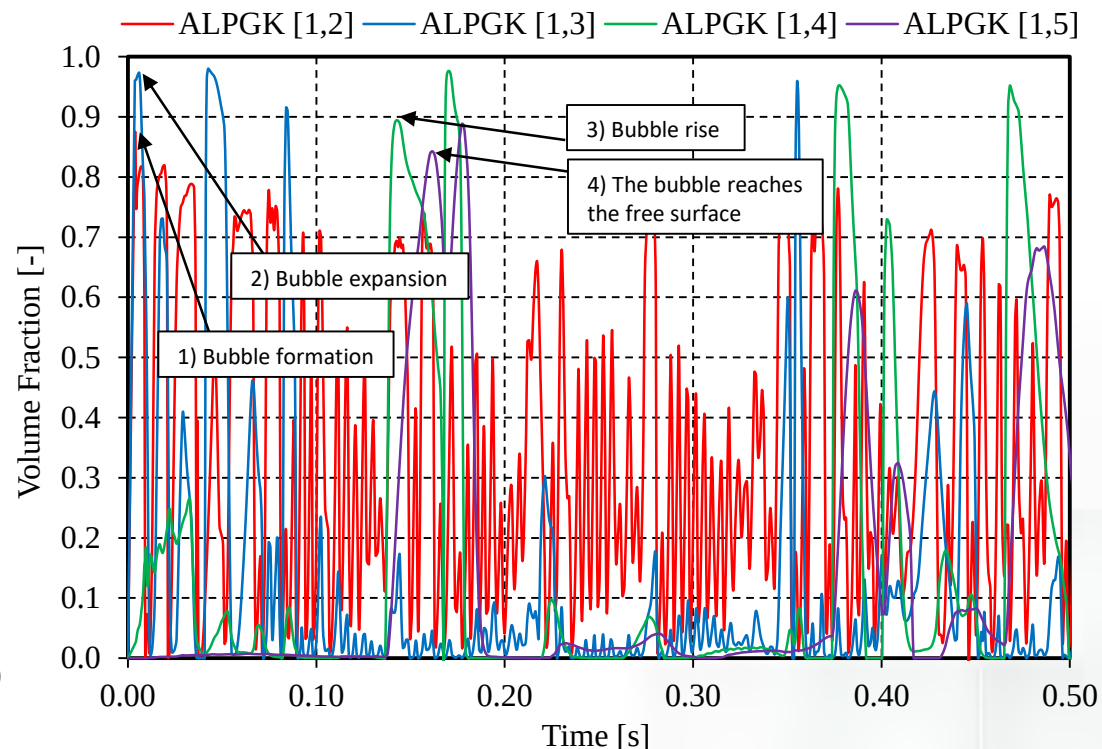
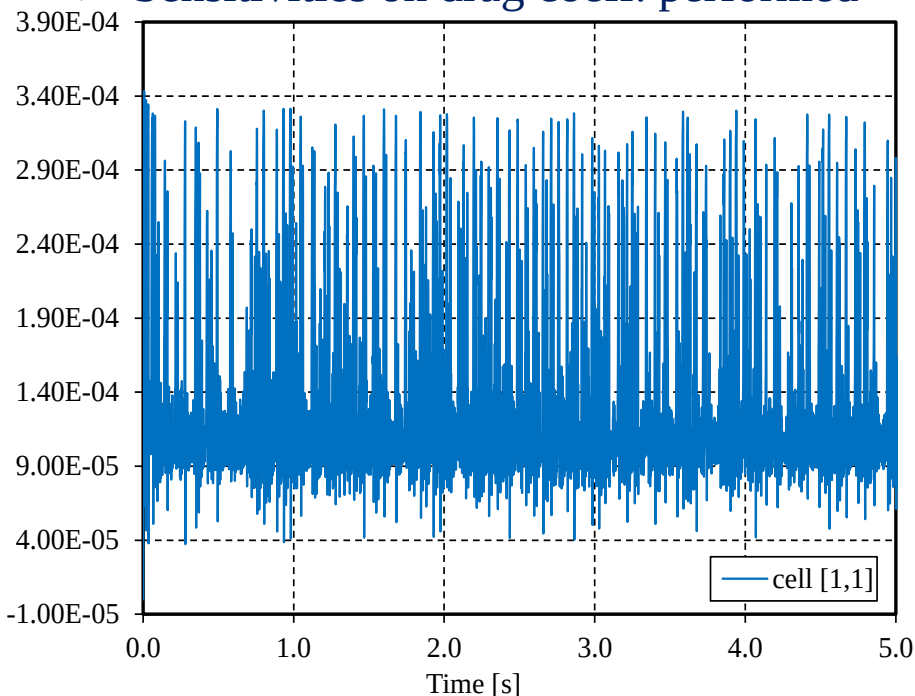
CODE ACTIVITY IN SUPPORT OF THE EXP [5/5]

SIMMER-III modeling and simulations



CASE #8 → D=0.1MM

- Results confirmed R5/M3.3 predictions concerning the possibility of LBE drop down
- Mass flow rate behavior is slightly different from RELAP5 results because
 1. reverse of the LBE towards the injector during the transient
 2. bubble formation and expansion in the cells above the injector
- Bubble formation (voidf) and bubble rising in melt during the transient is characterized
- Sensitivities on drag coeff. performed



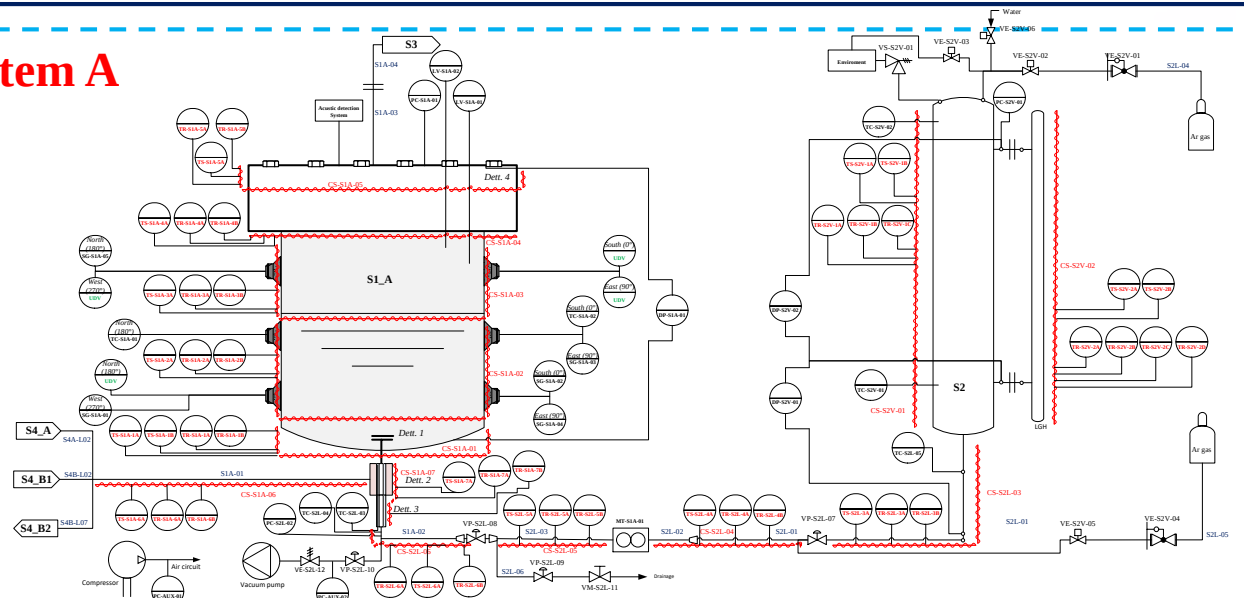
□ ACTIVITY IN PROGRESS

- “ADDITIONAL” INSTRUMENTATIONS (I.E. MAGNETIC GRID SENSOR AND ACOUSTIC SENSOR IN LBE) WOULD BE AN ADDED VALUE → FEASIBILITY WILL BE ADDRESSED BY EARLY 2016
- PROCUREMENTS ARE IN PROGRESS
- COMMISSIONING TESTS OF LIFUS5/Mod3 EXPECTED BY JUNE 2016
- END OF ACTIVITY BY END OF 2016

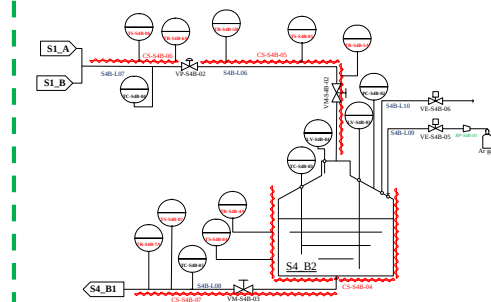
... INCLUDING EUROFUSION PBLI TESTS

LIFUS5/Mod3 facility

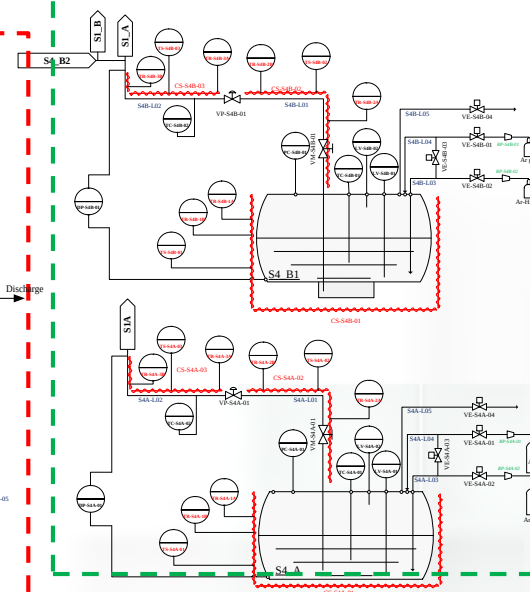
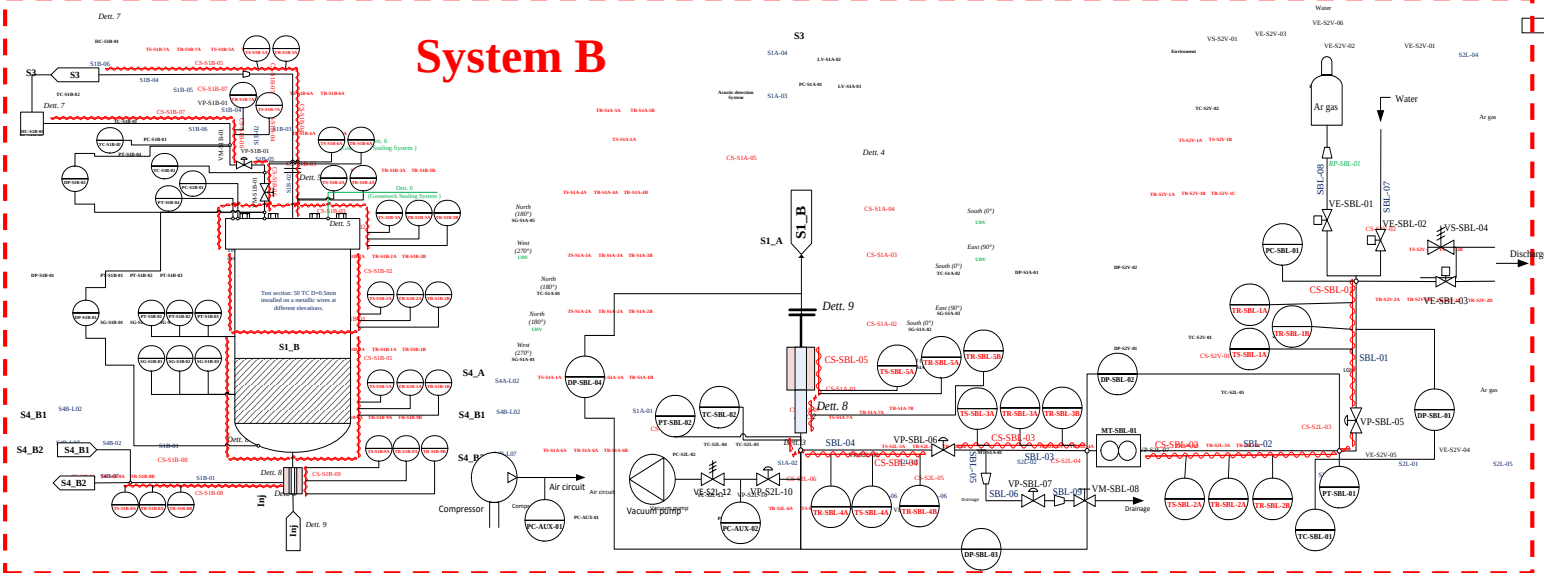
System A



**PAR, EUROfusion
Consortium and MAXSIMA
EC FP7 projects**



System B



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Giuseppe Polazzi – ENEA
Valerio Sermenghi – ENEA
Lorenzo Laffi – ENEA
Daniel Giannotti – ENEA
Mariano Tarantino – ENEA



- NACIE-UP facility
 - overall description
 - FPS test section
- Experimental test matrix and post-processing methods
- Obtained Results
 - tests P43X0 & P217
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NACIE-UP loop



Every side is composed by:

vertical pipes (O.D. 2.5") 8m long and two horizontal pipes (O.D. 2.5") 2.4m long;

Heater Simulator (19-pins) of **235 kW** maximum power;
Condenser and tube HX with two sections, operating at *low power* (5-50 kW) and *high power* (50-250 kW);

Gas injection device, placed inside the riser, as the driving force to enhance the circulation;

Expansion tank, at the end of the riser, partially filled with water;

Several tubes and several thermocouples to monitor pressure and temperature along the flow path.

Due to the distance between the heat source and the condenser **H** is about **5.5 m** the **natural circulation regime** can be established inside the loop.

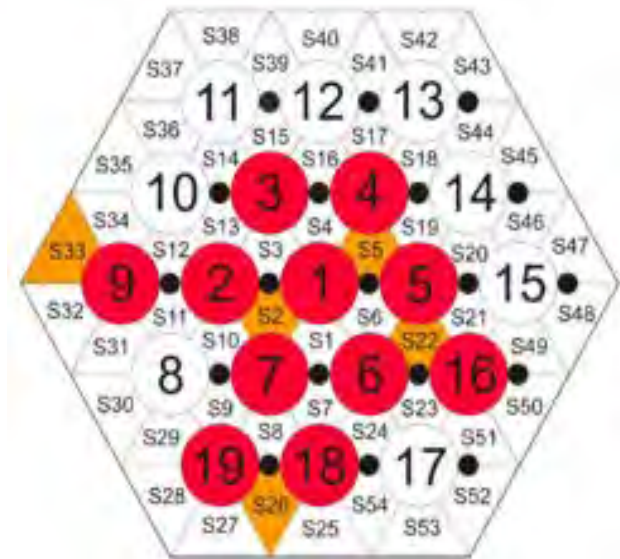


NACIE-UP test section

19 pins **wire-spaced** arranged in triangular lattice

235 kW maximum power

D_{pin}	6.55 mm
P	8.4 mm
P/D	1.2824
d	1.75 mm
P_{wire}	262 mm
L_{tot}	2000 mm
L_{active}	600 mm
$D_{H,nom}$	3.84 mm

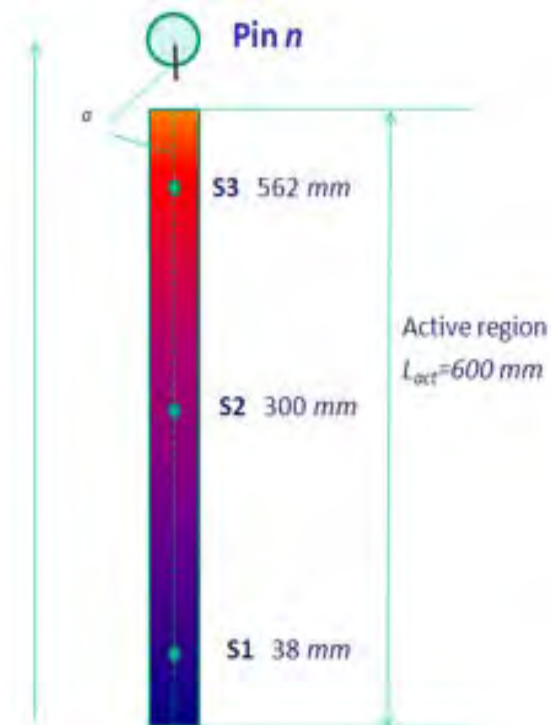
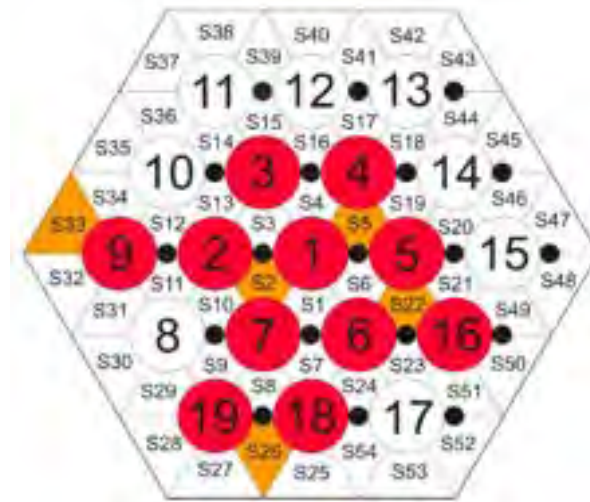


- In **red** instrumented pins
- In **orange** instrumented sub-channels



FPS Instrumentation

- **11 pins** instrumented
Embedded-wall TCs 0.35 mm (52)
- **5 sub-channels** instrumented
Sub-channel TCs 0.5 mm (15)
- Pins 1,2,4,5,6,7,9,16,18,19 instrumented at three axial positions: **$z = 38, 300, 562 \text{ mm}$** from the *beginning of the active length*
($562 - 300 \text{ mm} = 300 - 38 \text{ mm} = 262 \text{ mm} = P_w$, at the three axial position the same relative position between pin and wire)
- Pin 3 instrumented with wall embedded TCs **every 43.66 mm** (13 TCs). This will allow to study *axial thermal development*



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Experimental Matrix

PC TEST	Q[kW]	Q _{lin} [kW/m]	m _{NACIEUP} [kg/s]	Re _{sc} ×10 ⁻³	Pe _{sc}
P99	11	0.96	2.92	7.08	236
P100	11	0.96	2.28	5.45	188
P11X0	11	0.96	1.06	2.72	84
P102	11	0.96	0.72	1.93	55
P102b	11	0.96	0.68	1.84	51
P103	11	0.96	0.36	1.13	26
P202	20	1.75	4.17	10.65	332
P203	20	1.75	3.10	8.09	245
P20X0	20	1.75	1.49	4.01	116
P204	20	1.75	0.73	2.24	52
P212	36	3.16	1.17	3.69	83
P213	36	3.16	3.33	10.06	242
P214	36	3.16	2.22	6.88	159
P217	43	3.77	1.15	3.96	77
P218	43	3.77	3.2	9.98	228
P43X0	43	3.77	2.8	8.75	199
P223	52	4.56	1.62	5.35	111
P224	52	4.56	3.40	10.81	237
P265	54	4.74	2.24	7.44	151
P269	108	9.47	3.23	10.21	226

$$u_{sc} \approx 0.1 - 0.9 \text{ m / s}$$

$$Re_{sc} \approx 2000 - 20000$$

$$\dot{m}_{NACIE} \approx 0.4 - 5.0 \text{ kg / s}$$

$$\dot{m}_{FA} \approx 2.3 - 28.7 \text{ kg / s}$$

$$Q_{lin} \approx 0.9 - 9.5 \text{ kW / m}$$

$$Q_{FPS} \approx 11 - 110 \text{ kW}$$

Post-processing method

- Acquisition frequency of data **1 Hz** (duration 15-20 min)
- Matlab routines were written for data post-processing
- **Error analysis implemented.** Sources of error considered: *statistical error, instrumental error and uncertainties on LBE properties*

- Mass flow rate calculated through the energy balance across the heated length
- Definition of **section-averaged** bulk and wall temperatures

$$\bar{T}_b = T_{bS2} \cdot w_2 + T_{bS5} \cdot w_5 + T_{bS22} \cdot w_{22} + T_{bS26} \cdot w_{26} + T_{bS33} \cdot w_{33}$$

$$\bar{T}_w = T_{wS2} \cdot w_2 + T_{wS5} \cdot w_5 + T_{wS22} \cdot w_{22} + T_{wS26} \cdot w_{26} + T_{wS33} \cdot w_{33}$$

- Wall temperatures correction for embedded thermocouples

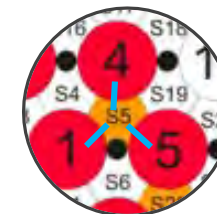
$$T_w = T_{ac} - \frac{Q}{2\pi M L_{active} k_{ss}} \ln \left(\frac{D/2}{D/2 - \delta_g} \right)$$

- **Re, Pe** and **Pr** numbers computed in each section from $\bar{T}_b$

- **Average Nusselt** number is computed using $\bar{T}_b$ and $\bar{T}_w$

- **Local Nusselt** number is computed in each monitored subchannel

$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$

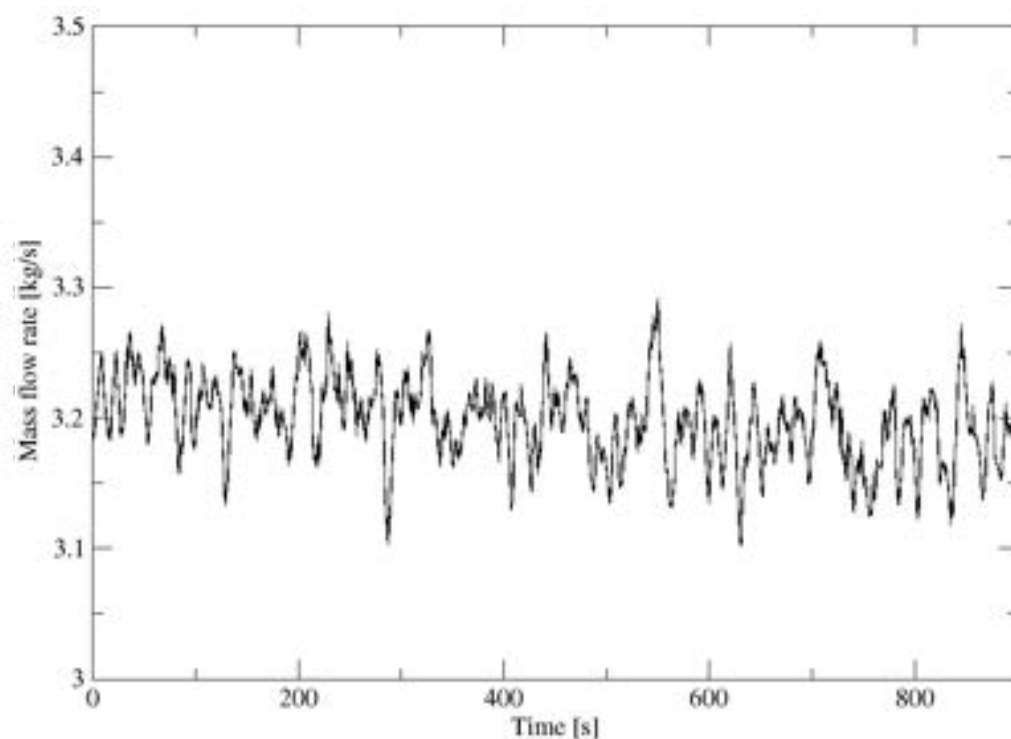
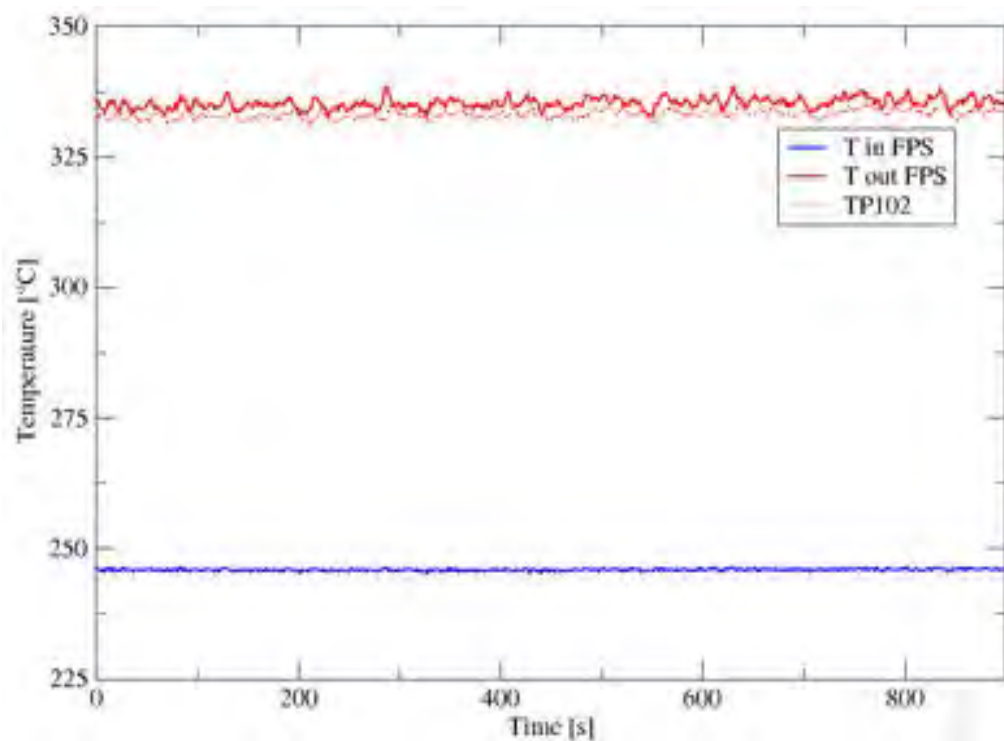


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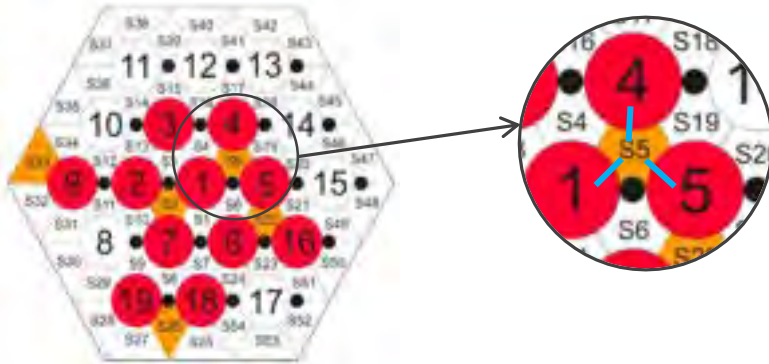
Tests P43X0 & P217 1/2

PEC TEST	Q [kW]	Gas flow rate [NI/min]	ΔT_{FPS} [°C]	u_{sc} [m/s]	$m_{NACIEUP}$ [kg/s]	$m_{MYRRHAFA}$ [kg/s]	Re_{sc}	Pe_{sc}
P43X0	43	-	176.9	0.24	1.63	9.38	5350	111
P217	43	15	89.4	0.47	3.21	18.49	9980	228

P217

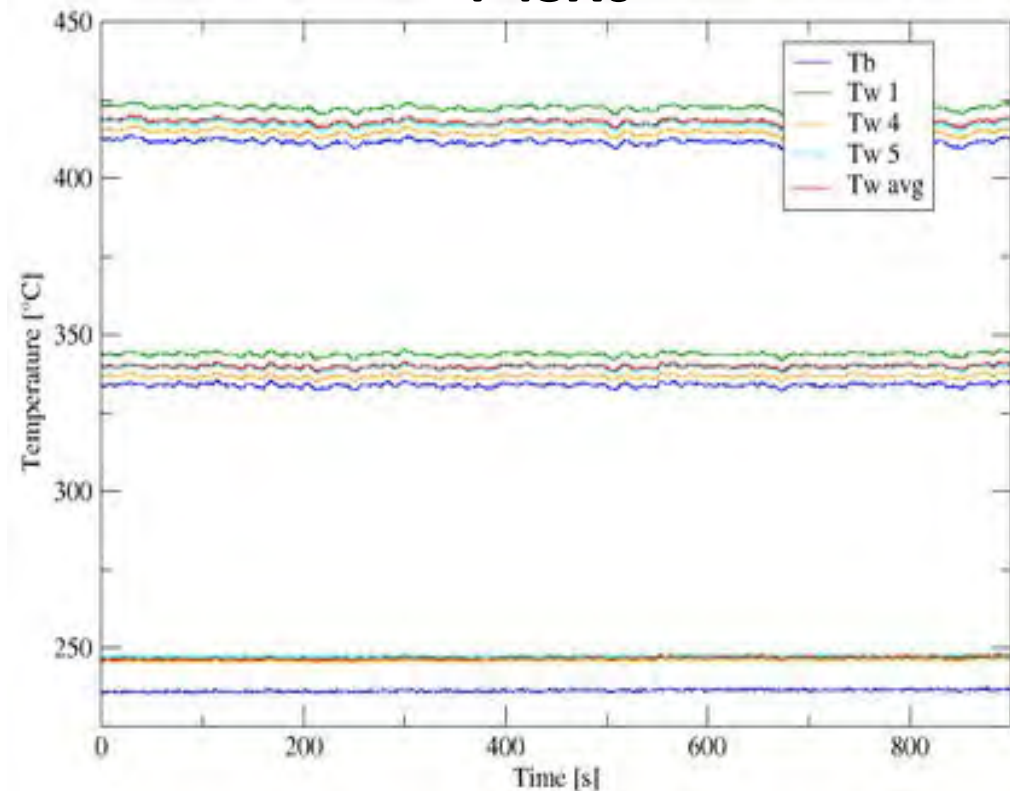


Tests P43X0 & P217 2/2

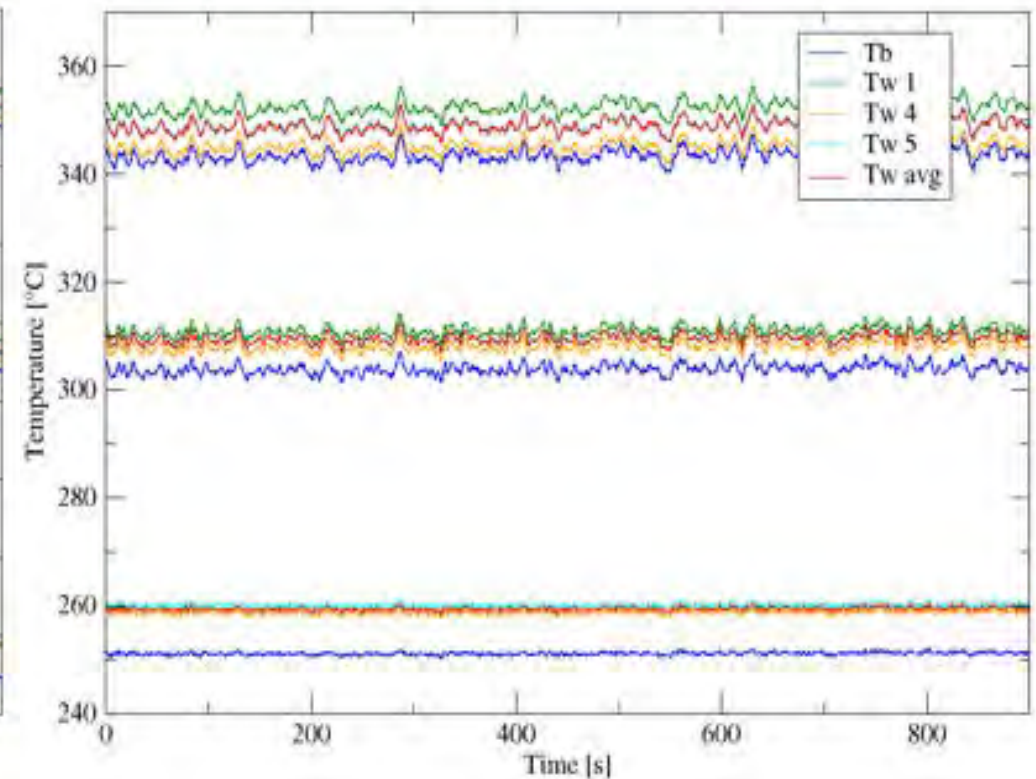


Wall (T_w) and sub-channel (T_b) temperatures
sub-channel S5
sections A, B and C

P43X0



P217

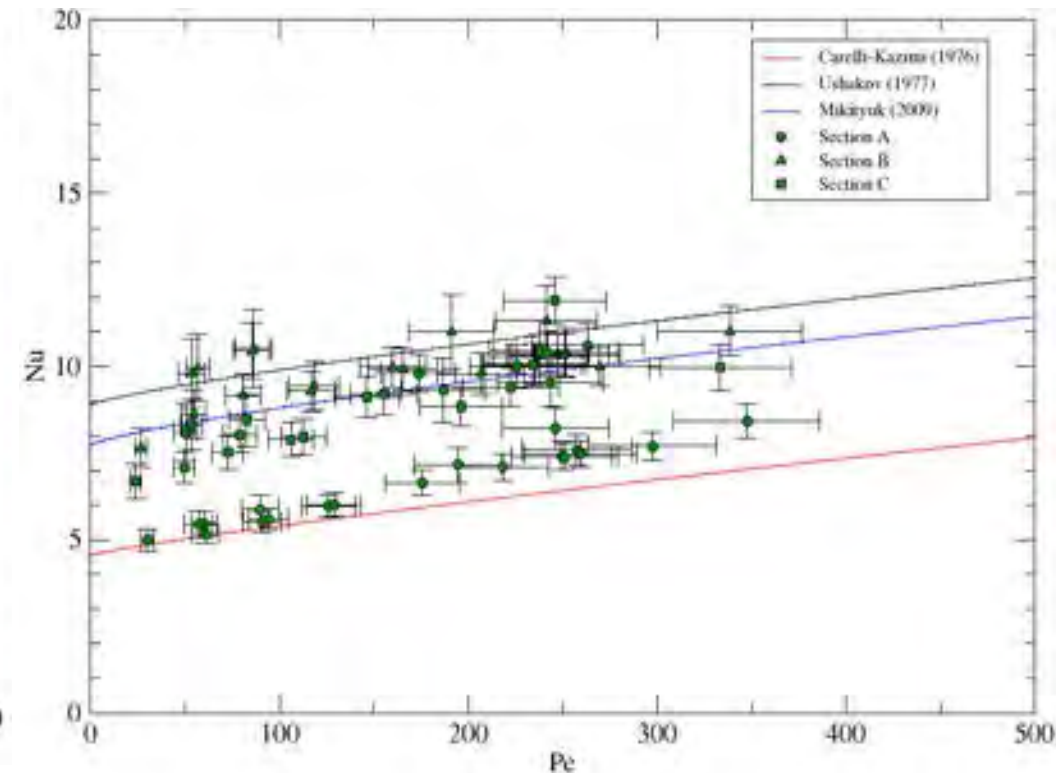
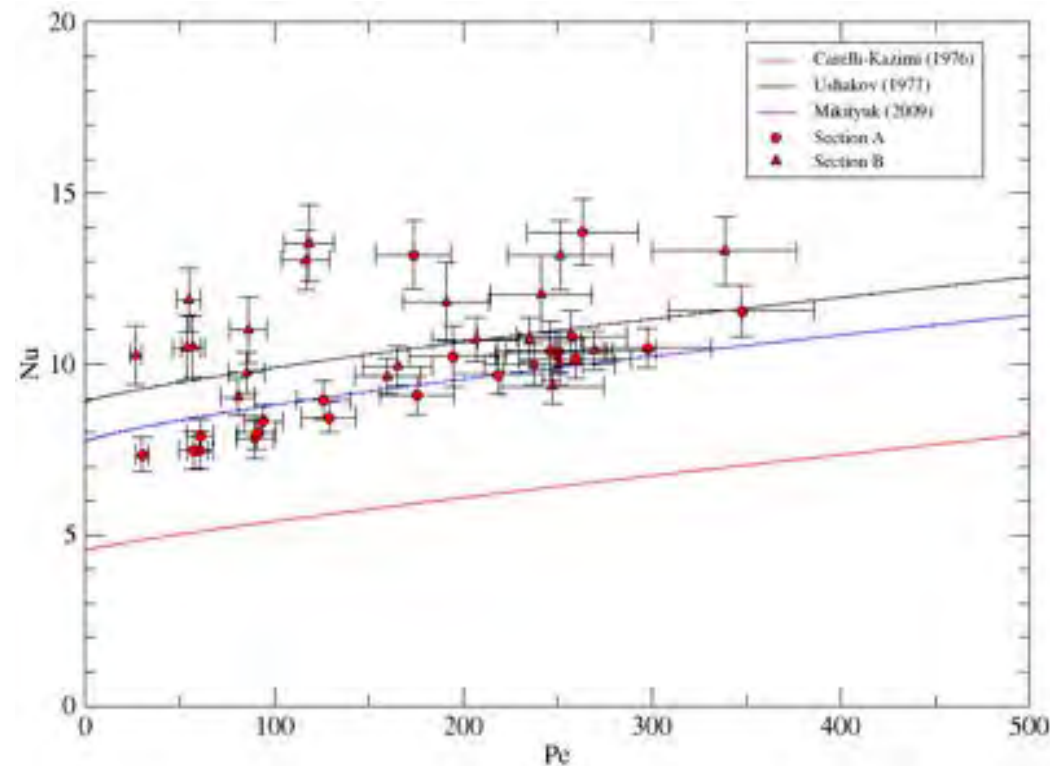


Nusselt number: S2 & S5



Nu vs Pe – Inner rank: sub-channels S2 and S5

$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$

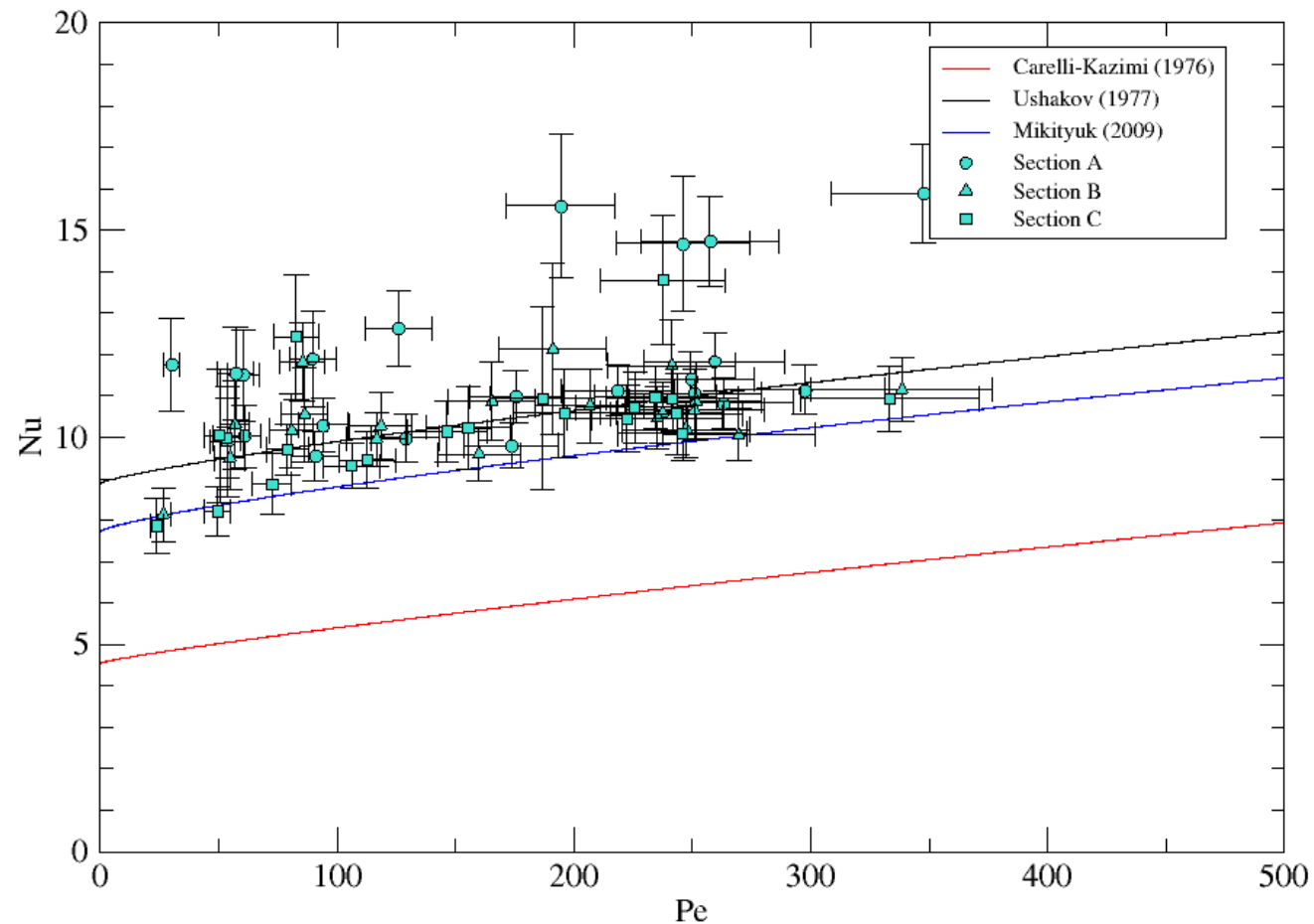


Nusselt number: S22

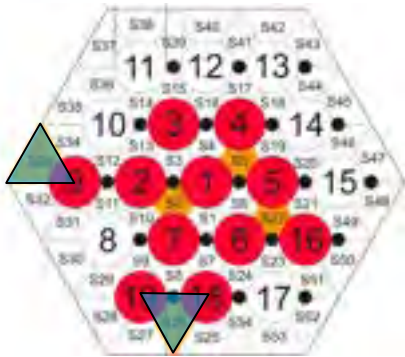


Nu vs Pe – Intermediate rank: sub-channels S22

$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$

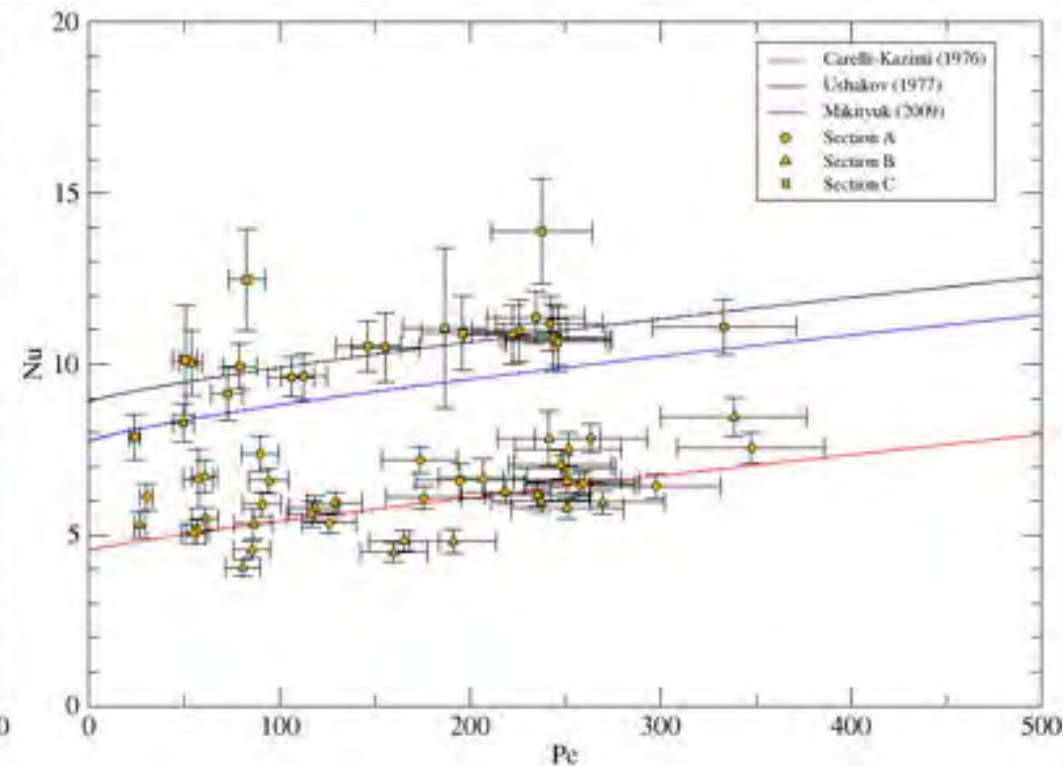
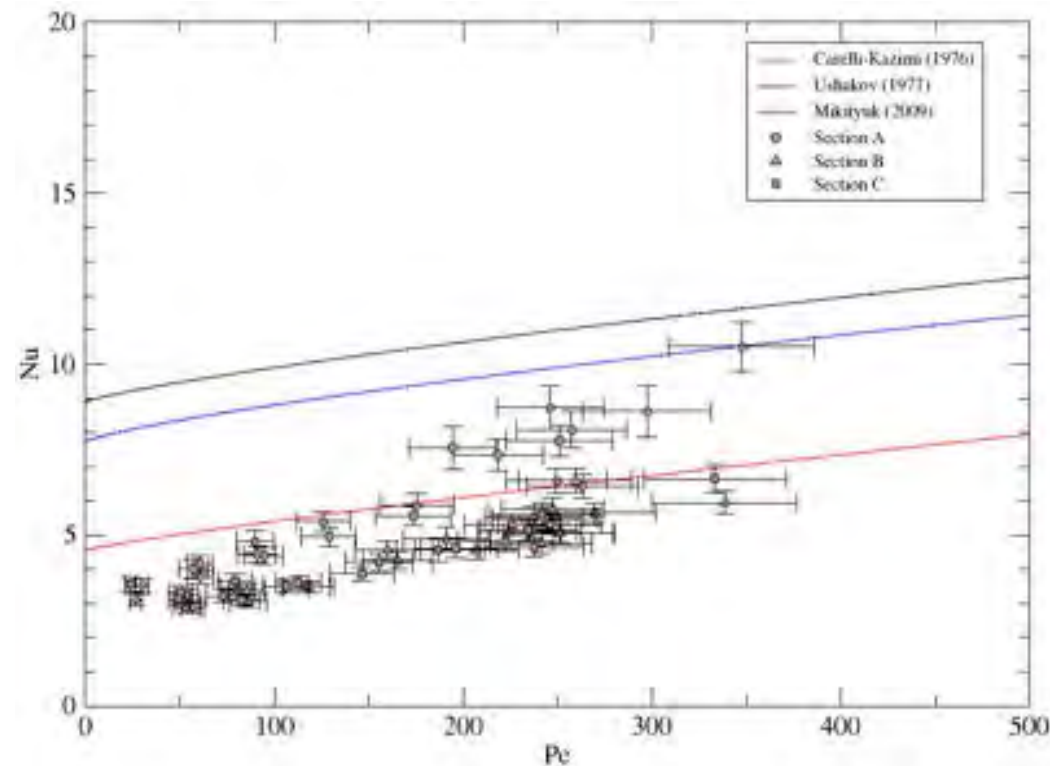


Nusselt number: S26 & S33



Nu vs Pe – External rank: sub-channels S26 and S33

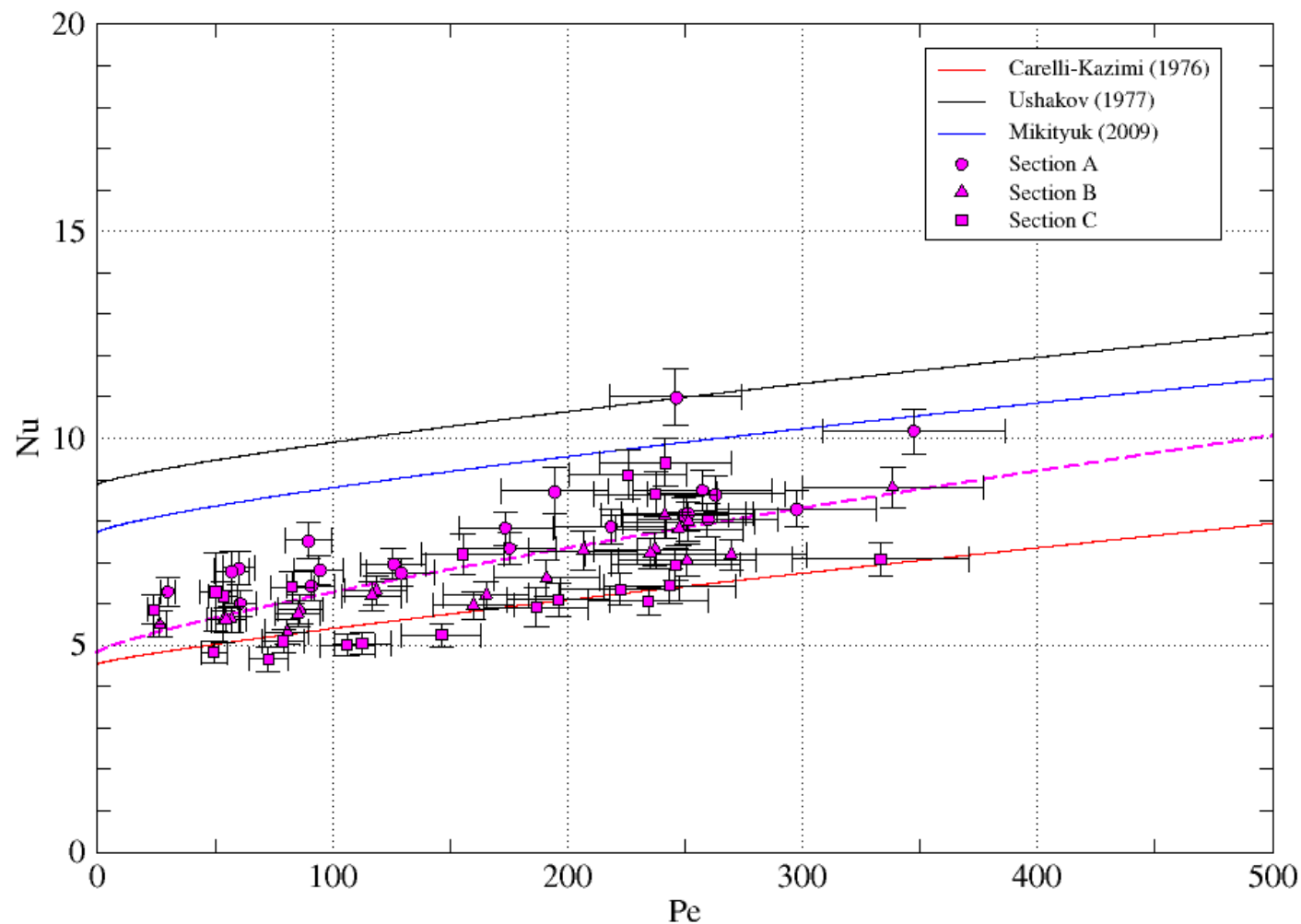
$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$



Overall heat transfer

Nu vs Pe – Section-averaged heat transfer

$$Nu_1 = \frac{q''}{(\bar{T}_w - \bar{T}_b)} \cdot \frac{D_{H,nom}}{k}$$



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NACIE-UP: upgrade



Upcoming Experiments



New experimental campaigns are foreseen in 2016:

- **Preliminary tests:**
 - **Zero power-very low mass flow rate test** to characterize heat losses through the structure ($T=400^{\circ}\text{C} \rightarrow 250^{\circ}\text{C}$);
 - **Isothermal test** at 350°C and **different mass flow rates of gas** injected (in the range of 0-20 Nl/min);
- Further **steady-state tests** in order to **complete** the characterization of the **bundle coolability** (in natural and forced circulation regimes);
- **Steady state tests for the INERI benchmark** for CFD codes on the NACIE-UP 19-pins bundle;
- **Transient tests for a benchmark for CFD and STH/CFD coupled calculations** inside the **SESAME** project;
- Several **transient** tests characterized by transitions **from high power** and **relative high mass flow rates to low power** and **natural circulation** regime (**PLOFA-like tests**).

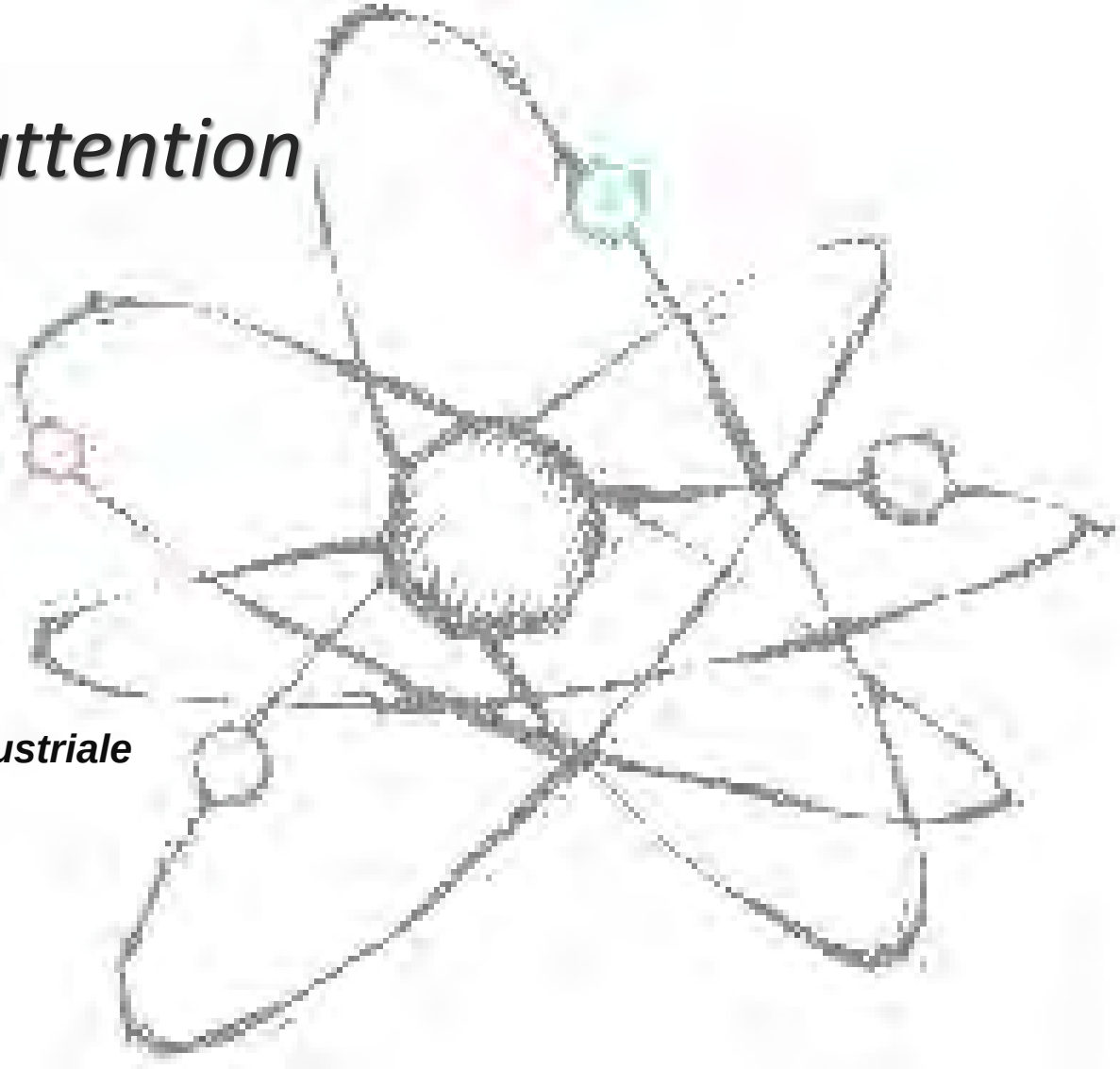
Conclusions



- An **experimental campaign** was performed at ENEA Brasimone PEC Lab (NACIE-UP facility) on a LBE cooled **19-pins bundle** in the context of the SEARCH FP7 EU
- A well instrumented 19-pin bundle test section was specifically designed and manufactured for the experiment
- Several **tests** have been performed both in **Natural** and **Forced Circulation** (range explored: $Re_{sc}=2000-20000$, $Q=11-110$ kW)
- Post-test error analysis was performed according to the error propagation theory
- **Analysis of local Nusselt and average Nusselt**
 - Local Nusselt for inner sub-channels in agreement with existing correlations
 - Local Nusselt for external sub-channel is lower than in the inner ranks
 - Section-averaged Nusselt number is in accordance with the Carelli-Kazimi correlation
- Some improvements are being implemented in the facility for the **upcoming experimental campaign** that will focus on the thermal-hydraulic behavior of the sub-channels during **transients**

Thank you for your attention

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Flow Blockage experimental studies in HLM systems

R. Marinari (ENEA/UniPi), P. B. Ghionzoli (ENEA/UniPi),

I. Di Piazza (ENEA), M. Serra (ENEA),

F. Magugliani (ANN)

- Introduction
- NACIE-UP present status and upgrade
- NACIE-UP FPS test section: present configuration
- BFPS test section design: present status
- CFD pre-test analysis
- Timeline & Conclusions



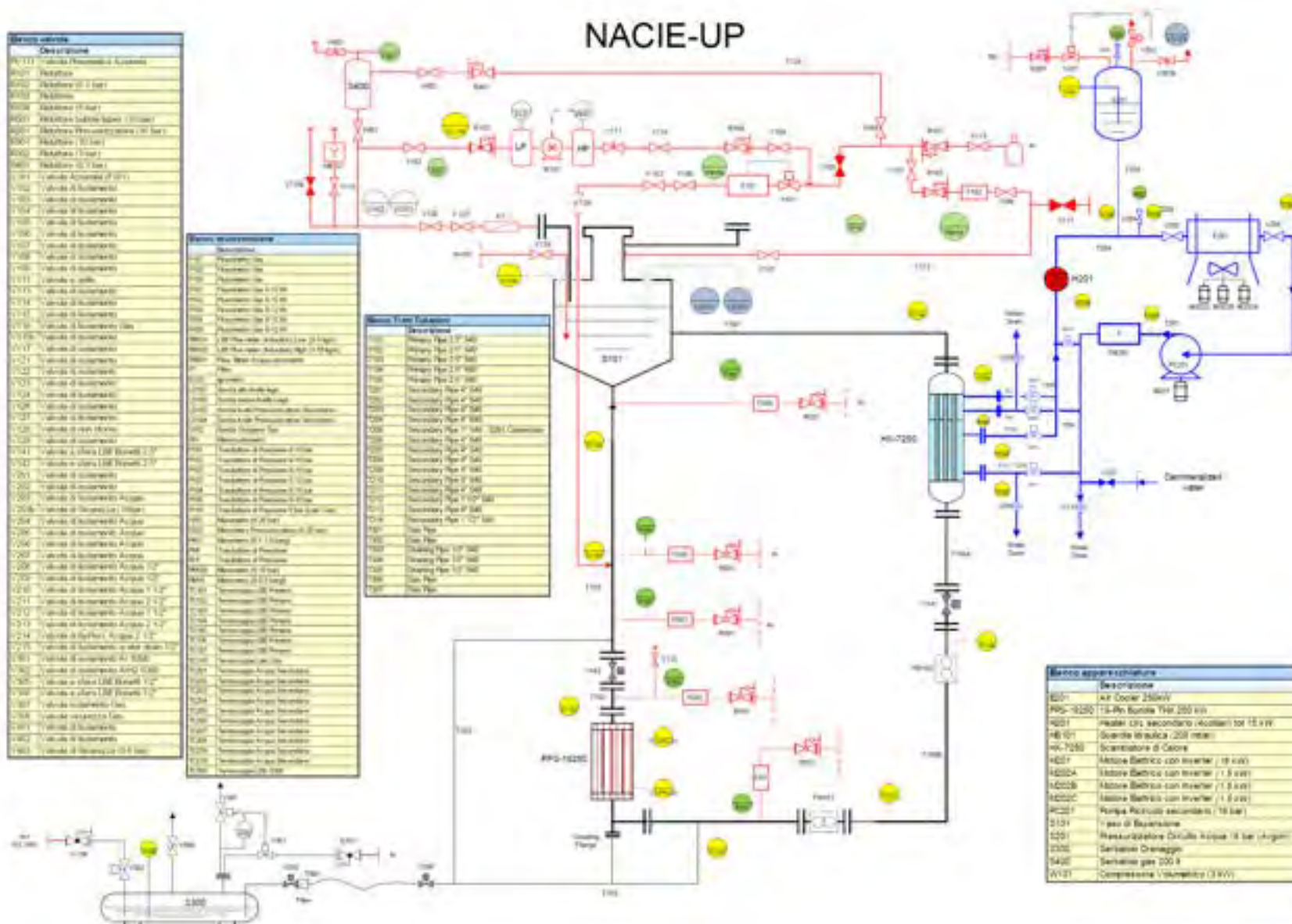
INTRODUCTION



Thermal-hydraulics of the flow in fuel assemblies with grid spacers with and without blockage is investigated experimentally and numerically. **Reference data obtained from the NACIE-UP experiment** as well as from DNS data will be used for the validation of CFD models. The validated models are used to develop a reduced resolution CFD approach to simulate a real size ALFRED fuel assembly.

The NACIE-UP loop is an LBE loop working in natural circulation and with gas-lift pumping. The facility is already arranged with Induction flow meters in the primary side and with a pressurized water secondary side to remove heat.

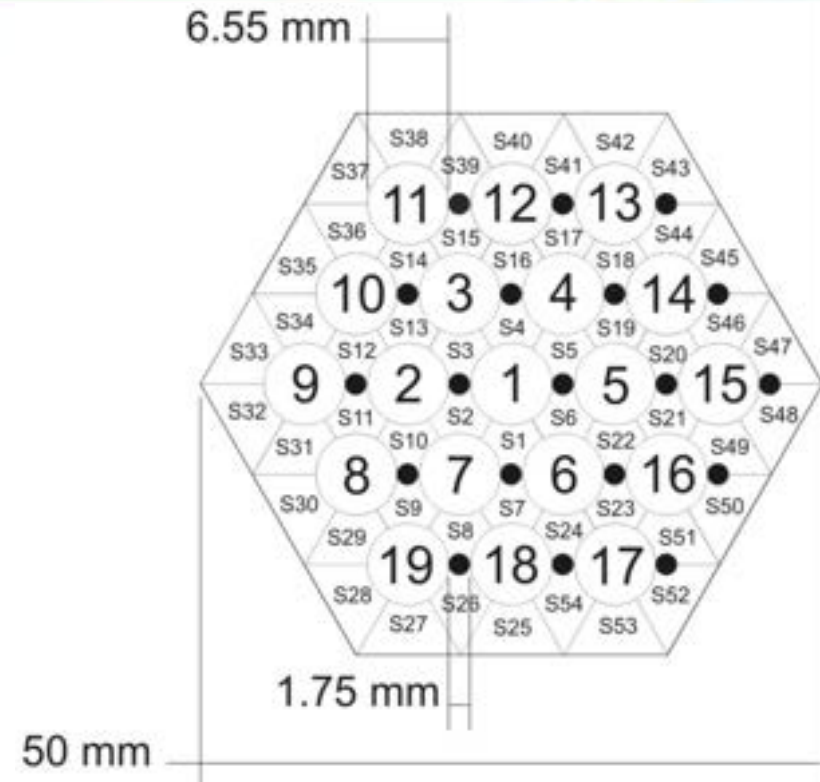
The test section will consist of a 19 pin rod bundle, 250 kW power, hexagonally staggered, with a rod diameter 10.5 mm and with a maximum heat flux 0.7 MW/m^2 , of the same order of what is expected in the ALFRED demonstrator reactor. The test section is named Blocked Fuel Pin Simulator (**BFPS**). **A special spacer grid will be manufactured and mounted at the beginning of the active region**, in order to have the correct pitch to diameter ratio and to close some sub-channels **to operate with a degree of blockage**. Two or three different spacer grids will be manufactured and mounted to achieve different levels of blockage. **The bundle will be instrumented with several thermocouples in the whole region behind the blockage and along the active region to assess the clad temperature distribution**. Both the local phenomena and the integral phenomena due to the blocked mass flow rate in the sub-channels will be experimentally assessed. A large test matrix will be carried out to collect as much data as possible on turbulent convective heat transfer and its effect on maximum clad temperature. Mass flow rate and inlet temperature will be also available and stationary conditions will be reached by exchanging heat with the secondary water loop. Transient data will be also available to assess the role of the thermal inertia of the pins.



- The facility includes:
 - ✓ **The Primary side**, filled with LBE, with 2 ½" pipes, where the main new components and instruments are placed;
 - ✓ A **Fuel Pin Simulator** (19-pins) **250 kW** maximum power;
 - ✓ A **Shell and tube HX** with two sections, operating at **low power (5-50 kW)** and high **power (50-250 kW)**;
 - ✓ A mass flow rate induction flow meter (3-15 kg/s) **FM102**;
 - ✓ Absolute pressure transducer;
 - ✓ **Differential pressure transducers**;
 - ✓ **Several bulk thermocouples** to monitor the temperature along the flow path;
 - ✓ **Motorized valve to regulate mass flow rate**;
 - ✓ **Difference in height between Heat Source and Heat sink 4.8 m (natural circulation)**;
 - ✓ **The Secondary side**, filled **with water at 16 bar**, connected to the HX, shell side. It includes a pump, a pre-heater, an air-cooler, by-pass and isolation valves, and a pressurizer (S201) with cover gas;
 - ✓ **An ancillary gas system**, to ensure a proper cover gas in the expansion tank, and to provide **gas-lift enhanced circulation (0-20 NI/min)**;
 - ✓ **A LBE draining section**, with ½" pipes, isolation valves and a storage tank (S300);
 - ✓ The ancillary gas system is practically identical to the previous configuration of the NACIE facility and does not have significant upgrade. It has the function to ensure the cover gas in S101 and to manage the gas-lift system in the riser (T103) for enhanced circulation regime;

–Features:

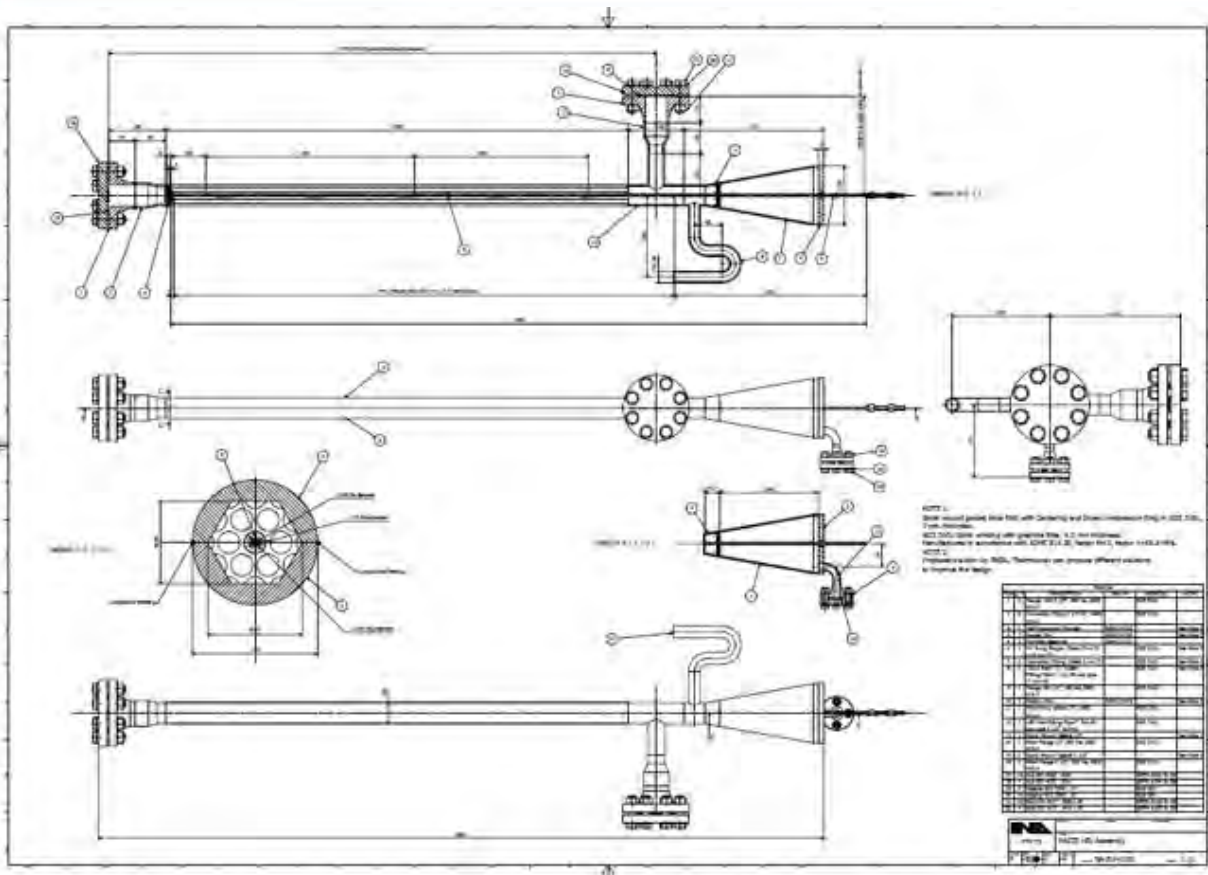
- 19 pins (triangular lattice);
- $d = 6.55 \text{ mm}$, $L_{\text{active}} = 600 \text{ mm}$;
- $L_{\text{entry}} > 600 \text{ mm}$ (> 2 pitches);
- $p/d = 1.28$;
- $q'' = 1 \text{ MW/m}^2$, uniform ($\approx 235 \text{ kW}$);
- **wire spaced** ($d = 1.75 \text{ mm}$).
- Configuration relevant for MYRRHA
- Each pin can be fed separately



$$D_{eq} = \frac{4(A_{\text{wrap}} - A_{\text{pins}} - A_{\text{wire}})}{L_w} = 4.147 \text{ mm}$$



NACIE-UP FPS (PRESENT CONFIGURATION)



6.55 mm

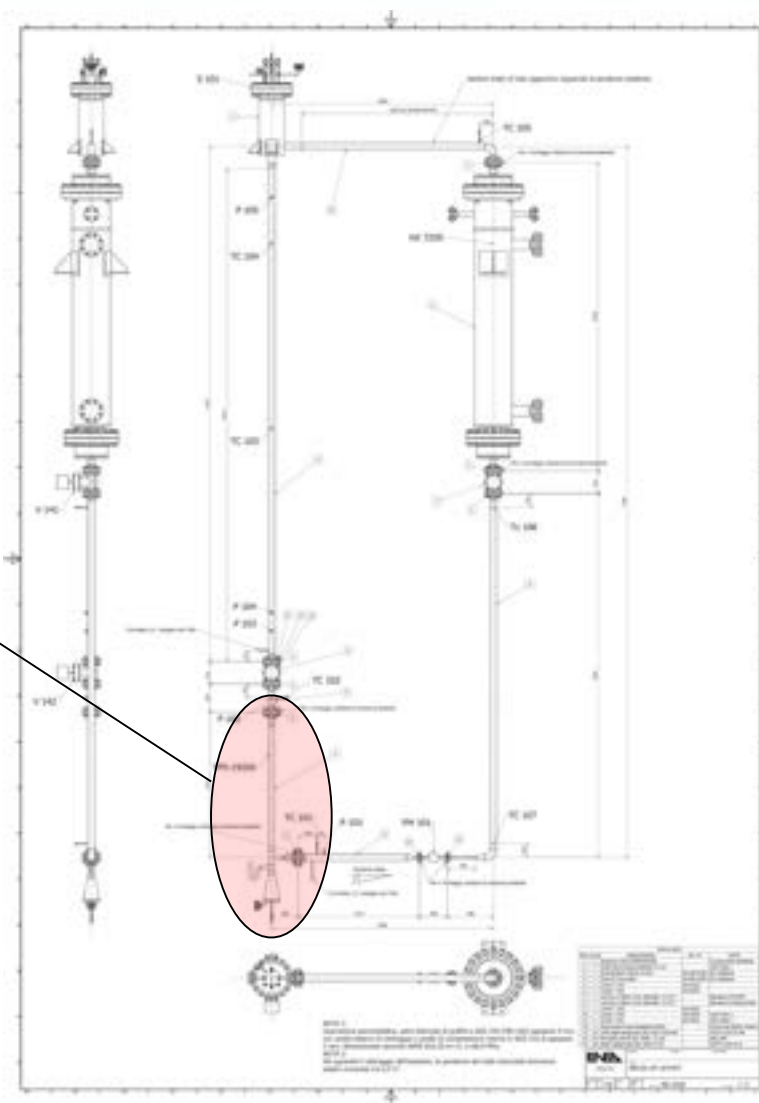


50 mm



NACIE-UP PRIMARY SIDE

**Instrumented Bundle
(19 pins, 250 kW)**



NACIE-UP PRIMARY SIDE

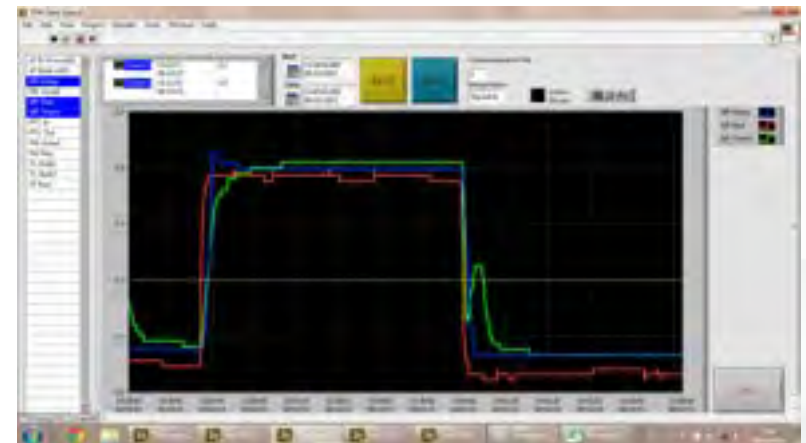
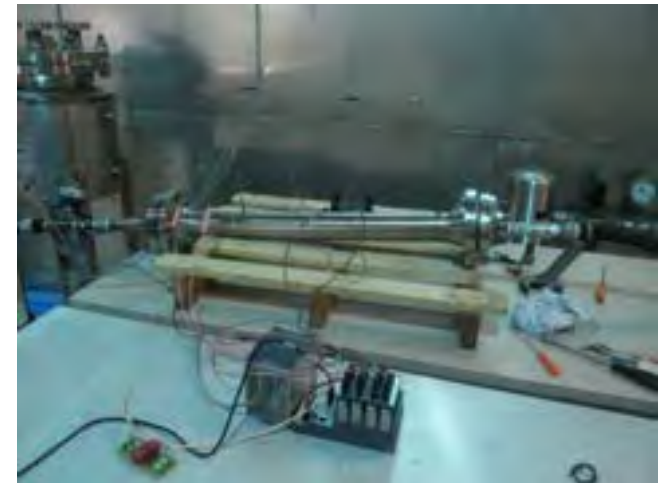


NACIE-UP SECONDARY SIDE



The facility is under upgrade/improvement

- Mass flow rate will be measured accurately in the whole range by innovative **thermal flow meter** (ENEA/Thermocoax design) (European patent): tests in water with very promising results. It should be very accurate and reliable in the range 0-20 kg/s.
- Differential pressure across the test section will be measured by accurate **differential pressure transducer** (Rosemount 1199, 0-1000 mbar, 1 mbar accuracy)
- Improvement in the **auxiliary systems and HX** (maldistribution corrected)
- **Low oxygen tests by Ar-H₂ injection** in the expansion tank
- **Gas injection system improvement to increase flow rate**
- Expansion tank enlarged
- Filter section to be installed
- Then preliminary tests on the instrumentation with the present test section can start by the end of the year



NEW BFPS TEST SECTION

- A new **FPS test section was designed** in order to assess the flow blockage local and global effect
- The test section will have **the same 'flange-to-flange' dimensions** of the present FPS in order to mount it directly in NACIE-UP
- It will have **19 pins, 250 kW power**, but **grid-spaced**: the pin number and the power will be identical to the present configuration and will minimize the facility refurbishment (plug and play strategy)
- The **p/d ratio was fixed to 1.4 close to the ALFRED FA**
- **ALFRED FA 19-pin Mock-up for thermal investigations, $d_{pin}=10$ mm**
- The test section will investigate **a degree of blockage and possibly several degrees**
- It will be **instrumented with wall-embedded thin thermocouples in the region behind the blockage (local effect) and in several subchannels at the end of the active region (global effect)** (experience with previous FPS, 100 TCs)
- The mixing in the FA plenum will be investigated
- Experiments without blockage are also feasible
- It will provide a **valid data set** for CFD code validation
- In parallel **a detailed CFD model of the test section** will be developed for pre and post-test in collaboration with UniPi/Ansaldo/UniGe
- Ansaldo feedback is mandatory for design and to plan a good experiment



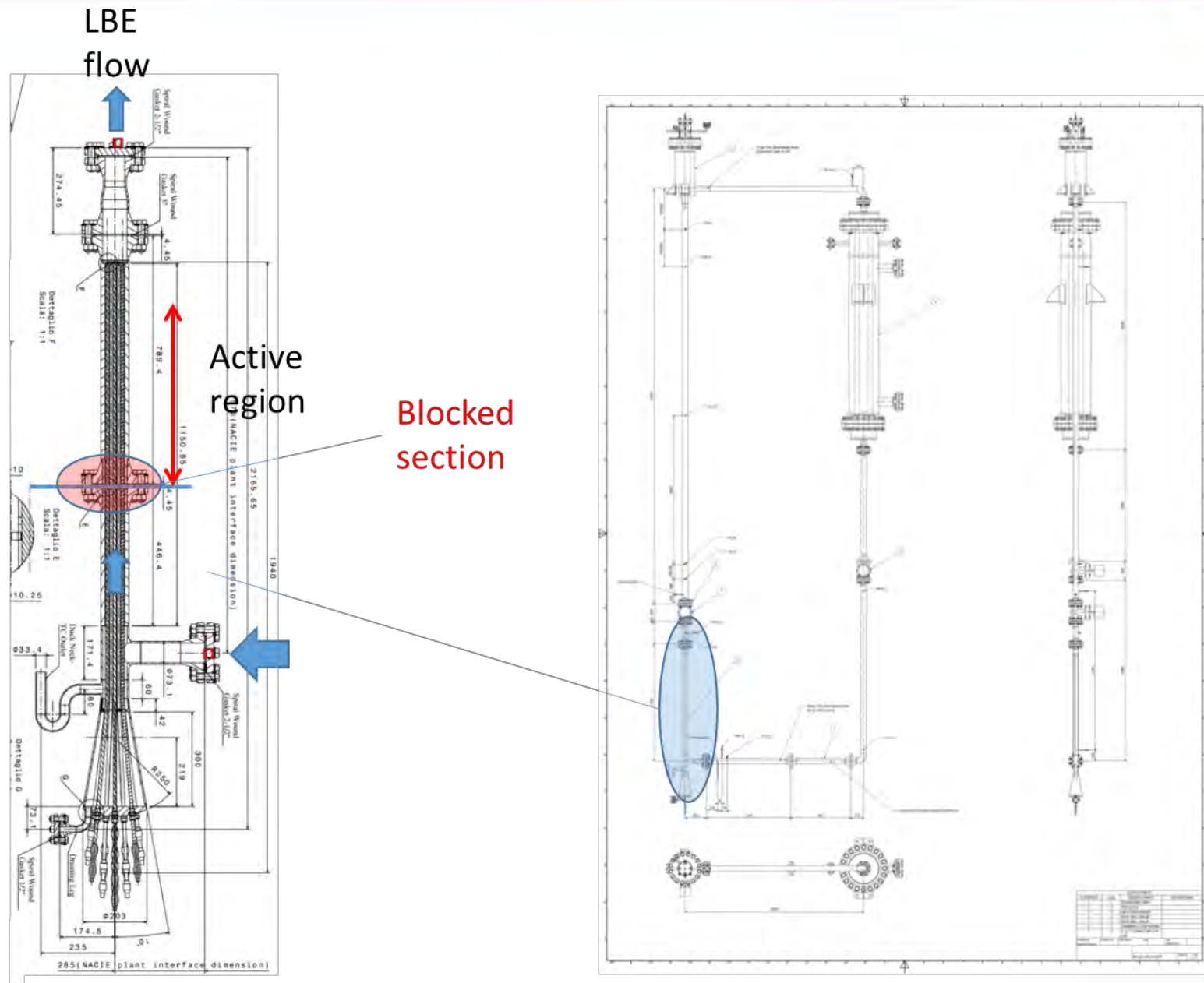
NEW BFPS TEST SECTION: PARAMETERS



Parameter	BFPS	ALFRED FA	
$d_{pin}[mm]$	10	10.5	Pin Outer diameter
p/d	1.4	1.32	Pitch to diam ratio
Power [kW]	250	-	Total power
Pin power [kW]	13	-	Pin power
Wall heat Flux [MW/m ²]	0.7	0.7-1	Heat flux
Subch velocity [m/s]	0.8	1.1	Subch velocity
N_{pin}	19	127	Number of pins
$L_{active}[mm]$	600	600	Active region
$L_{plenum}[mm]$	500	500	FA mixing region



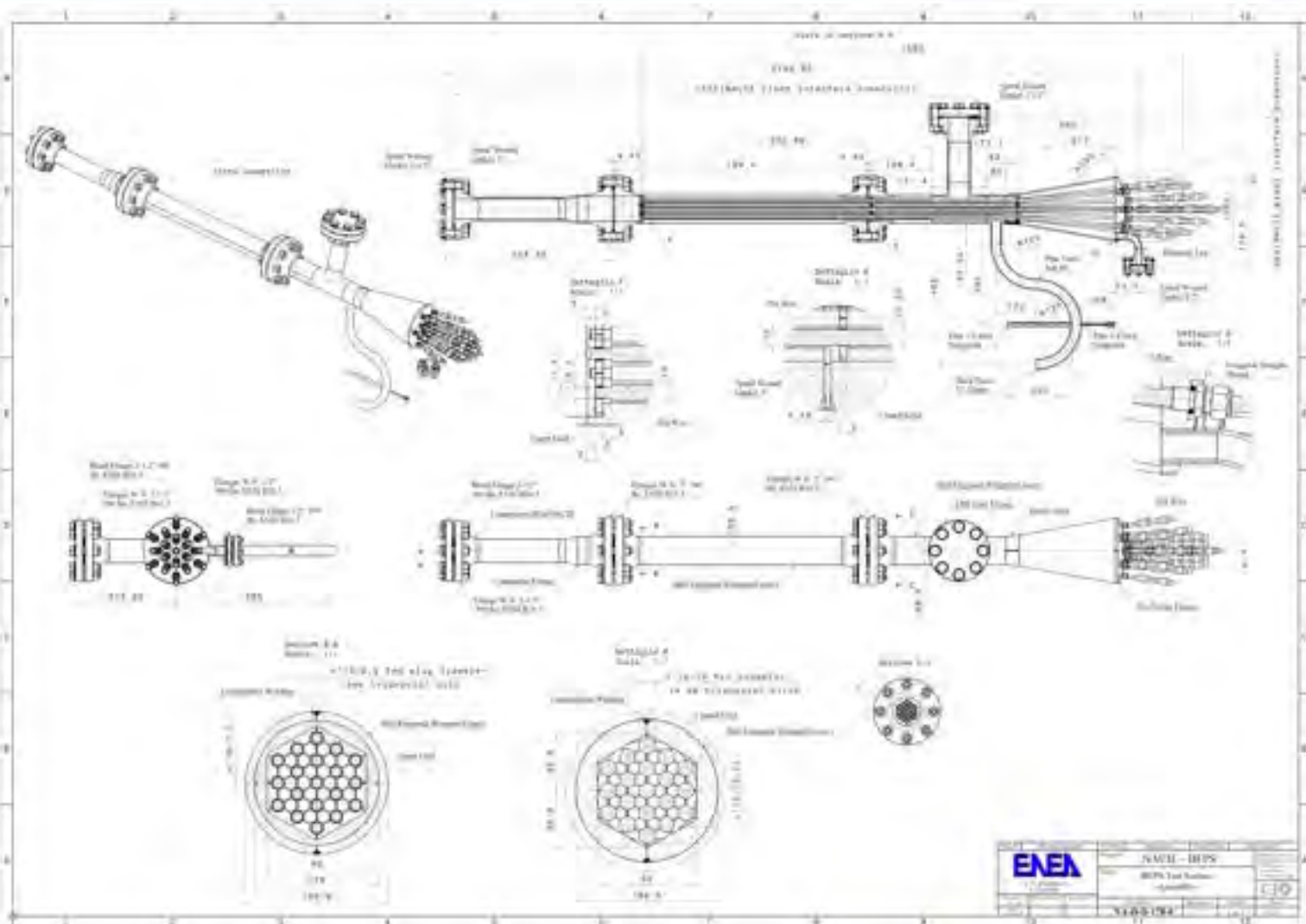
BFPS TEST SECTION





UNIVERSITÀ DI PISA

BFPS TEST SECTION



Mechanical design is completed

The **flow blockage accident** in a Fuel Assembly (FA) of a nuclear reactor consists in a **partial or total occlusion of the flow passage area**. This leads in general to a **reduced heat transfer** between the FA and the coolant and/or **reduced mass flow rate** potentially causing a temperature peak in the clad which can eventually lead to the fusion of the clad itself.

While a partial blockage at the **fuel assembly foot** may be dangerous for the integrity of the FA (e.g. *Fermi 1 fuel meltdown accident*), see NRC (2011) and Bertini (1980), the phenomena can be investigated and assessed by an integral system code in order to devise proper mitigation actions. On the other hand, **an internal blockage can be even more dangerous** and it is not easy to detect; this kind of blockage can be more effectively modeled and studied by a proper use of a **CFD** code.

Regarding the **sodium fast reactors**, they adopt generally **wire-spaced bundles**, and the accumulation of debris from failed fuel pins or broken wires, generally occurs **along the wire**. Therefore, in this case, the preferential shape of the blockage is elongated *and it follows the helicoid wire* (Schultheiss, 1987).

For **grid-spaced fuel assemblies**, experimental results on blockage growth by particles show that particles with sizes spread around the subchannel dimensions are collected at the spacer grid. A horizontal **plate like** particle bed with strong radial growth tendency has been found (Schultheiss, 1987).

FLOW BLOCKAGE: TYPES

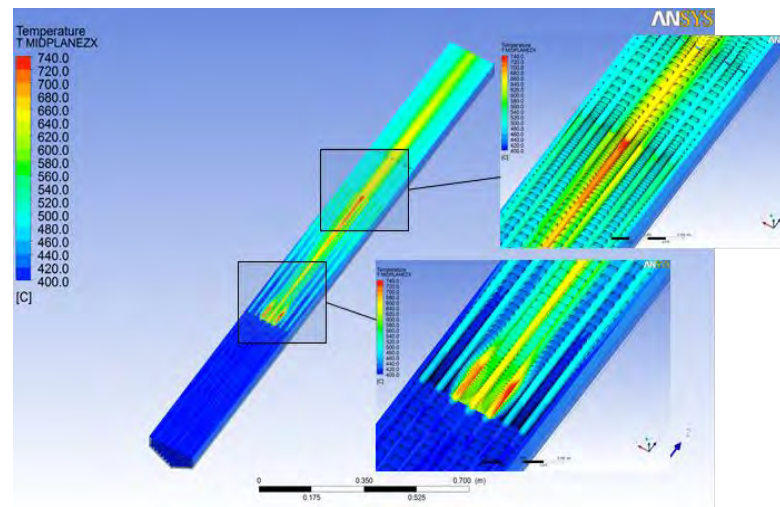
- **External**
 - Central hole in SA foot part is blocked, coolant enters only through the side openings
 - **Internal**
 - Internal blockage inside fuel SA in a form of a thin plate (grid spaced FA)
 - Internal blockage inside fuel SA in a form of an elongated Pb oxide slug (wire-spaced FA)
-
- The ENEA experiment will focus on Internal blockage in grid-spaced FA.
 - A feedback from the designers (ANN) was required for the BFPS test section design



From these remarks, the most likely internal blockage in a grid-spaced bundle is **at the lower spacer grid**, and, if the spacer grid is positioned in the active region, a remarkable effect can be evidenced and a possible damage can occur.

In principle, in the latter case, two different effects can be distinguished:

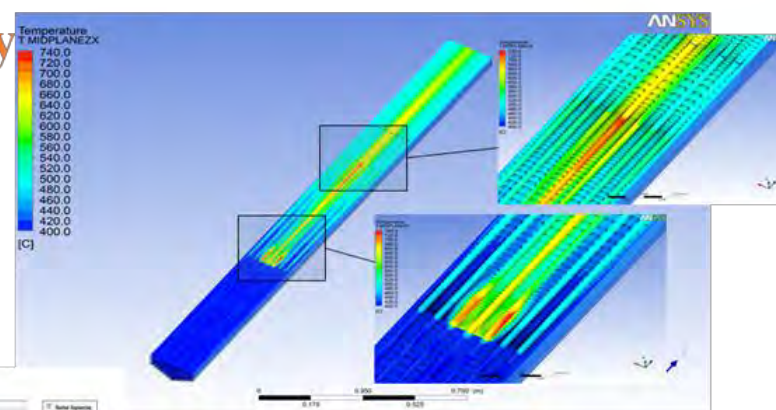
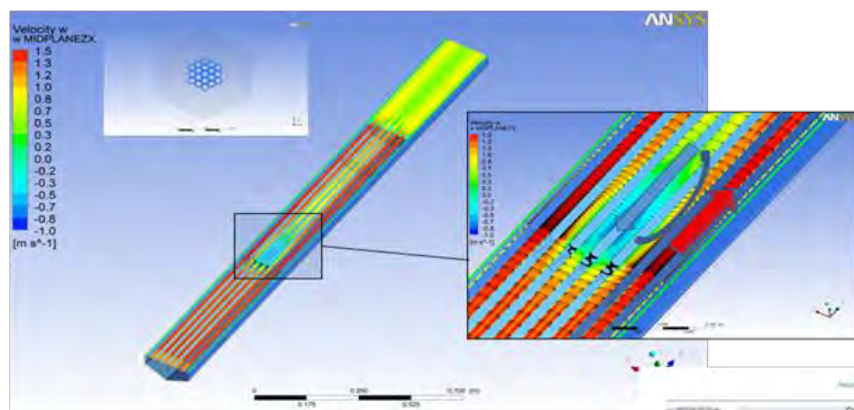
- A **local** effect due to the stagnation-recirculation/wake region downstream of the blockage, with a local minimum of the heat transfer and a clad temperature peak;
- A **global** ‘subchannel’ effect due to the lower mass flow rate in the blocked subchannels; this effect leads to an increase of the bulk fluid temperature with respect to the ‘unblocked’ regions and a consequent peak in the clad temperature at the end of the active region.



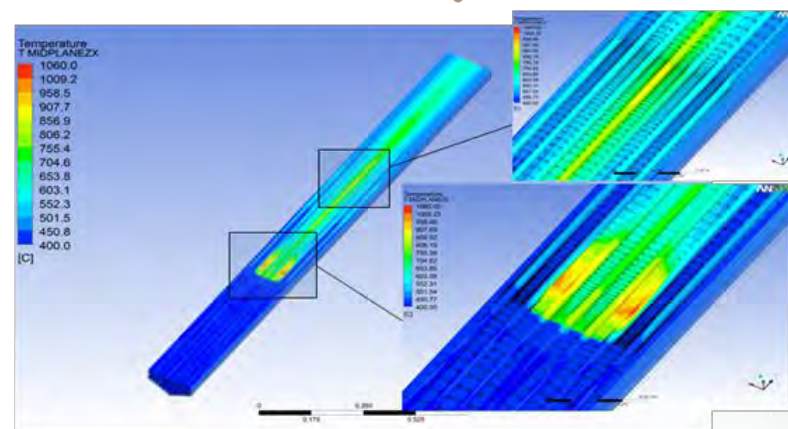
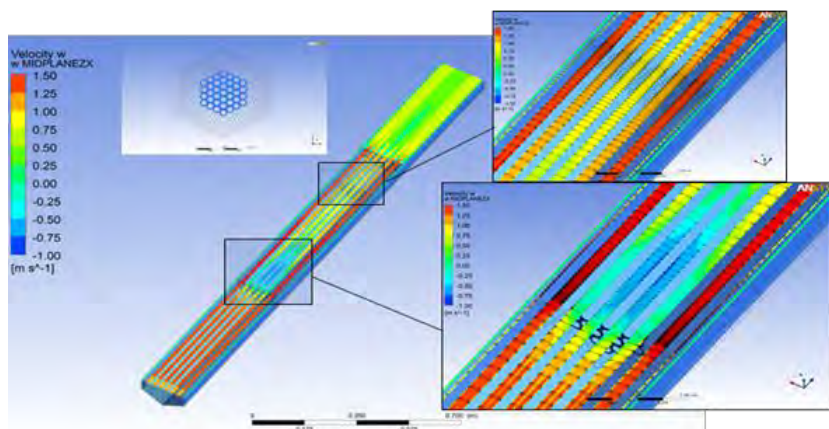
ALFRED FA CFD STUDY

Nblock=19, $\beta=0.15$, case 11,

stationary



Nblock=37, $\beta=0.29$, case 12, stationary



Flow rate	BFPS	ALFRED
A	4 kg/s	27 kg/s
B	8 kg/s	54 kg/s
C	16 kg/s	108 kg/s

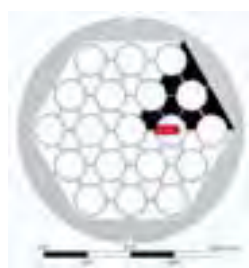
Alfred FA nominal flow rate 144 kg/s

Blockage type	Description	Blockage %
0	No blockage	0%
1	Total sector	16,67%
2	Central blockage	6,89%
3	Corner blockage	13,22%
4	Edge blockage	14,94%
5	2 Sectors blockage	33%

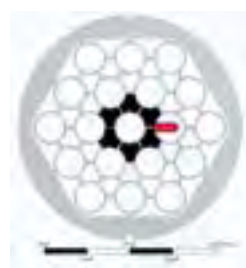
Blockage type



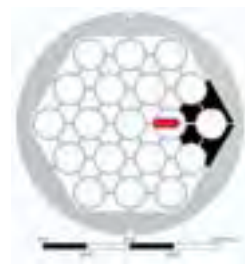
0



1



2



3



4



5



CFD TEST MATRIX

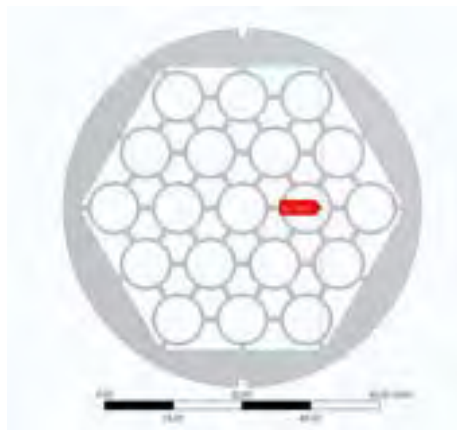


Case Number	Case	Mesh	Turbulence model	Calculation Type	Blockage Type	Blockage %	Mflow BFPS [Kg/s]	Power [W]	ΔT LBE	T INLET	Notes	Computation
0of	A_C0of	A	SST k-om	STATIONARY	0		16	94284,80	40	200	UNBLOCKED, mesh indep, only fluid	ENEA
1of	B_C1of	B	SST k-om	STATIONARY	0		16	94284,80	40	200	UNBLOCKED, mesh indep, only fluid	ENEA
2of	C_C2of	C	SST k-om	STATIONARY	0		16	94284,80	40	200	UNBLOCKED, mesh indep, only fluid	ENEA
3of	D_C3of	D	SST k-om	STATIONARY	0		16	94284,80	40	200	UNBLOCKED, mesh indep, only fluid	ENEA
2	C_C2	C	SST k-om	STATIONARY	0		16	94284,80	40	200	UNBLOCKED	ENEA, ANSALDO
4	C_C4	C	SST k-om	STATIONARY	0		8	47142,40	40	200	UNBLOCKED	ENEA
5	C_C5	C	SST k-om	STATIONARY	0		4	23571,20	40	200	UNBLOCKED	ENEA
6	C_C6	C	SST k-om	STATIONARY	1	16,67%	16	94284,80	40	200	SECTOR BLOCKAGE	ENEA, ANSALDO
7	C_C7	C	SST k-om	STATIONARY	1		8	47142,40	40	200	SECTOR BLOCKAGE	O
8	C_C8	C	SST k-om	STATIONARY	1		4	23571,20	40	200	SECTOR BLOCKAGE	ENEA
9	C_C9	C	SST k-om	STATIONARY	2	6,89%	16	94284,80	40	200	CENTRAL BLOCKAGE	ENEA
10	C_C10	C	SST k-om	STATIONARY	2		8	47142,40	40	200	CENTRAL BLOCKAGE	ENEA
11	C_C11	C	SST k-om	STATIONARY	2		4	23571,20	40	200	CENTRAL BLOCKAGE	ENEA
12	C_C12	C	SST k-om	STATIONARY	3		16	94284,80	40	200	CORNER BLOCKAGE	ANSALDO
13	C_C13	C	SST k-om	STATIONARY	3		8	47142,40	40	200	CORNER BLOCKAGE	ANSALDO
14	C_C14	C	SST k-om	STATIONARY	3	13,22%	4	23571,20	40	200	CORNER BLOCKAGE	ANSALDO
15	C_C15	C	SST k-om	STATIONARY	4	14,94%	16	94284,80	40	200	SIDE BLOCKAGE	ANSALDO
16	C_C16	C	SST k-om	STATIONARY	4		8	47142,40	40	200	SIDE BLOCKAGE	ANSALDO
17	C_C17	C	SST k-om	STATIONARY	4		4	23571,20	40	200	SIDE BLOCKAGE	ANSALDO
18	C_C18	C	SST k-om	STATIONARY	5	33,00%	16	94284,80	40	200	2 SECTORS BLOCKAGE	ANSALDO
19	C_C19	C	SST k-om	STATIONARY	5	33,00%	8	47142,40	40	200	2 SECTORS BLOCKAGE	ANSALDO
20	C_C20	C	SST k-om	STATIONARY	5	33,00%	4	23571,20	40	200	2 SECTORS BLOCKAGE	ANSALDO
21	C_C21	C	RSM-om	STATIONARY	1		16	94284,80	40	200	SECTOR BLOCKAGE, model independence	ANSALDO
22	C_C22	C	SST, Prt=1.0	STATIONARY	1		16	94284,80	40	200	SECTOR BLOCKAGE, Prt independence	ENEA
23	C_C23	C	SST, Prt=1.2	STATIONARY	1		16	94284,80	40	200	SECTOR BLOCKAGE, Prt independence	ENEA

Coolant constant Properties at 220 °C

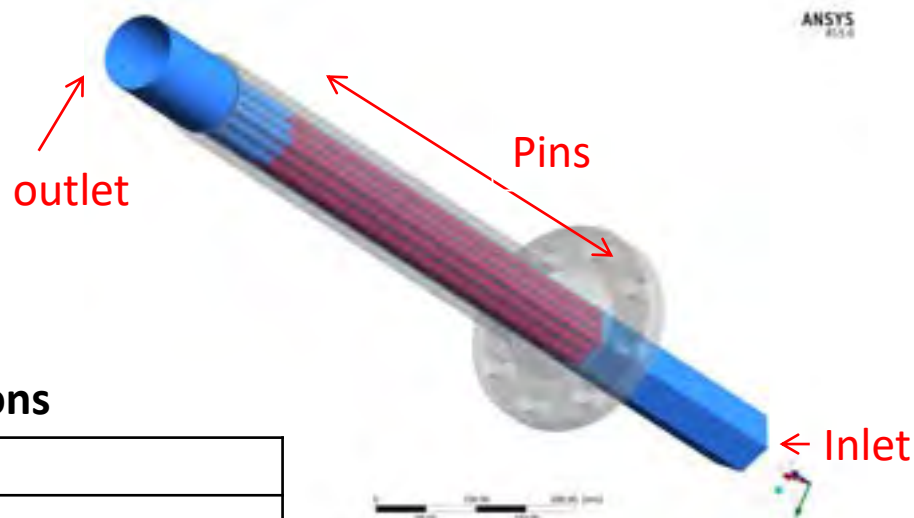
LBE	
BFPS Mass flow rate	16 kg/s
Density	10443,3 kg/m ³
Heat capacity at constant pressure	147,32 J/kg*K
Dynamic viscosity	2,28 10 ⁻³ Pa*s

Geometrical and thermal-hydraulic parameters



Hexagon internal key	62 mm
Active Length	600 mm
Pin diameter	10 mm
Pitch to diameter ratio P/D	1,4
Equivalent diameter D_h	9,05 mm
Number of pins	19
Mean assembly power	94,285 kW
LBE inlet temperature	200 °C
Lbe outlet temperature	240 °C

Solver	CFX-15
Type	Stationary
Discretization	2 nd order
Turbulence model	SST k- ω
Reynolds Number	~35 000
Initialization velocity	0,79 m/s

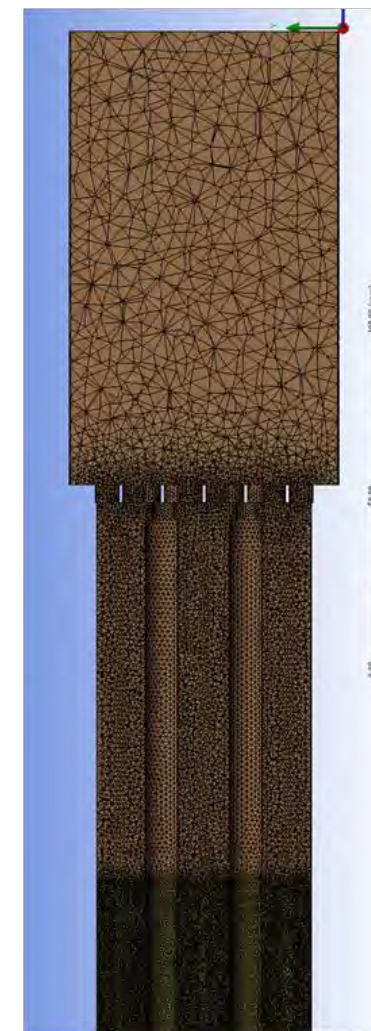
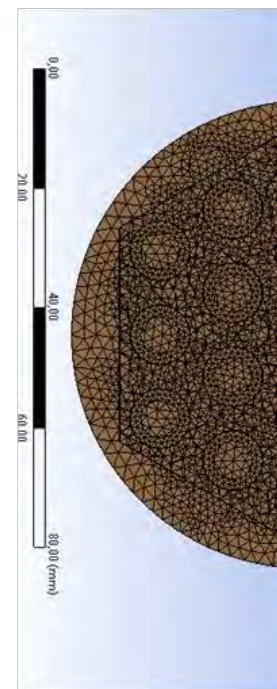


Boundary Conditions

Inlet	
Type	Inlet
Mass flow rate	16 [kg/s]
Static Temperature	200 °C
Outlet	
Type	Outlet
Relative Pressure	0 [Pa]
Pres. Profile Blend	0,05 [Pa]
Pins	
Type	Wall
Heat Flux	94284,8 [W]

Friction factor

Mesh	Mnodes	f Darcy	% [-]
Mesh A	10	0,01182	
Mesh B	15	0,01144	-3,21%
Mesh C	19	0,01130	-1,22%
Mesh D	24	0,01131	0,088 %

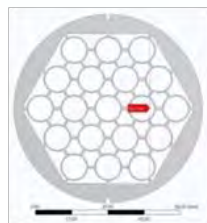


T max, T average pins, Nusselt number

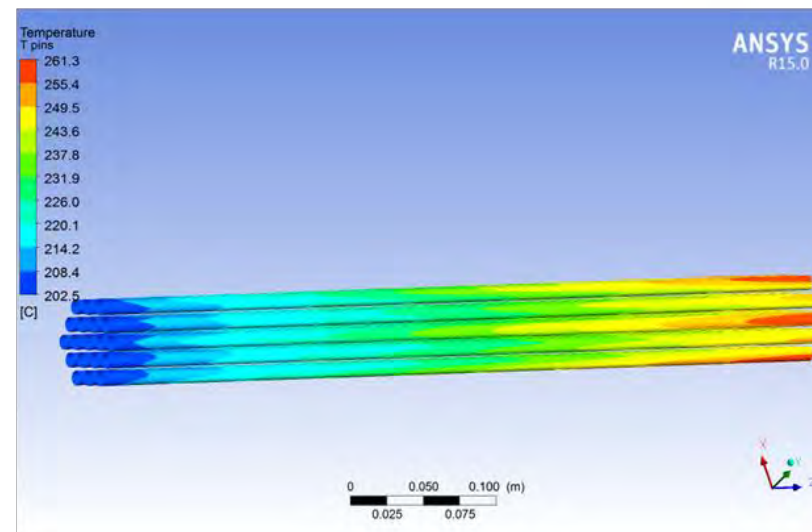
	$T_{pin\ max}$	$T_{average\ pins}$	T_{bulk}	Nu	% [-]
Mesh A	267,6 °C	222,35 °C	213,11°C	23,86	
Mesh B	269,8 °C	225,82 °C	213,11°C	17,31	-27,45%
Mesh C	272,4 °C	226,46 °C	213,11°C	16,48	-3,48%
Mesh D	272,6 °C	226,42 °C	213,11 °C	16,52	0,16%

UNBLOCKED CASE

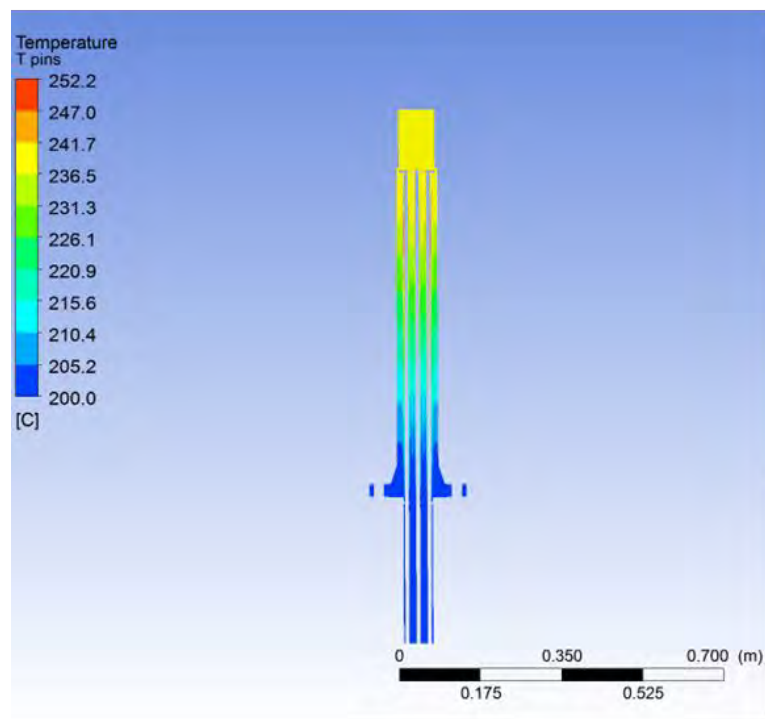
Mass flow rate	16 kg/s
Blockage type	0
Blockage %	0 %



LBE-Pins

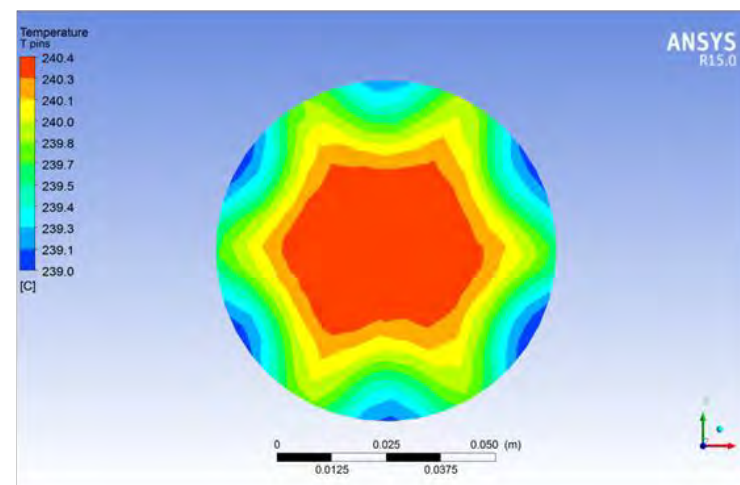


Temperature contours



T max= 261°C

LBE-Outlet

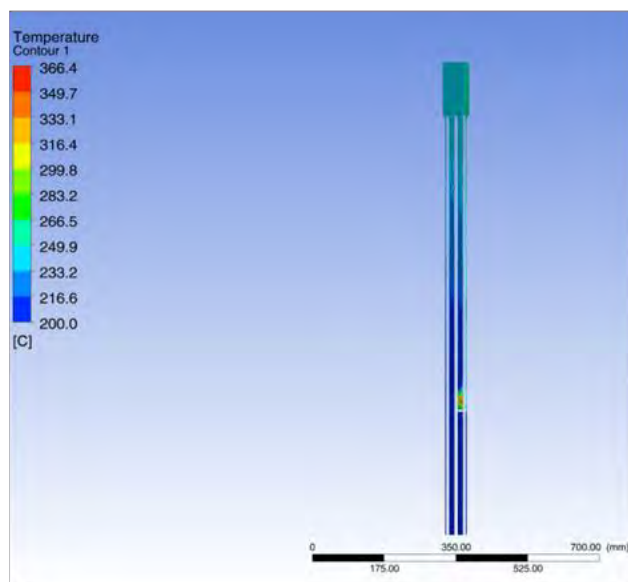


SECTOR BLOCKAGE CASE

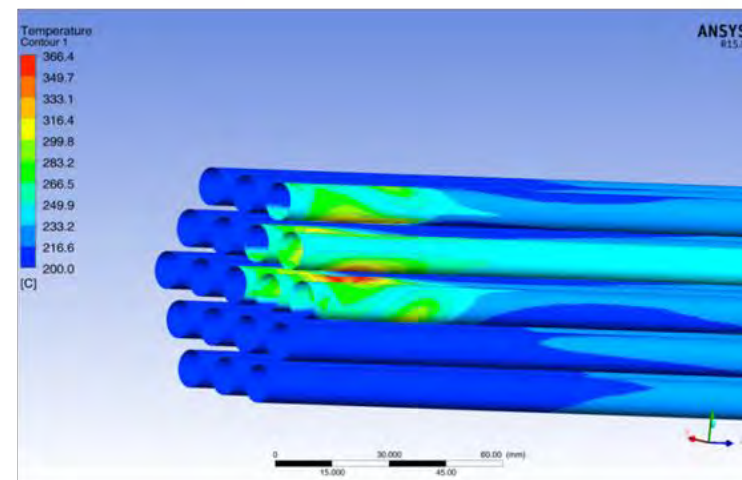
Mass flow rate	16 kg/s
Blockage type	1
Blockage %	16,67 %



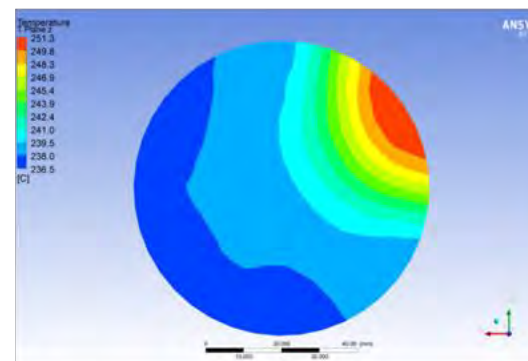
Temperature Contours



LBE-Pins



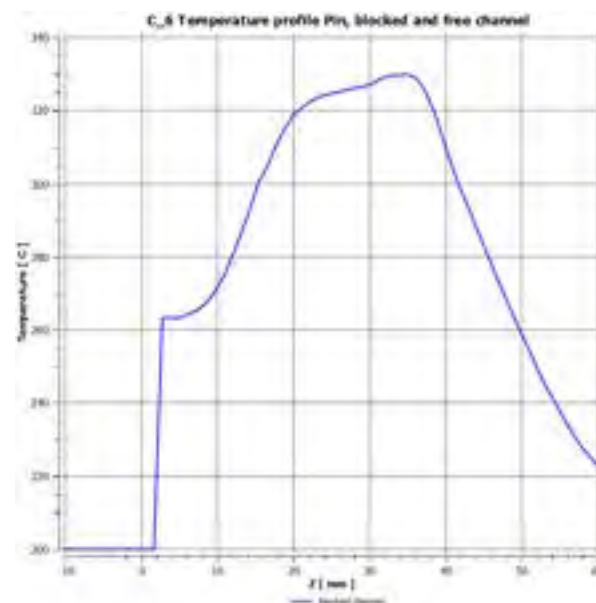
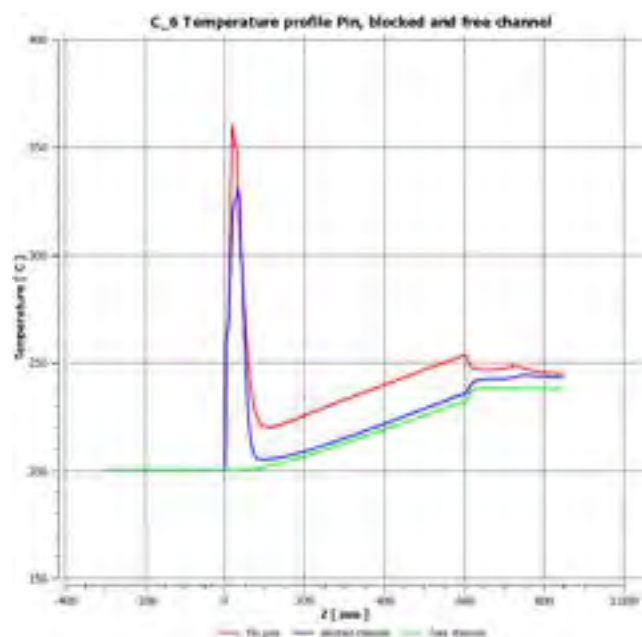
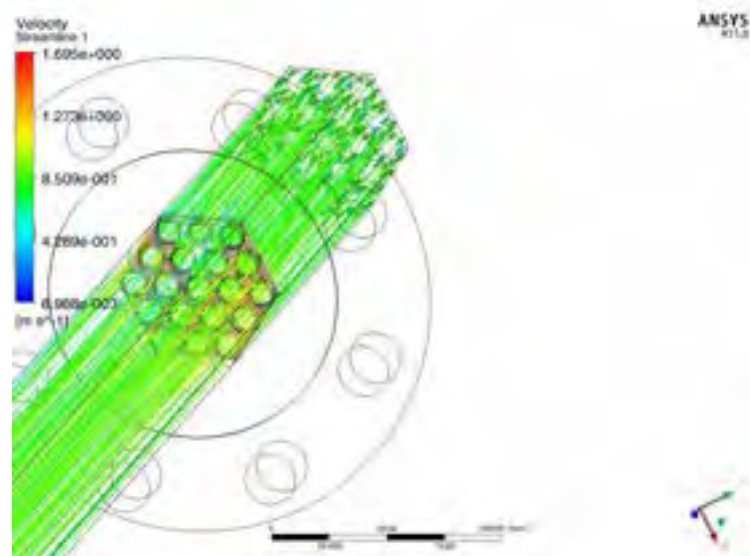
LBE-Outlet



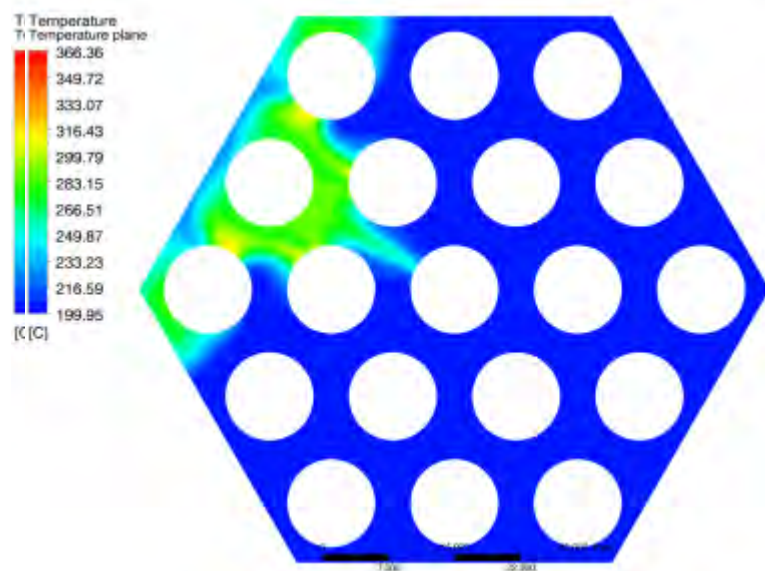
ΔT outlet
~ 15 °C

T Max		ΔT
No blockage	261 °C	
Sector Blockage	366 °C	~105°C

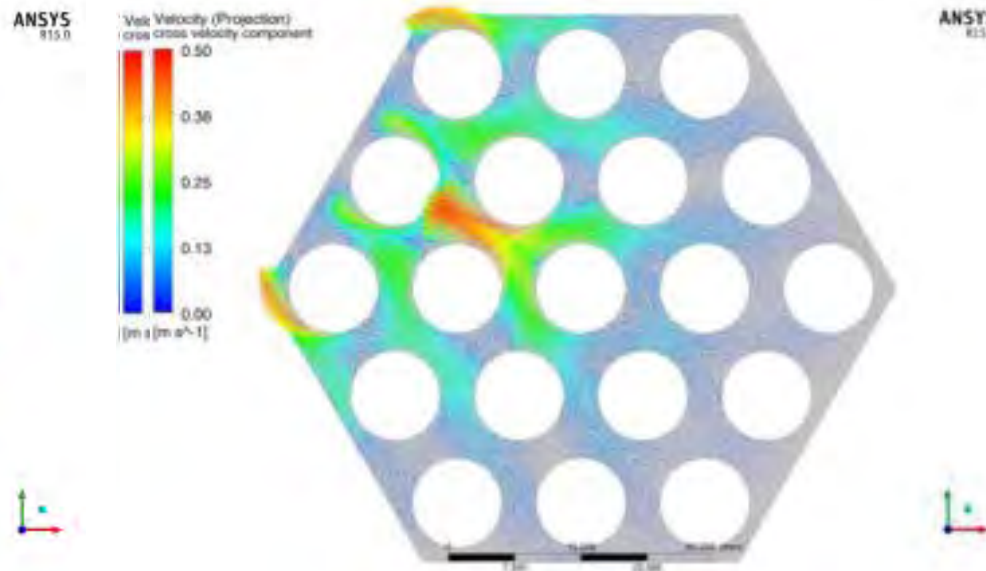
SECTOR BLOCKAGE CASE



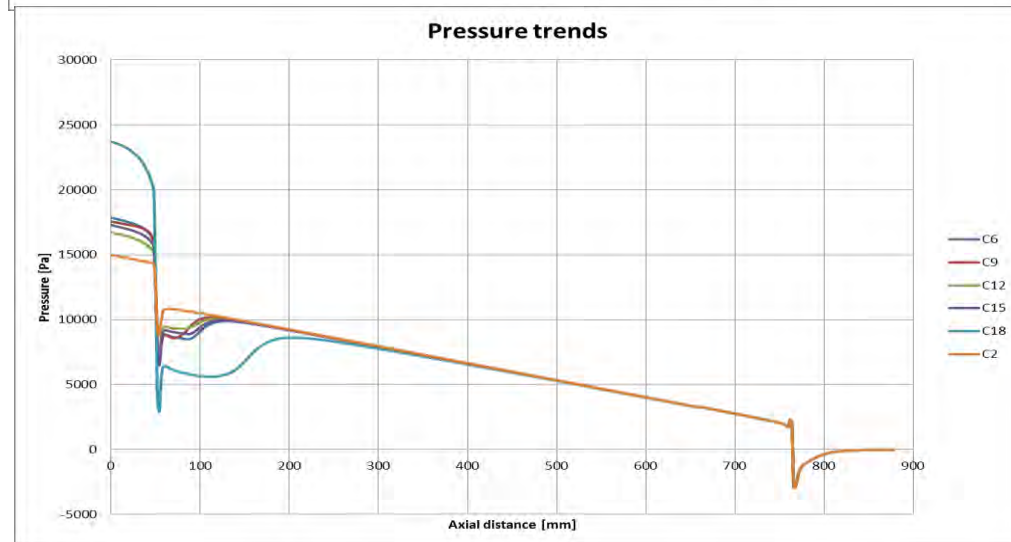
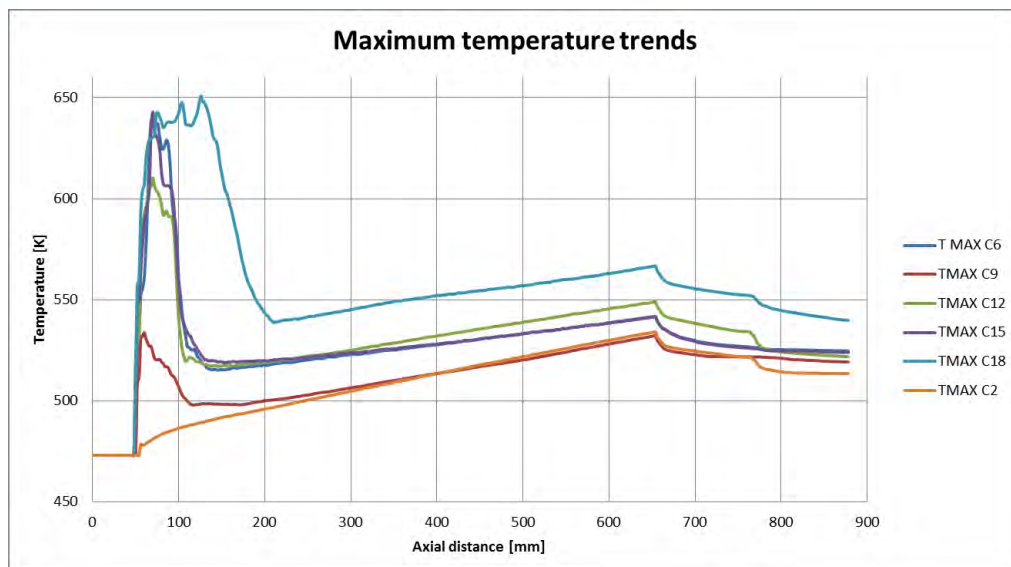
Plane 40 mm



Temperature Contours



Velocity Magnitude



The maximum temperature value is reached for the 2 sector blockage simulation as expected.

C₁₈, C₁₂, C₂ and C₉ have the same temperature profile behind the blockage, while C₁₅ and C₆ have a different profile

Blockage type		Blockage %	ΔT [°C]
0	No blockage	0%	
1	Total sector	16,67%	105°C
2	Central blockage	6,89%	~0°C
3	Corner blockage	13,22%	76°C
4	Edge blockage	14,94%	109°C
5	2 Sectors blockage	33%	117°C

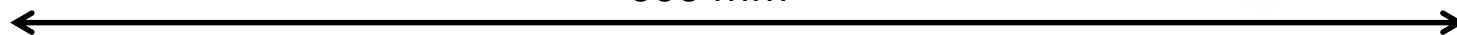


BFPS INSTRUMENTATION



Total amount of 100 TC into the pin bundle

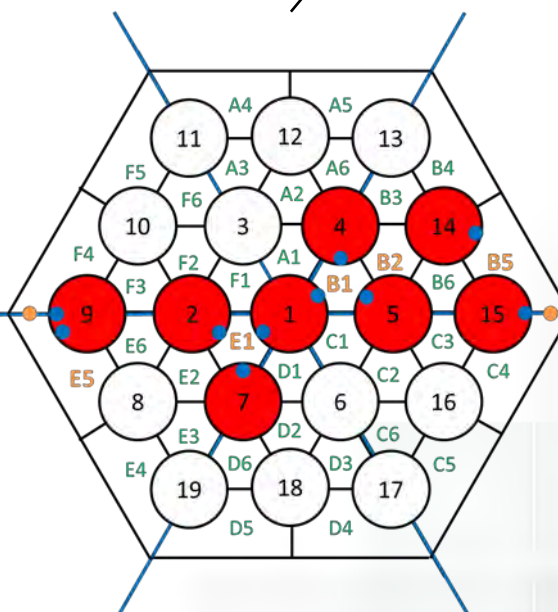
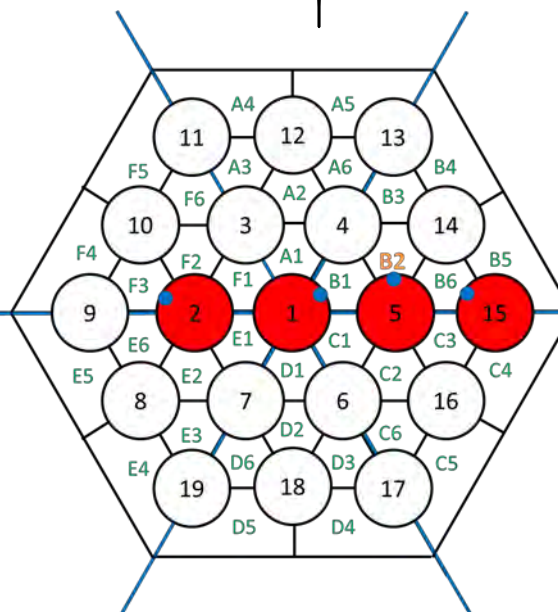
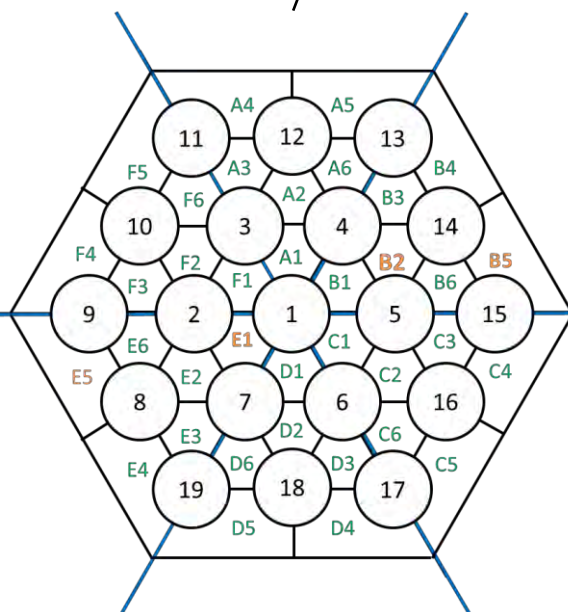
600 mm



$z = 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500, 600$

$z = -150$ mm

$z = 550$ mm





MIXING REGION INSTRUMENTATION



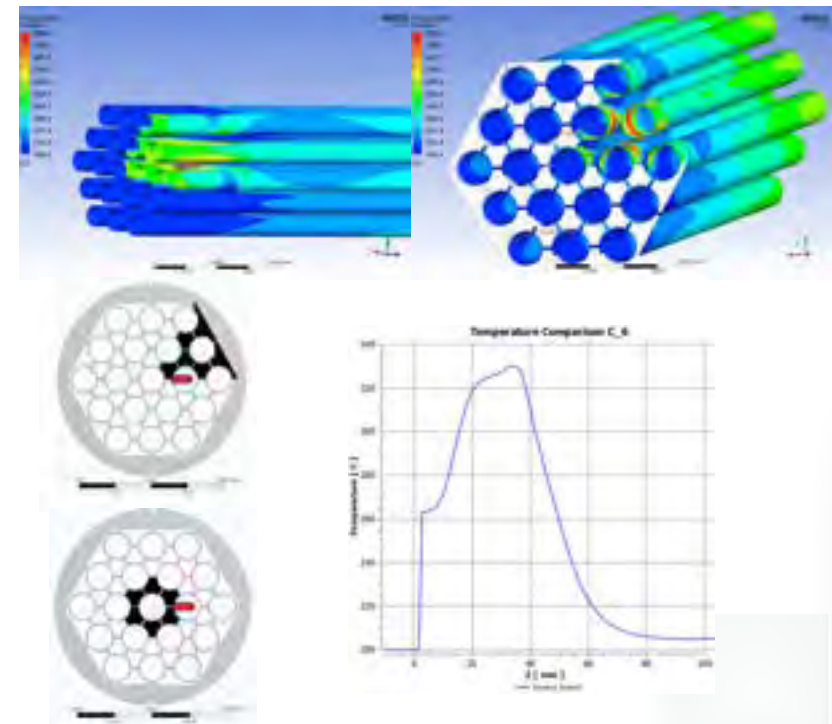
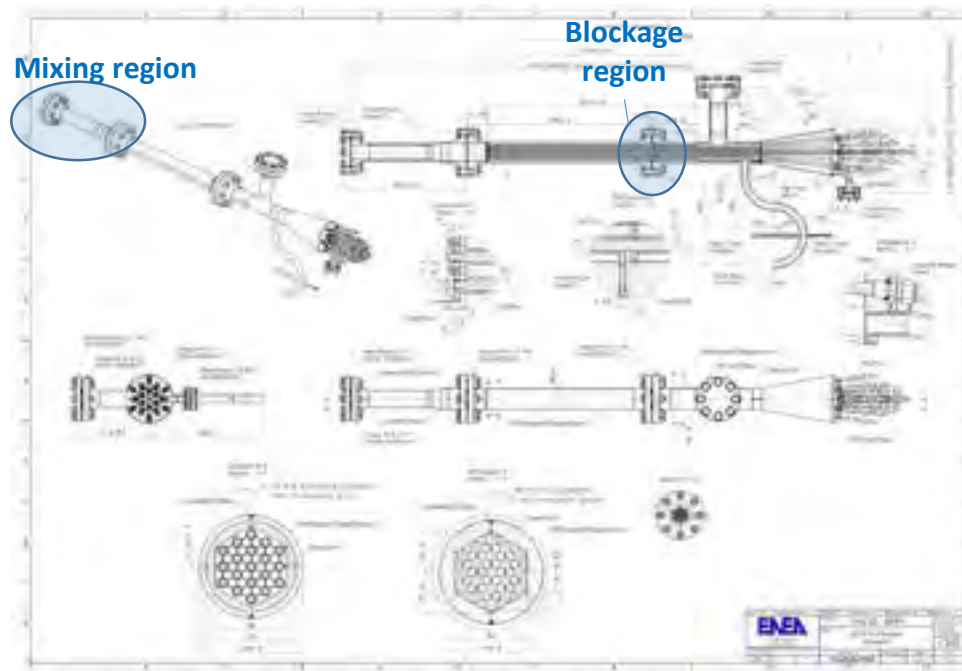
Total amount of 24 RTD/TC into the mixing region

TR name	r [mm]	Θ [°]	τ [mm]	BFPS sector	TR dimension [mm]
TR-1	0	60	85	C	5
TR-2	15	60	85	C	5
TR-3	30	60	85	C	5
TR-4	0	120	135	B	5
TR-5	15	120	135	B	5
TR-6	30	120	135	B	5
TR-7	0	60	185	C	5
TR-8	15	60	185	C	5
TR-9	30	60	185	C	5
TR-10	0	120	235	B	5
TR-11	15	120	235	B	5
TR-12	30	120	235	B	5
TR-13	0	60	285	C	5
TR-14	15	60	285	C	5
TR-15	30	60	285	C	5
TR-16	0	120	335	B	5
TR-17	15	120	335	B	5
TR-18	30	120	335	B	5
TR-19	0	60	385	C	5
TR-20	15	60	385	C	5
TR-21	30	60	385	C	5
TR-22	0	120	435	B	5
TR-23	15	120	435	B	5
TR-24	30	120	435	B	5

- A new **FPS test section was designed** in order to assess the flow blockage local and global effect: mechanical design is over.
- The test section will have **the same 'flange-to-flange' dimensions** of the present FPS in order to mount it directly in NACIE-UP
- It will have **19 pins, 250 kW power**, but **grid-spaced**: the pin number and the power will be identical to the present configuration and will minimize the facility refurbishment (plug and play strategy)
- The **p/d ratio was fixed to 1.4 close to the ALFRED FA**
- **ALFRED FA 19-pin Mock-up for thermal investigations**
- **A detailed CFD model of the test section** will be developed for pre and post-test in collaboration with UniPi/Ansaldo/UniGe
- **Ansaldo feedback is mandatory for design and to plan a good experiment (strong collaboration is active)**
- Results are in line with literature and previous studies
- **The dominant phenomenon is local (<100 mm) behind the blockage (Instrumentation)**
- **The recirculation region is of the same dimension of the blockage area**
- At higher level of blockage (2 sectors, 33%) the heated region is extended **200 mm** behind the blockage
- **The temperature distribution in the plenum region seems to be detectable at any blockage level (at least 10 °C section temperature drop)**
- **A more accurate model of the (500 mm) mixing region must be done** and further simulations carried out

Timeline & Conclusions 1/2

- A new **BFPS test section was designed** in order to assess the flow blockage local and global effect
- The **mechanical design** of the test section is finished
- The **design and pre-test analysis** was carried out by a joint tight collaboration among ENEA, Ansaldo Nucleare (ANN, Alfred designers) and UniPi
- From the pre-test analysis, the **experimental setup and test matrix will be developed**



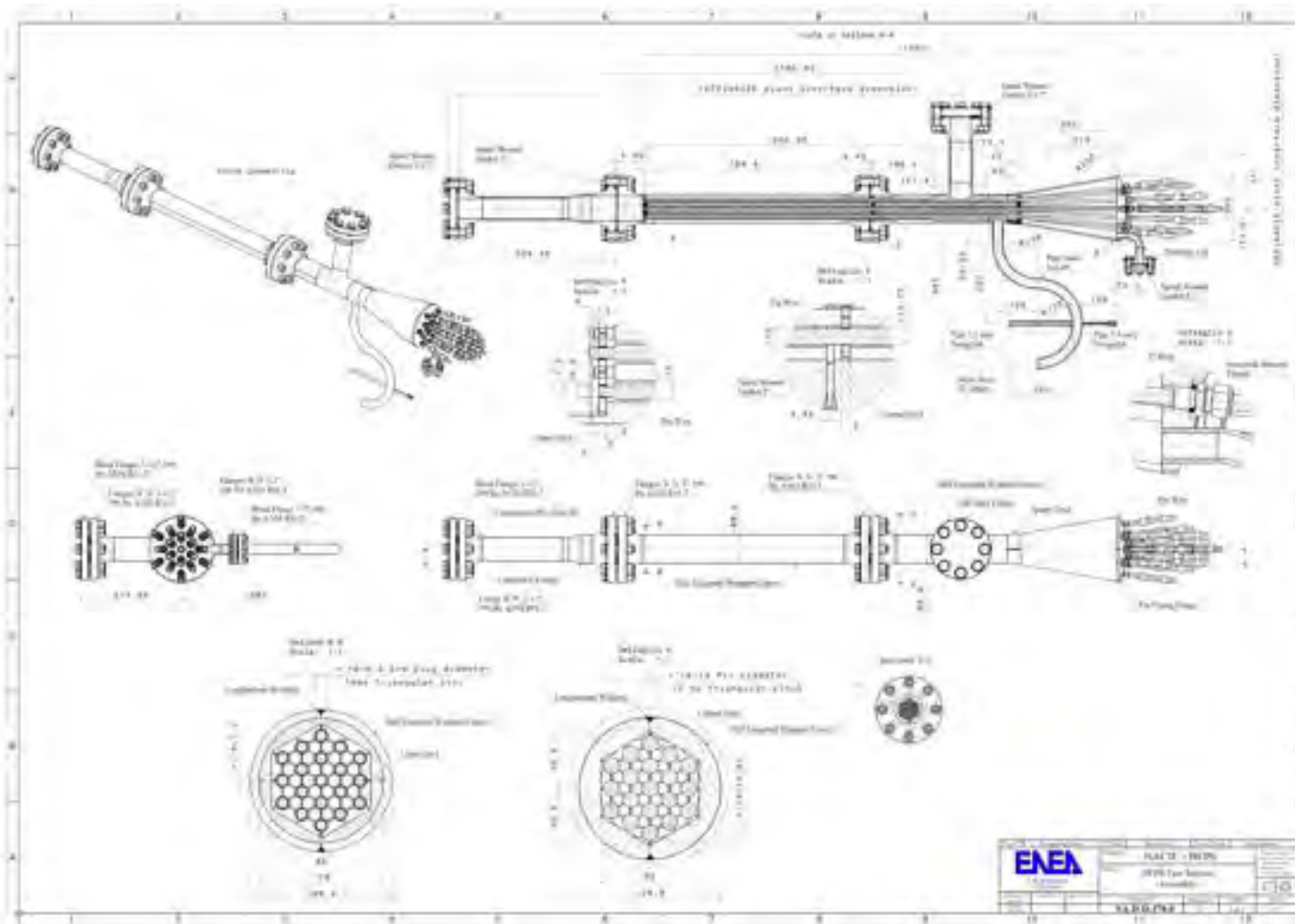
- Ansaldo stressed **the importance to study the mixing in the plenum region of the FA for blockage detection**
- The test section will be arranged with additional 24 RTD in the plenum region
- Technical specification for the test section will be written by the end of the year
- The test section will be manufactured in 2016
- **Experiments can start in January 2017 – *low risk margin*** for the results delivery
- Synergy with European H2020 project SESAME
- The test section will be used in ADP to characterize heat transfer in the ALFRED FA



Flow Blockage experimental studies in HLM systems



Thank you for your attention



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Daniel Giannotti – ENEA
Mariano Tarantino – ENEA



- NACIE-UP facility
 - overall description
 - FPS test section
- Experimental test matrix and post-processing methods
- Obtained Results
 - tests P43X0 & P217
 - Heat transfer analysis
- Planned work & Conclusions

NACIE-UP loop



Every side is composed by:

vertical pipes (O.D. 2.5") 8m long and two horizontal pipes (O.D. 2.5") 2.4m long;

Heater Simulator (19-pins) of **235 kW** maximum power; and **heat exchanger** with two sections, operating at *low power* (5-50 kW) and *high power* (50-250 kW);

Gas injection device, placed inside the riser, as the driving force to enhance the circulation;

Expansion tank, at the end of the riser, partially filled with water;

Several tubes and several thermocouples to monitor pressure and temperature along the flow path.

Due to the distance between the heat source and the heat sink **H** is about **5.5 m** the **natural circulation regime** can be established inside the loop.

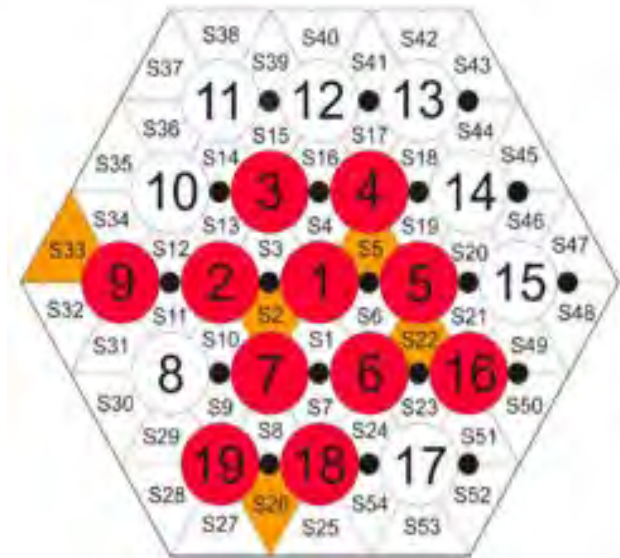


NACIE-UP test section

19 pins **wire-spaced** arranged in triangular lattice

235 kW maximum power

D_{pin}	6.55 mm
P	8.4 mm
P/D	1.2824
d	1.75 mm
P_{wire}	262 mm
L_{tot}	2000 mm
L_{active}	600 mm
$D_{H,nom}$	3.84 mm

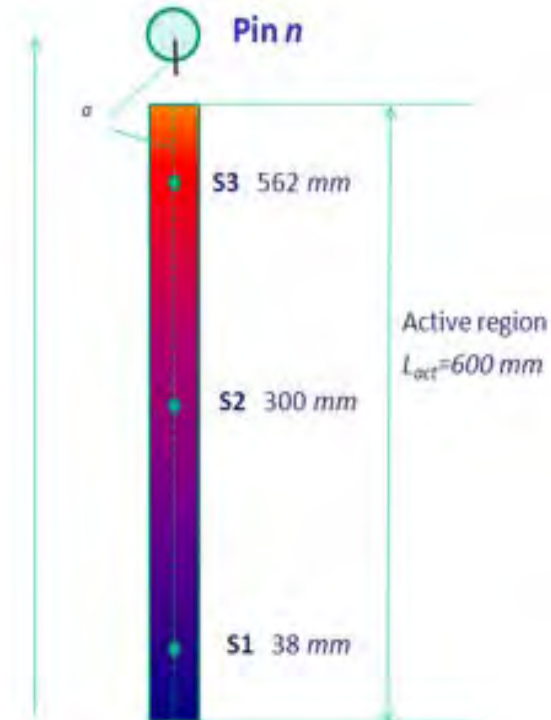
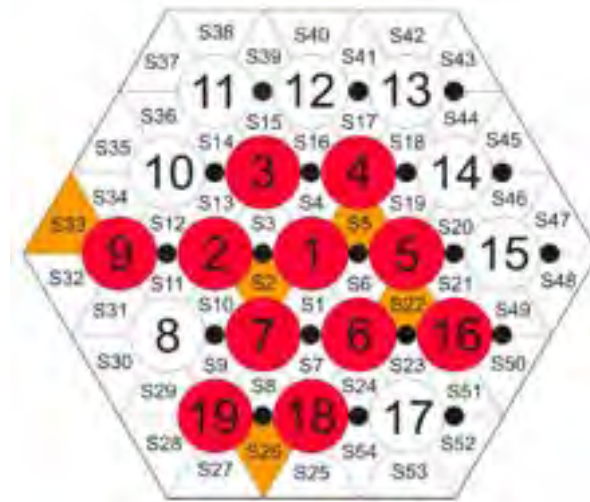


- In **red** instrumented pins
- In **orange** instrumented sub-channels



FPS Instrumentation

- **11 pins** instrumented
Embedded-wall TCs 0.35 mm (52)
- **5 sub-channels** instrumented
Sub-channel TCs 0.5 mm (15)
- Pins 1,2,4,5,6,7,9,16,18,19 instrumented at three axial positions: **$z = 38, 300, 562 \text{ mm}$** from the *beginning of the active length*
($562 - 300 \text{ mm} = 300 - 38 \text{ mm} = 262 \text{ mm} = P_w$, at the three axial position the same relative position between pin and wire)
- Pin 3 instrumented with wall embedded TCs **every 43.66 mm** (13 TCs). This will allow to study *axial thermal development*



- NACIE-UP facility
 - overall description
 - FPS test section
- Experimental test matrix and post-processing methods
- Obtained Results
 - tests P43X0 & P217
 - Heat transfer analysis
- Planned work & Conclusions

Experimental Matrix

PC TEST	Q[kW]	Q _{lin} [kW/m]	m _{NACIEUP} [kg/s]	Re _{sc} ×10 ⁻³	Pe _{sc}
P99	11	0.96	2.92	7.08	236
P100	11	0.96	2.28	5.45	188
P11X0	11	0.96	1.06	2.72	84
P102	11	0.96	0.72	1.93	55
P102b	11	0.96	0.68	1.84	51
P103	11	0.96	0.36	1.13	26
P202	20	1.75	4.17	10.65	332
P203	20	1.75	3.10	8.09	245
P20X0	20	1.75	1.49	4.01	116
P204	20	1.75	0.73	2.24	52
P212	36	3.16	1.17	3.69	83
P213	36	3.16	3.33	10.06	242
P214	36	3.16	2.22	6.88	159
P217	43	3.77	1.15	3.96	77
P218	43	3.77	3.2	9.98	228
P43X0	43	3.77	2.8	8.75	199
P223	52	4.56	1.62	5.35	111
P224	52	4.56	3.40	10.81	237
P265	54	4.74	2.24	7.44	151
P269	108	9.47	3.23	10.21	226

$$u_{sc} \approx 0.1 - 0.9 \text{ m / s}$$

$$Re_{sc} \approx 2000 - 20000$$

$$\dot{m}_{NACIE} \approx 0.4 - 5.0 \text{ kg / s}$$

$$\dot{m}_{FA} \approx 2.3 - 28.7 \text{ kg / s}$$

$$Q_{lin} \approx 0.9 - 9.5 \text{ kW / m}$$

$$Q_{FPS} \approx 11 - 110 \text{ kW}$$

Post-processing method

- Acquisition frequency of data **1 Hz** (duration 15-20 min)
- Matlab routines were written for data post-processing
- **Error analysis implemented.** Sources of error considered: *statistical error, instrumental error and uncertainties on LBE properties*

- Mass flow rate calculated through the energy balance across the heated length
- Definition of **section-averaged** bulk and wall temperatures

$$\bar{T}_b = T_{bS2} \cdot w_2 + T_{bS5} \cdot w_5 + T_{bS22} \cdot w_{22} + T_{bS26} \cdot w_{26} + T_{bS33} \cdot w_{33}$$

$$\bar{T}_w = T_{wS2} \cdot w_2 + T_{wS5} \cdot w_5 + T_{wS22} \cdot w_{22} + T_{wS26} \cdot w_{26} + T_{wS33} \cdot w_{33}$$

- Wall temperatures correction for embedded thermocouples

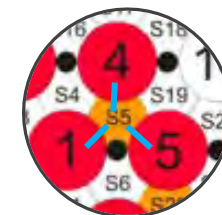
$$T_w = T_{ac} - \frac{Q}{2\pi M L_{active} k_{ss}} \ln \left(\frac{D/2}{D/2 - \delta_g} \right)$$

- **Re, Pe** and **Pr** numbers computed in each section from $\bar{T}_b$

- **Average Nusselt** number is computed using $\bar{T}_b$ and $\bar{T}_w$

- **Local Nusselt** number is computed in each monitored subchannel

$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$

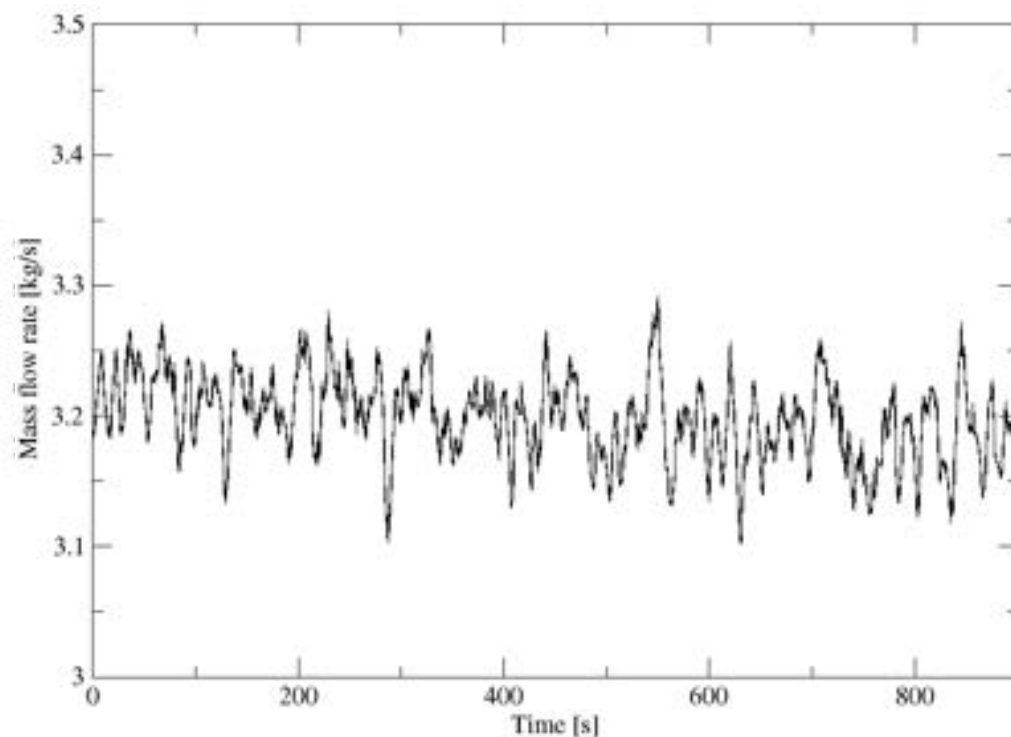
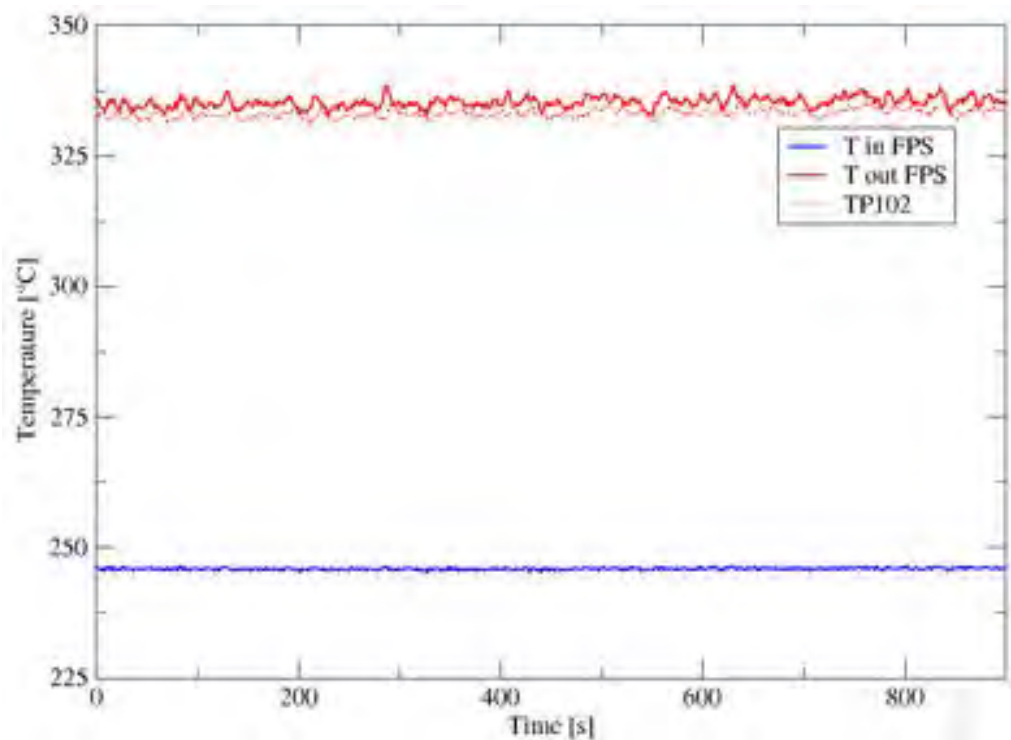


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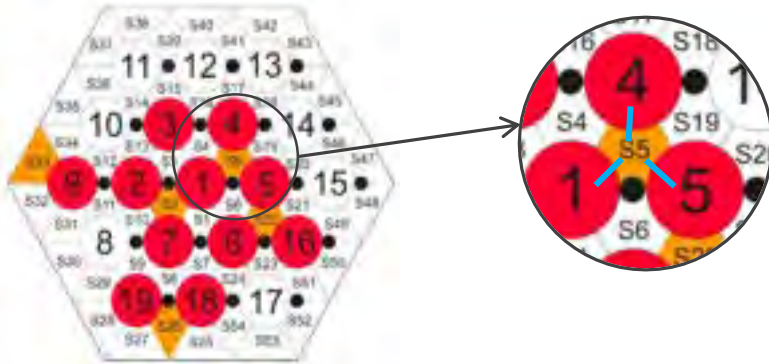
Tests P43X0 & P217 1/2

PEC TEST	Q [kW]	Gas flow rate [NI/min]	ΔT_{FPS} [°C]	u_{sc} [m/s]	$m_{NACIEUP}$ [kg/s]	$m_{MYRRHAFA}$ [kg/s]	Re_{sc}	Pe_{sc}
P43X0	43	-	176.9	0.24	1.63	9.38	5350	111
P217	43	15	89.4	0.47	3.21	18.49	9980	228

P217

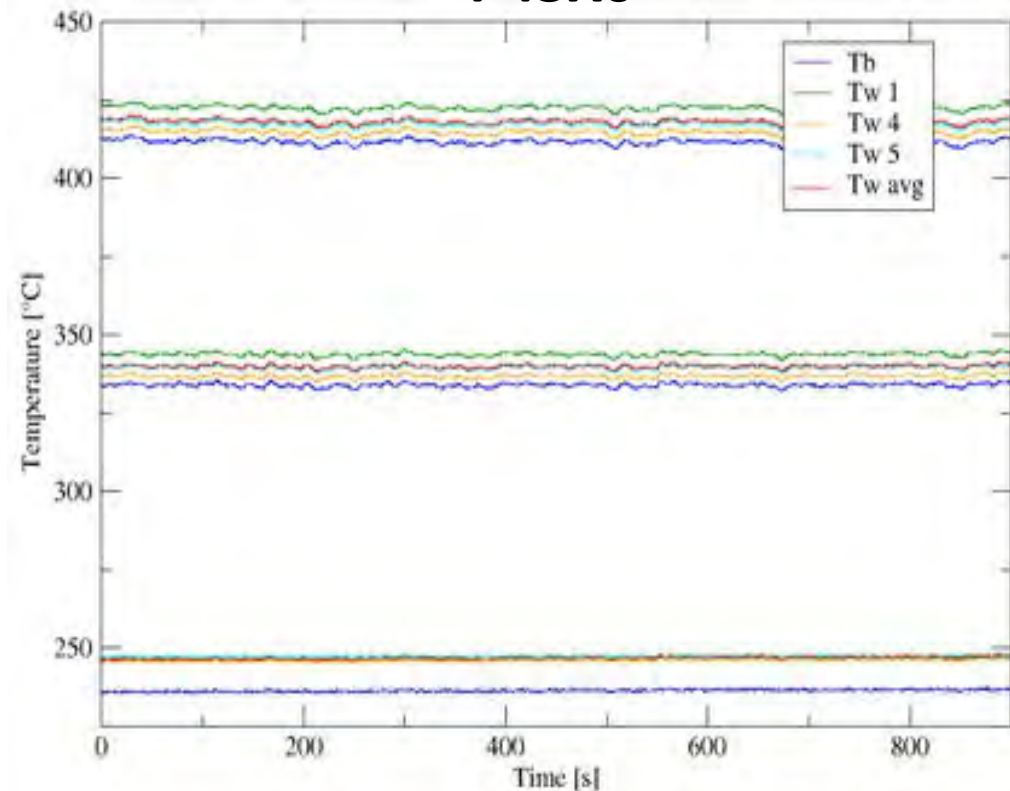


Tests P43X0 & P217 2/2

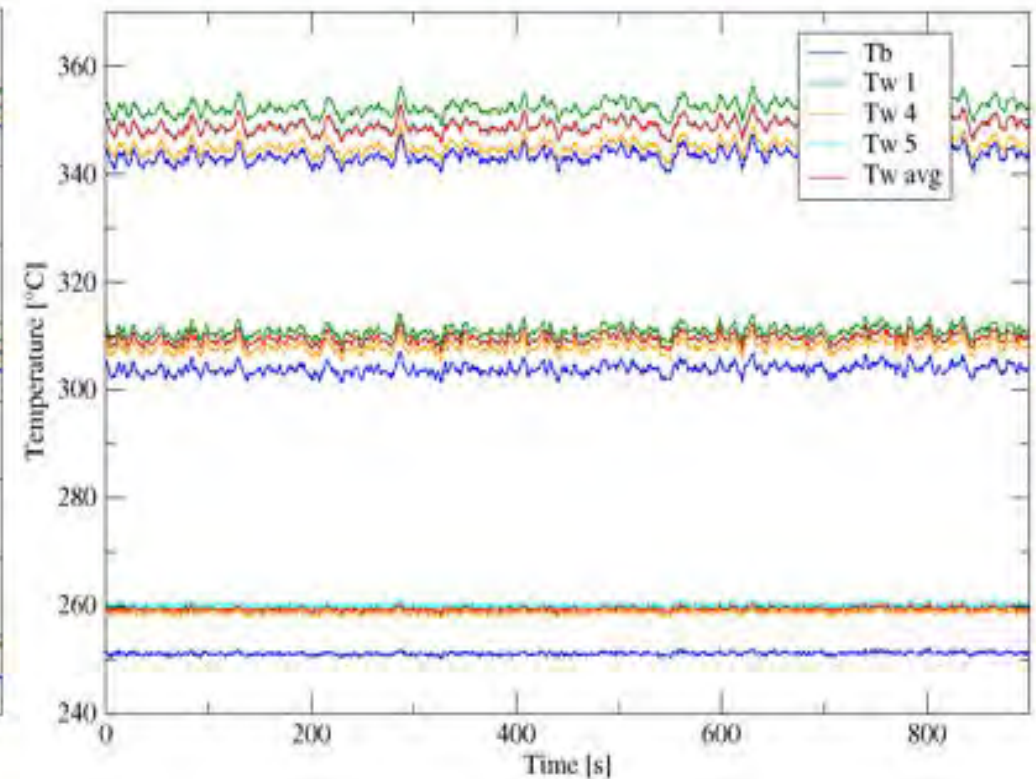


Wall (T_w) and sub-channel (T_b) temperatures
sub-channel S5
sections A, B and C

P43X0



P217

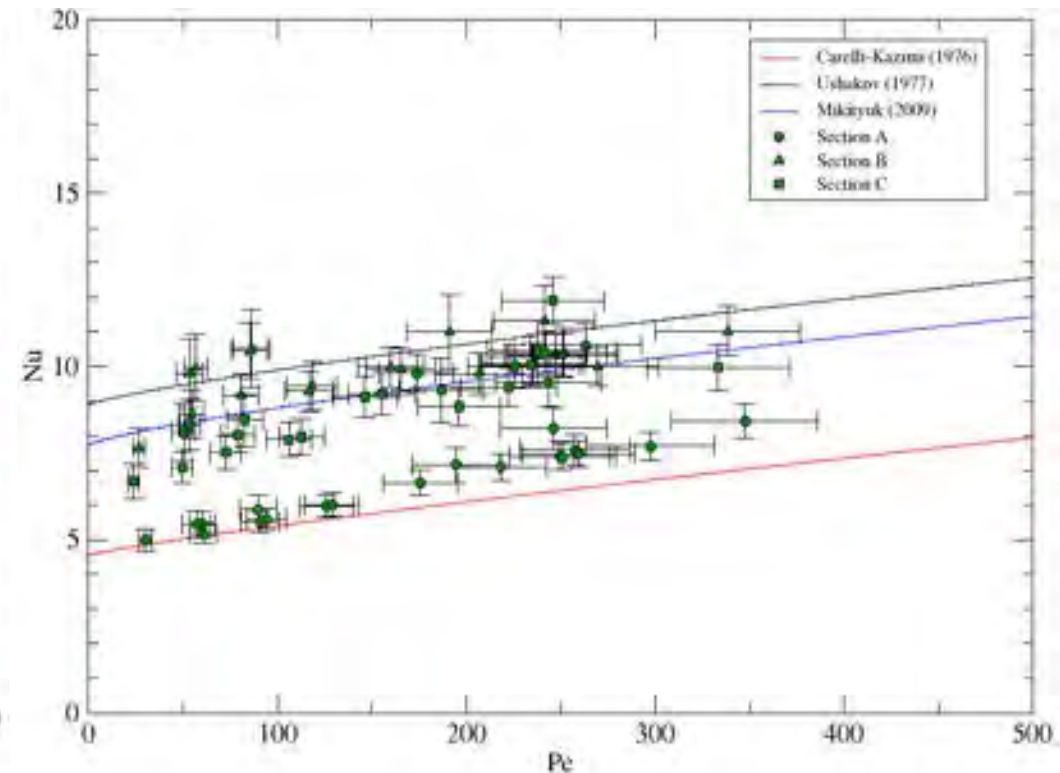
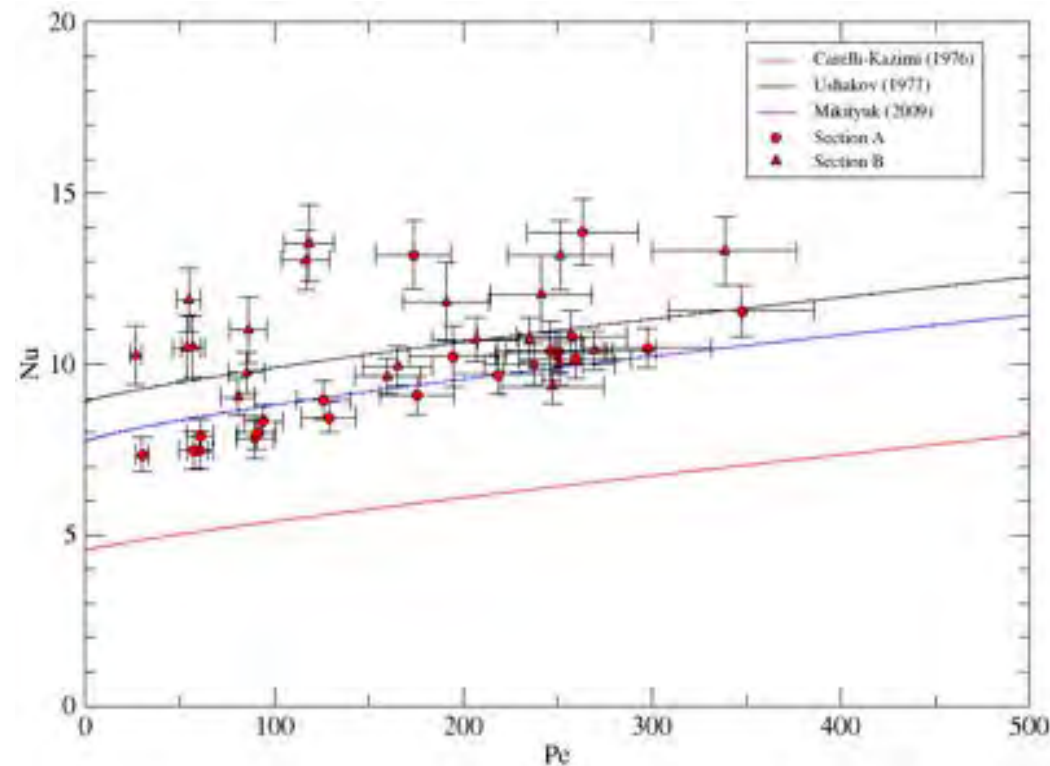


Nusselt number: S2 & S5



Nu vs Pe – Inner rank: sub-channels S2 and S5

$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$

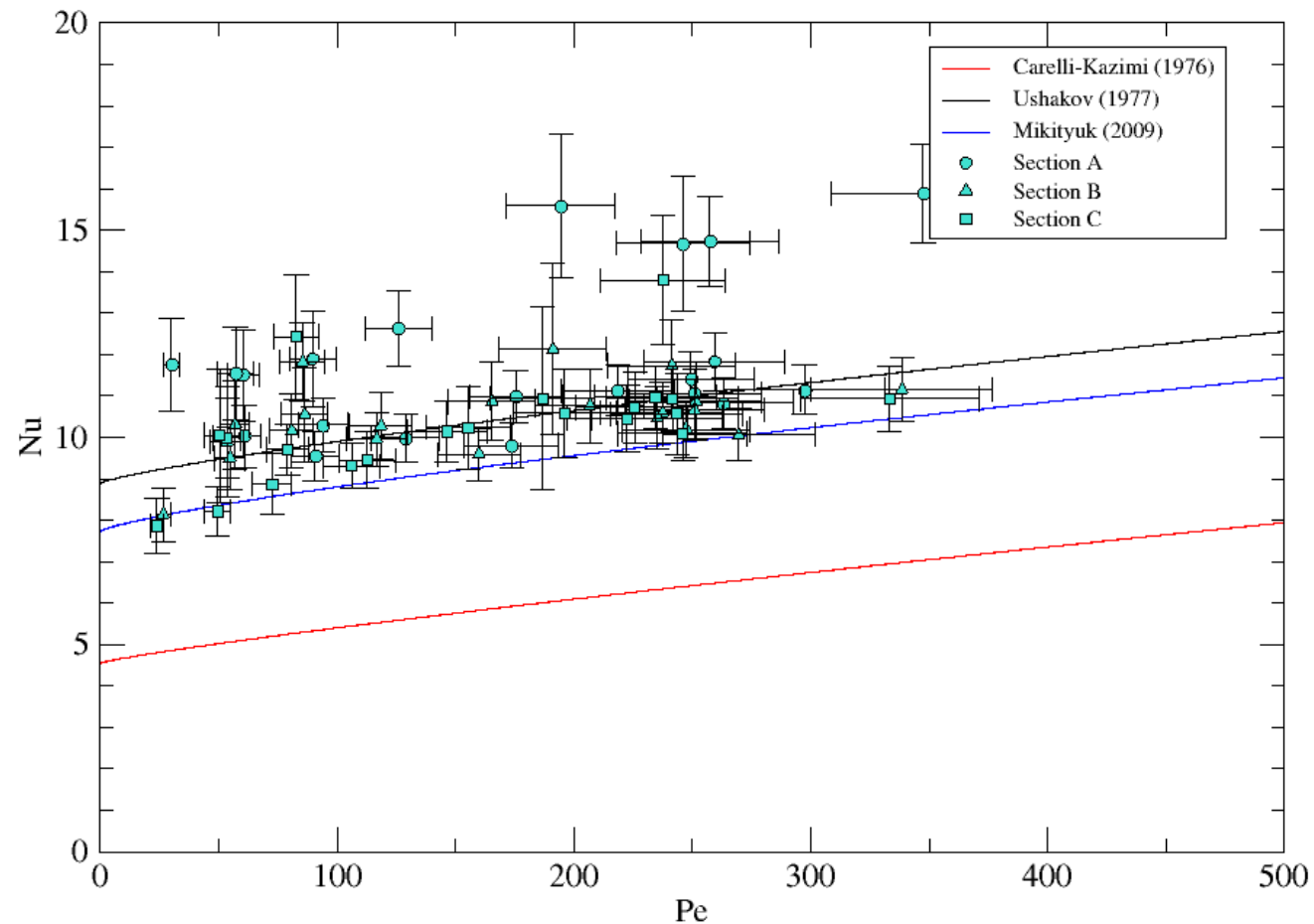


Nusselt number: S22

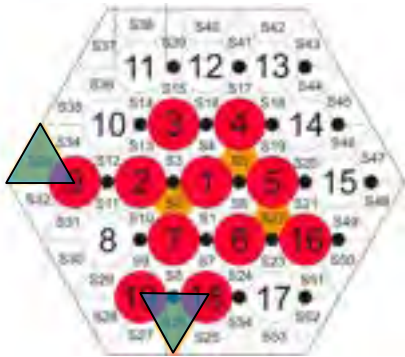


Nu vs Pe – Intermediate rank: sub-channels S22

$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$

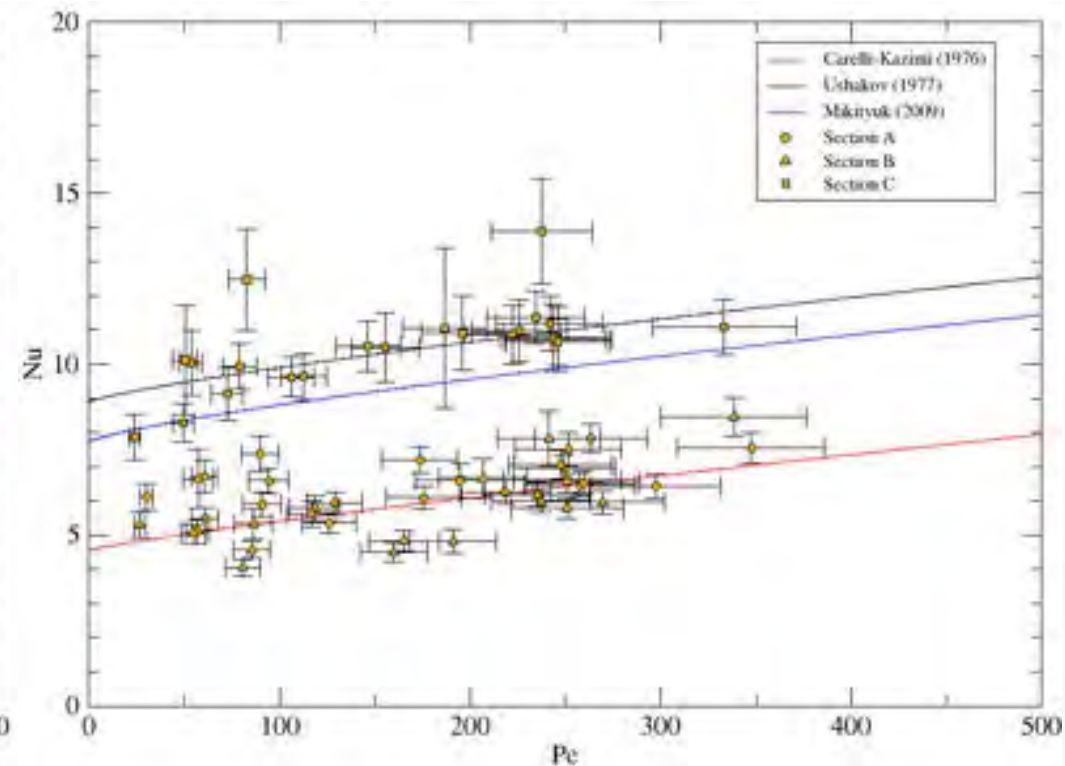
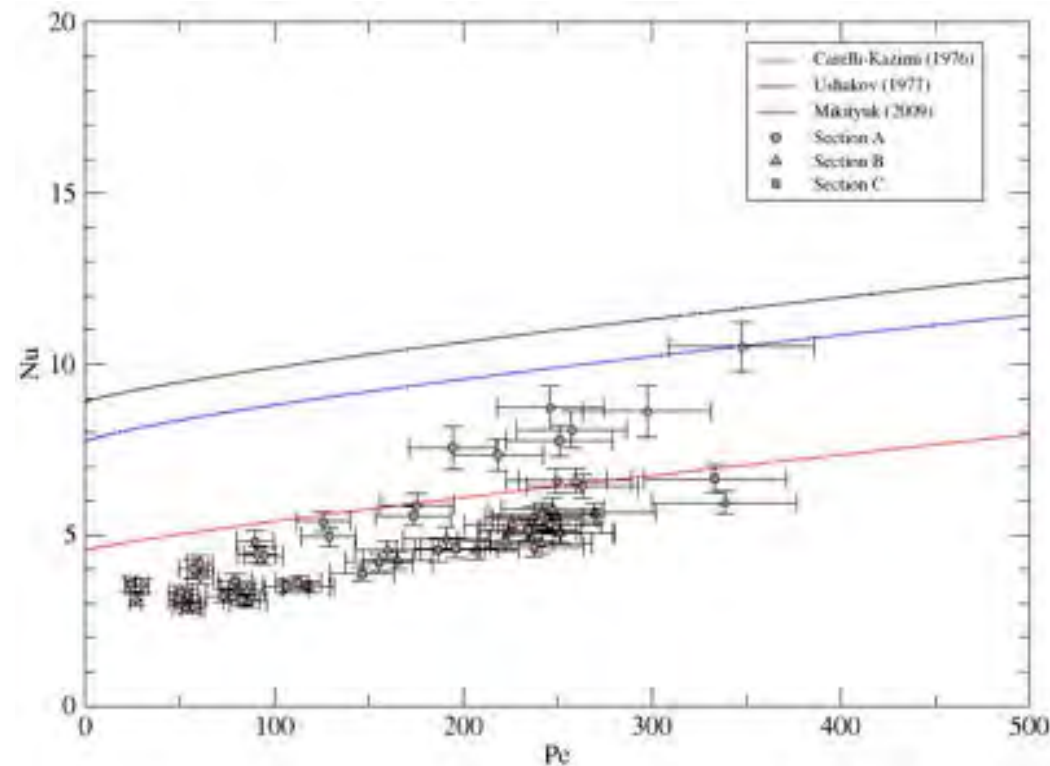


Nusselt number: S26 & S33



Nu vs Pe – External rank: sub-channels S26 and S33

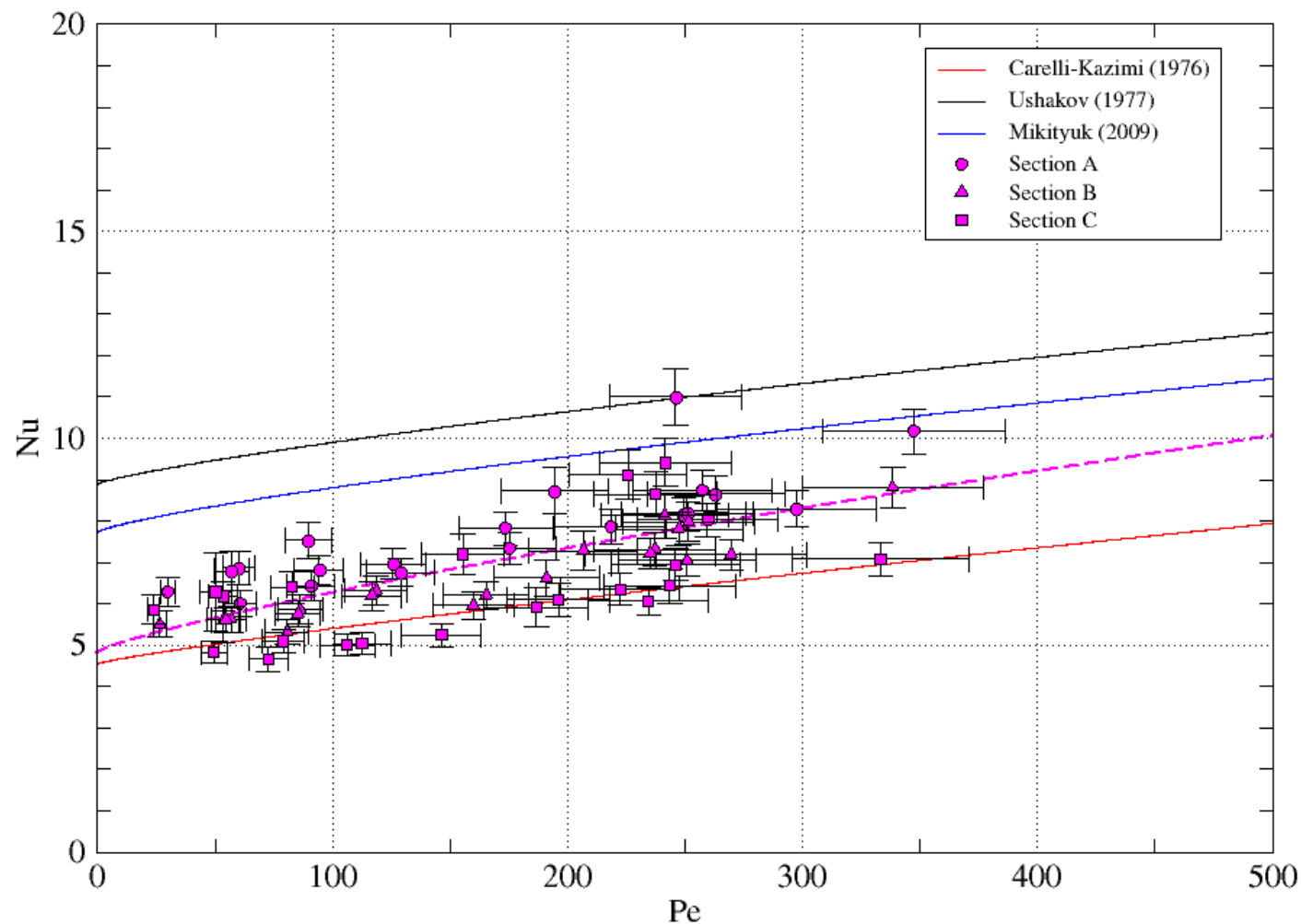
$$Nu_{sc} = \frac{q''}{(T_{w,sc} - T_{b,sc})} \cdot \frac{D_{H,nom}}{k}$$



Overall heat transfer

Nu vs Pe – Section-averaged heat transfer

$$Nu_1 = \frac{q''}{(\bar{T}_w - \bar{T}_b)} \cdot \frac{D_{H,nom}}{k}$$



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NACIE-UP: upgrade



Upcoming Experiments



New experimental campaigns are foreseen in 2016:

- **Preliminary tests:**
 - **Zero power-very low mass flow rate test** to characterize heat losses through the structure ($T=400^{\circ}\text{C} \rightarrow 250^{\circ}\text{C}$);
 - **Isothermal test** at 350°C and **different mass flow rates of gas** injected (in the range of 0-20 Nl/min);
- Further **steady-state tests** in order to **complete** the characterization of the **bundle coolability** (in natural and forced circulation regimes);
- **Steady state tests for the INERI benchmark** for CFD codes on the NACIE-UP 19-pins bundle;
- **Transient tests for a benchmark for CFD and STH/CFD coupled calculations** inside the **SESAME** project;
- Several **transient** tests characterized by transitions **from high power** and **relative high mass flow rates to low power** and **natural circulation** regime (**PLOFA-like tests**).

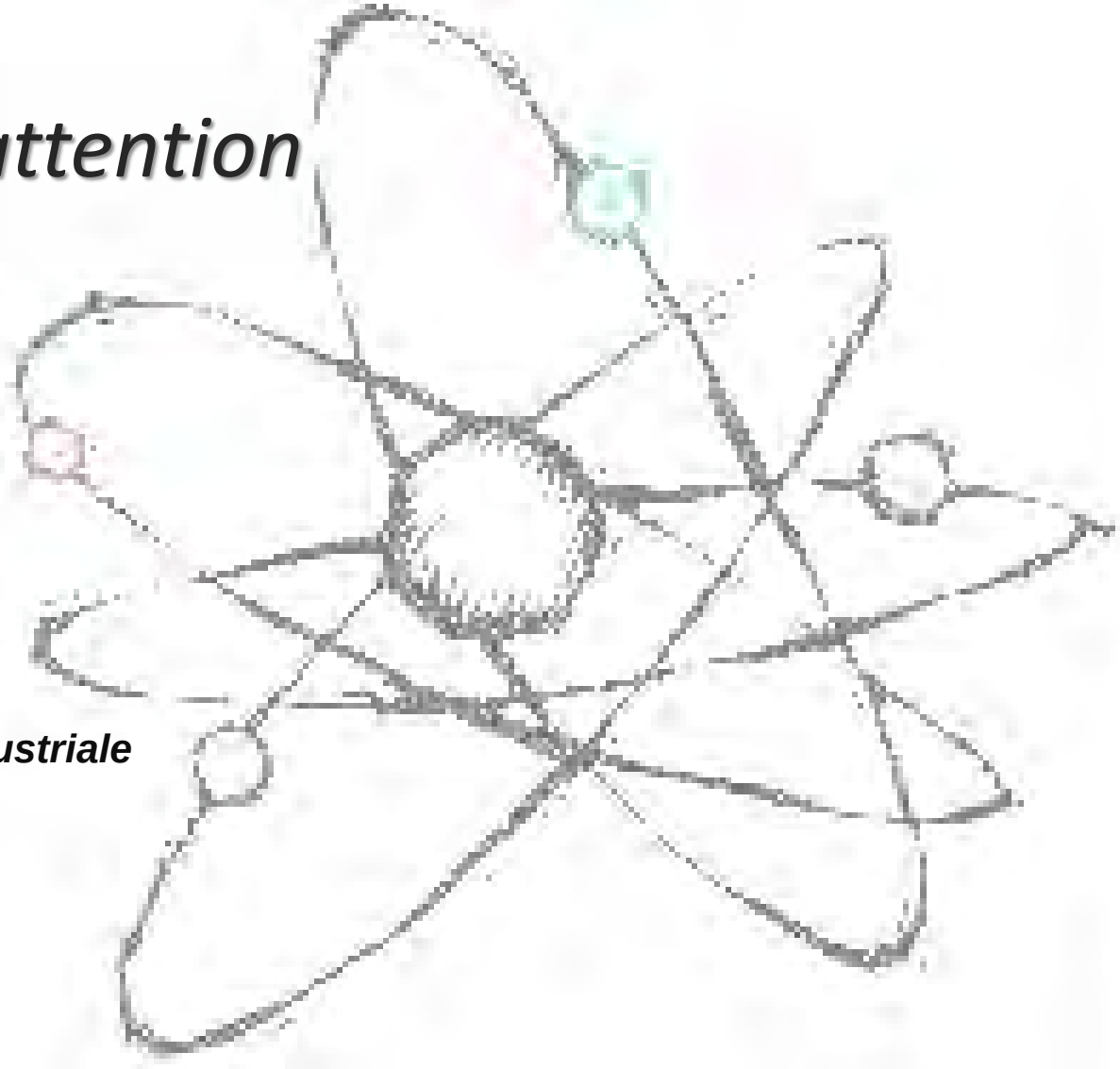
Conclusions



- An **experimental campaign** was performed at ENEA Brasimone PEC Lab (NACIE-UP facility) on a LBE cooled **19-pins bundle** in the context of the SEARCH FP7 EU
- A well instrumented 19-pin bundle test section was specifically designed and manufactured for the experiment
- Several **tests** have been performed both in **Natural** and **Forced Circulation** (range explored: $Re_{sc}=2000-20000$, $Q=11-110$ kW)
- Post-test error analysis was performed according to the error propagation theory
- **Analysis of local Nusselt and average Nusselt**
 - Local Nusselt for inner sub-channels in agreement with existing correlations
 - Local Nusselt for external sub-channel is lower than in the inner ranks
 - Section-averaged Nusselt number is in accordance with the Carelli-Kazimi correlation
- Some improvements are being implemented in the facility for the **upcoming experimental campaign** that will focus on the thermal-hydraulic behavior of the sub-channels during **transients**

Thank you for your attention

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Mixing and Stratification in HLM large pool facility

M. Tarantino (mariano.tarantino@enea.it)

C.R. ENEA Brasimone, 19th – 20th November 2015

@ **Goal of the CIRCE Experiments**

@ **CIRCE Overview**

@ **Experimental Results**

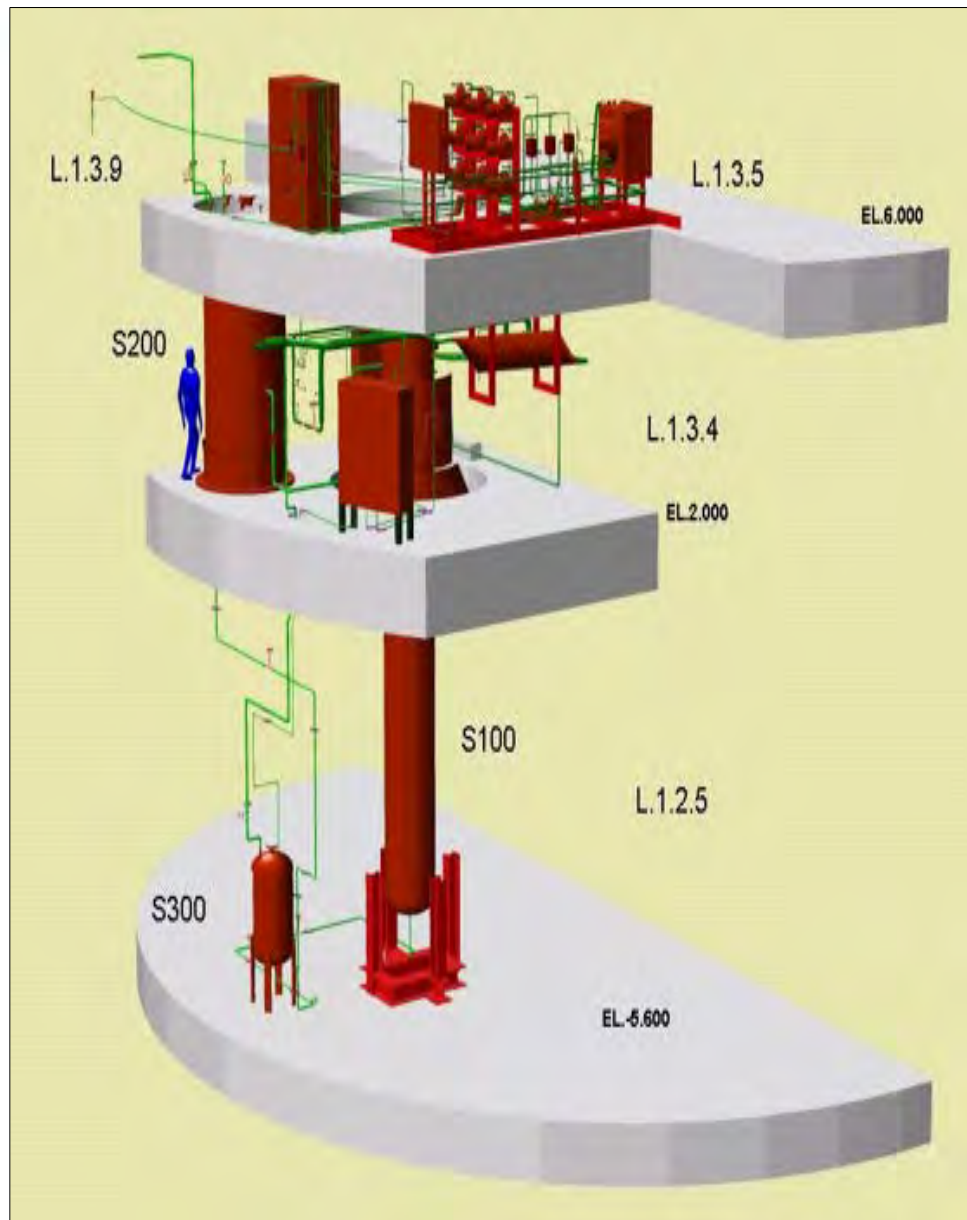
@ **Outlook**

Goal of the CIRCE Experiments



- ④ The main goal of the CIRCE Experiments is to provide data on steady-state and transient flow phenomena in HLM large pool, including the transition from forced to natural circulation
- ④ Experimental data will be used to develop and validate codes for their use in the design and safety analysis of ADS/LFR
- ④ Natural circulation in the primary system is the chosen option for the design in terms of decay heat removal. The viability of the natural circulation has to be fully demonstrated in large pool experiments
- ④ Investigate the stability of a large-scale pool system operating in natural circulation
- ④ A good knowledge of convection patterns, flow mixing and stratification in operational and accidental conditions (e.g. partial or complete loss-of-flow, loss-of-heat-sink) etc. is needed

CIRCE Overview



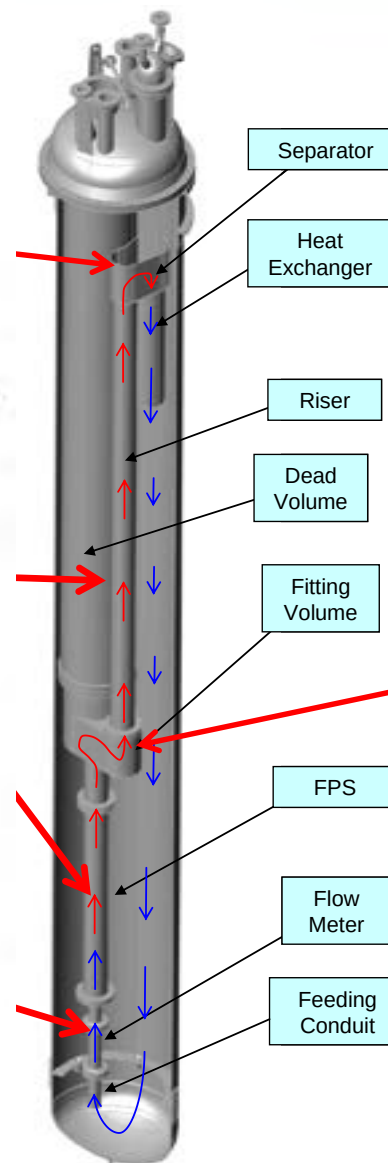
Parameters

Parameters	Value
Outside Diameter	1200 mm
Wall Thickness	15 mm
Material	AISI 316L
Max LBE Inventory	90000 kg
Electrical Heating	47 kW
Cooling Air Flow Rate	3 Nm ³ /s
Temperature Range	200 to 550 °C
Operating Pressure	15 kPa (gauge)
Design Pressure	450 kPa (gauge)
Argon Flow Rate	15 NI/s
Argon Injection Pressure	600 kPa (gauge)

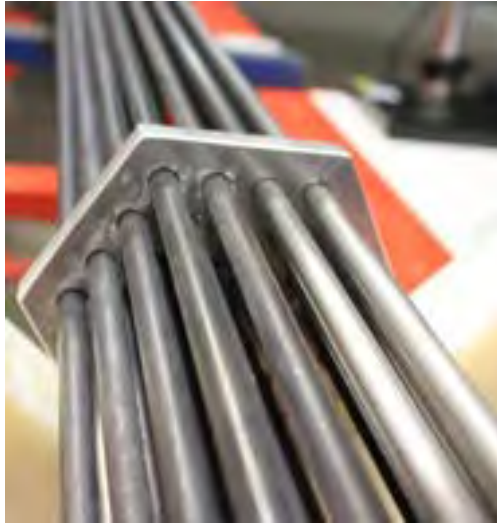
Electrical Power (Pin Bundle) ~ **1 MW**

CIRCE Overview

Thermal Duty	40 kW
Fluid Shell side	LBE
LBE inlet temperature	340 °C
LBE outlet temperature	306 °C
Fluid tube side	Low pressure air
Air Inlet temperature	20 °C
Air Outlet temperature	152 °C
Air flow rate	0.3 kg/s
Air pressure drops	8500 Pa
Shell Length (below the free level)	4435 mm
Active length	4028 mm
Straightener length	407 mm
Shell inner diameter	139.7 mm
Shell insulation gap thickness	4.6 mm
Bayonet inner tube (ID x thick.)	70 x 2.77 mm
Bayonet external tube (ID x thick.)	114.30 x 3 mm

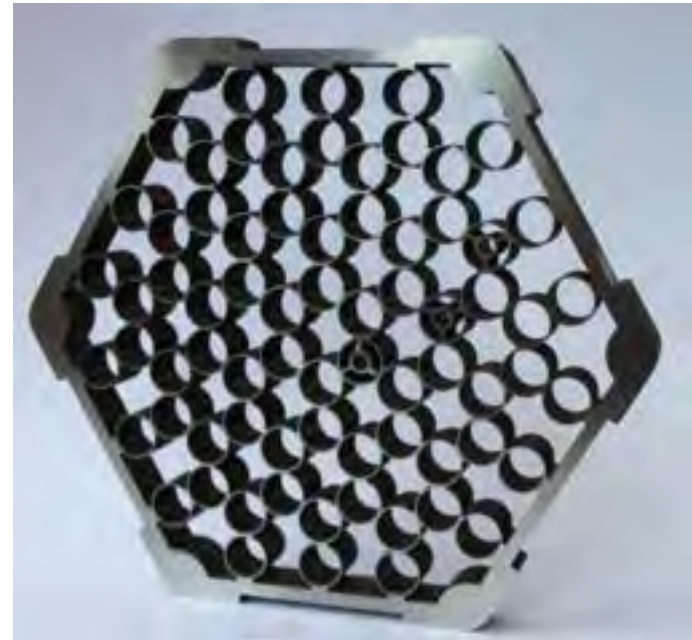


CIRCE Overview

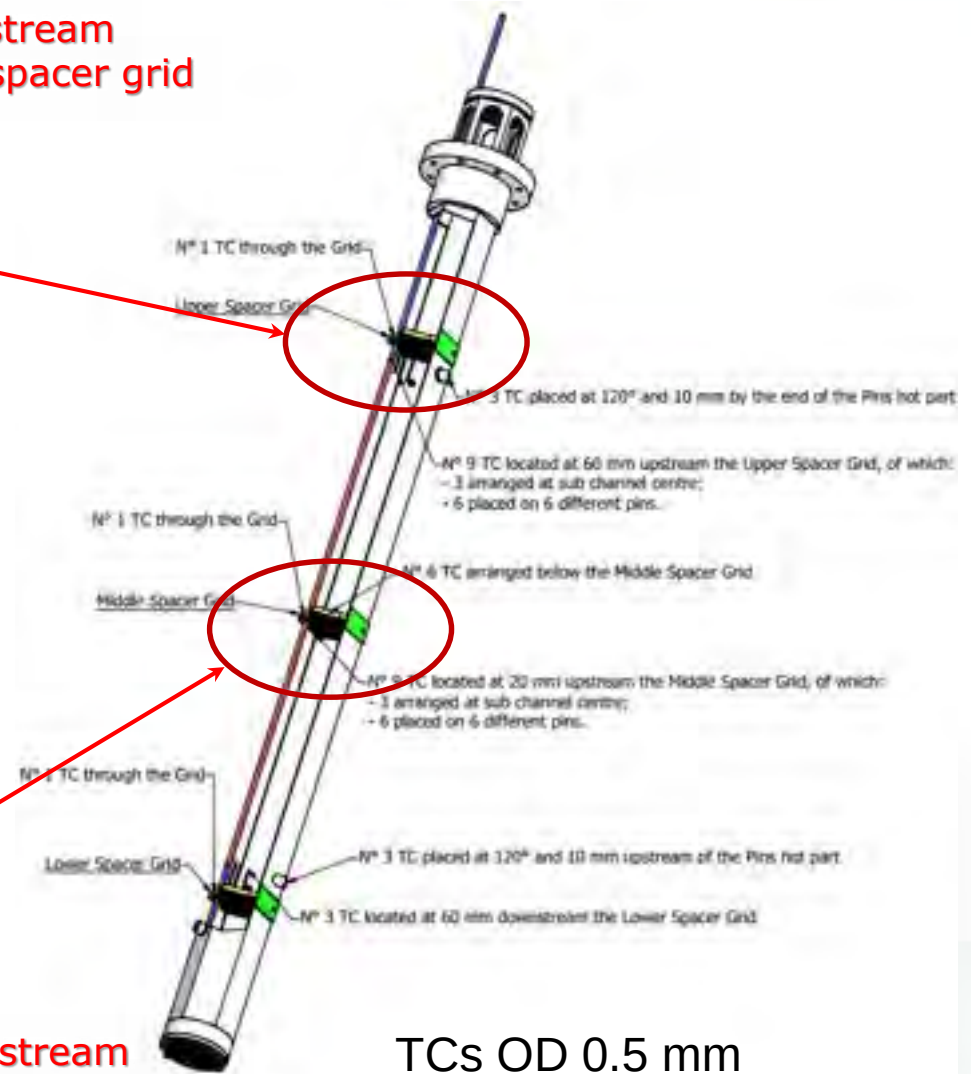
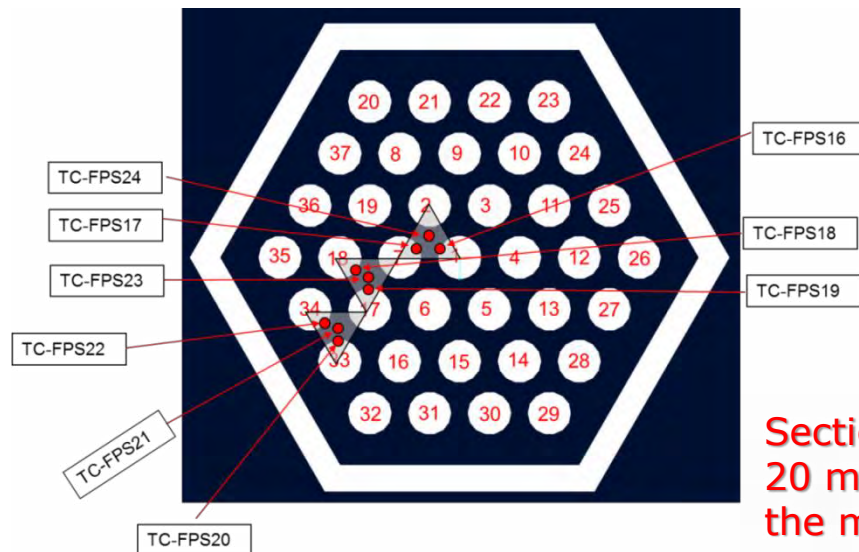
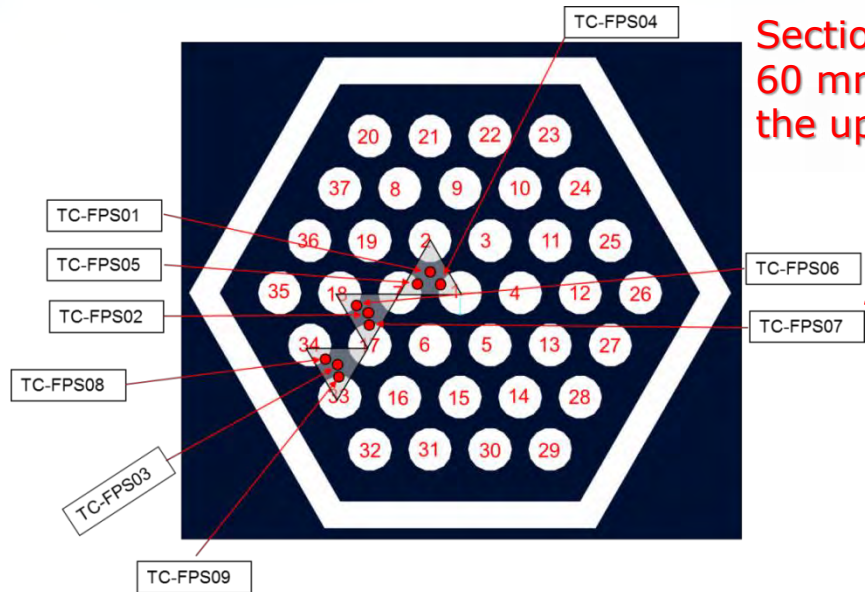


- Thermal Power: **800 - 925 kW**
- LBE T_{AV} : **300 - 350 °C**
- Core ΔT : 100 °C
- Core velocity: **1.0 m/s**
- LBE Flow Rate: 55.2 kg/s

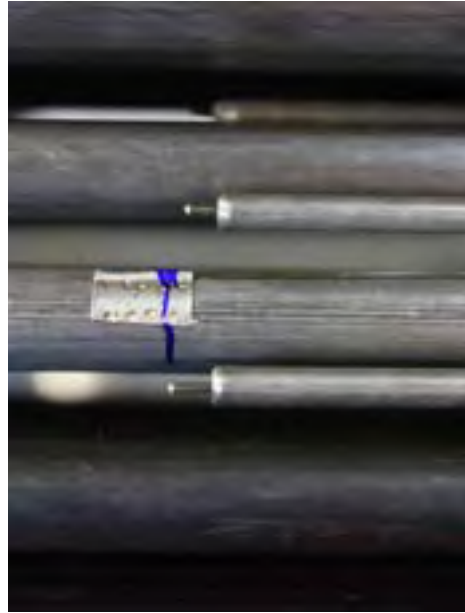
- Assembly: Hexagonal
- d : 8.2 mm
- p/d : 1.8
- L_{act} : 1000 mm
- N_{Pin} : **37**
- q'' : **100 W/cm²**
- Q_{Pin} : 26 kW



CIRCE Overview



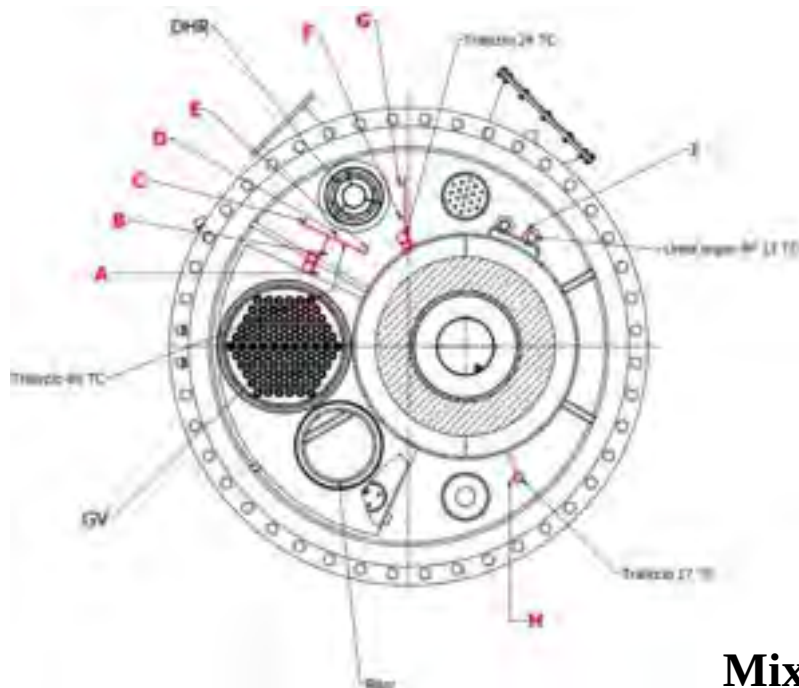
CIRCE Overview



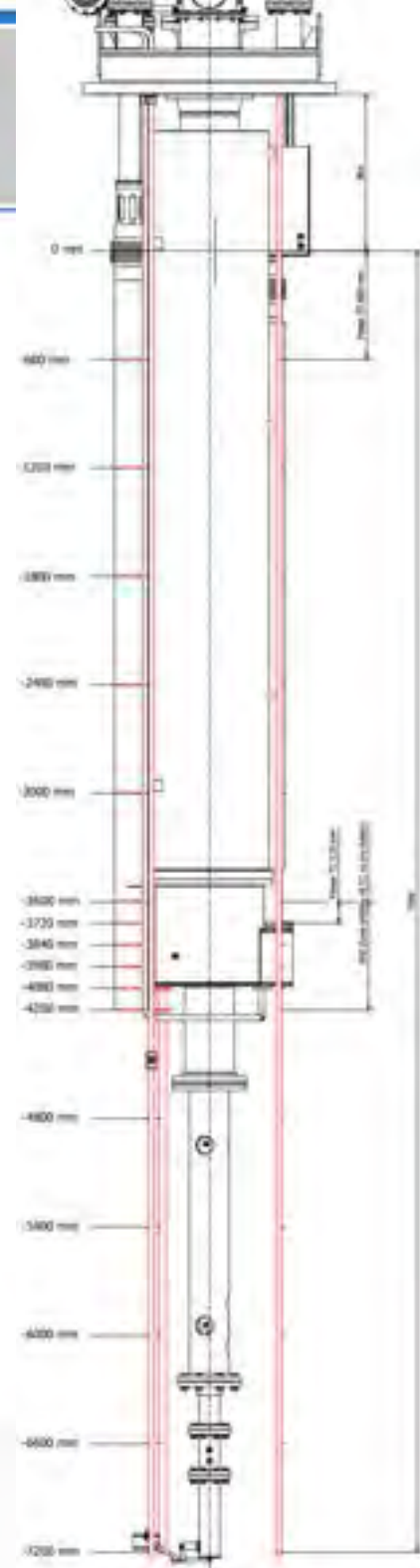
CIRCE Overview



T-MS-01 → T-MS-119



Mixing & Stratification



Test Matrix

Name	LBE Mass flow rate [kg/s]	Argon Mass flow rate [kg/s]	FPS Electrical Power [kW]	Δt (outlet- inlet) FPS	Δt (clad- bulk) Mikityuk	Δt (clad- bulk) Ushakov
1-FC	70	5	800	80	35	36
2-FC	65	4.4	760	80	37	39
3-FC	60	3	700	80	39.5	41
4-FC	55	2.4	640	80	41.6	43.5
5-FC	50	1.6	580	80	43.5	45.7
6-FC	45	1.45	525	80	45.4	47.8
7-FC	40	1.41	465	80	47	49.5

$$Nu = \frac{HTC \cdot D_{eq}}{K}$$

$$T_c - T_b = \frac{q'' \cdot D_{eq}}{Nu \cdot K}$$

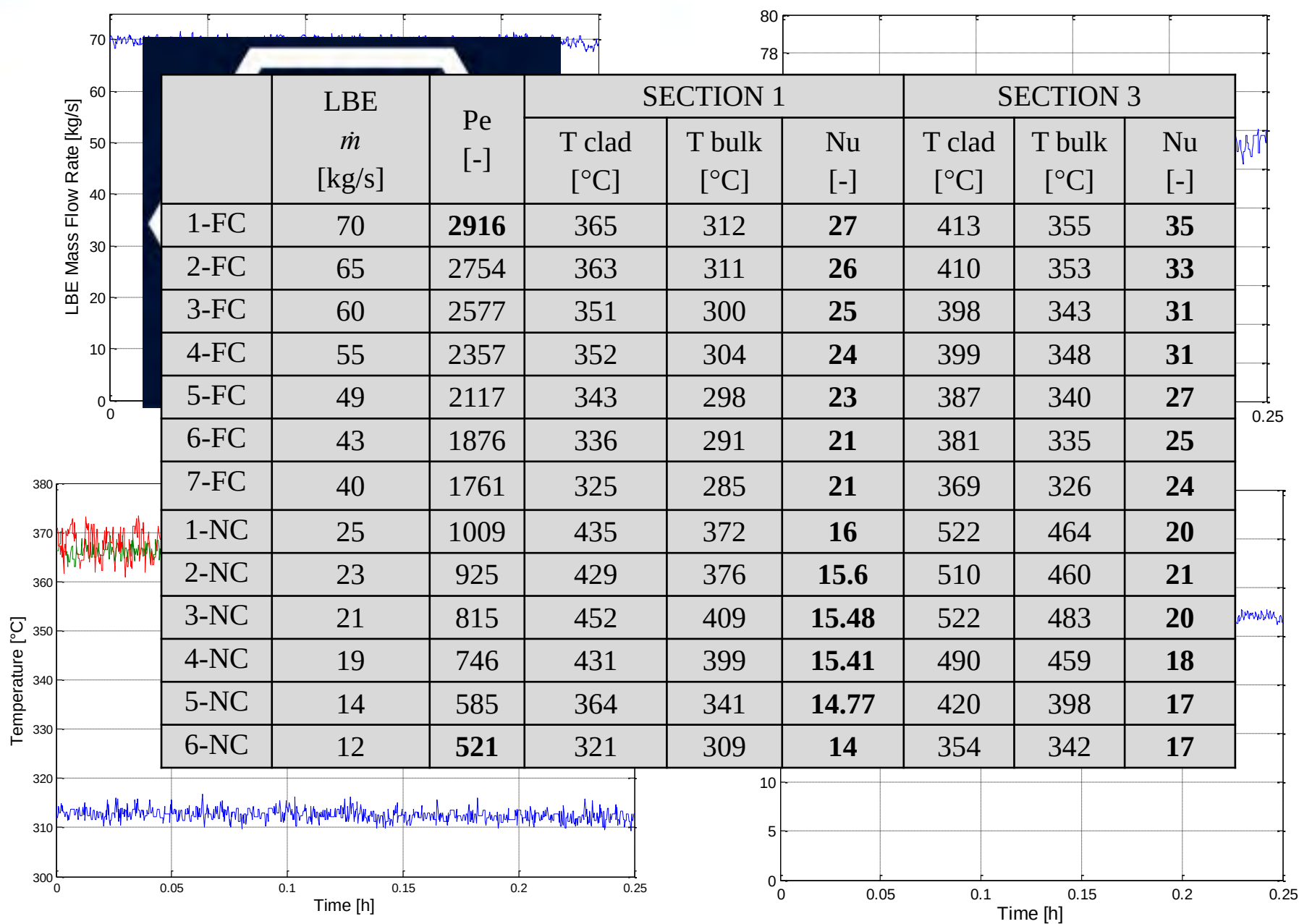
$$D_{eq} = 4 \frac{\left(\frac{\sqrt{3}}{4} p^2 - \pi d \right)}{\frac{\pi d}{2}}$$

521 < Pe < 2916

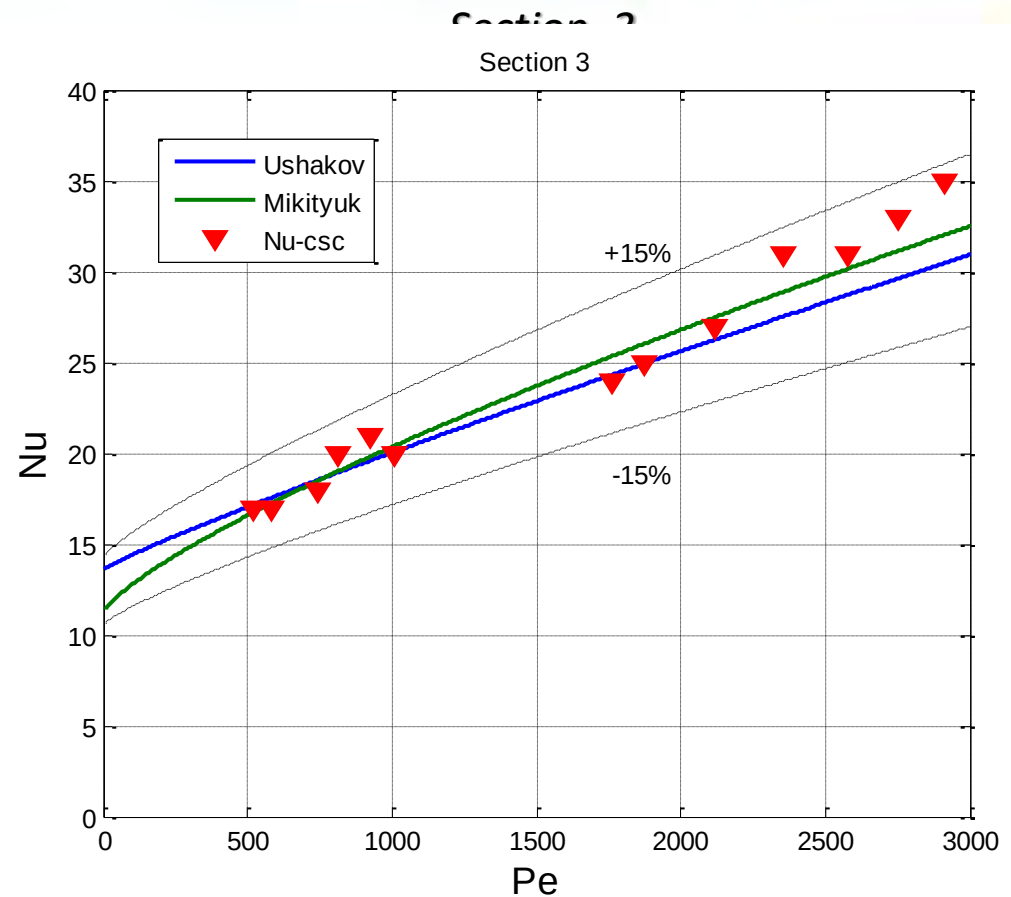
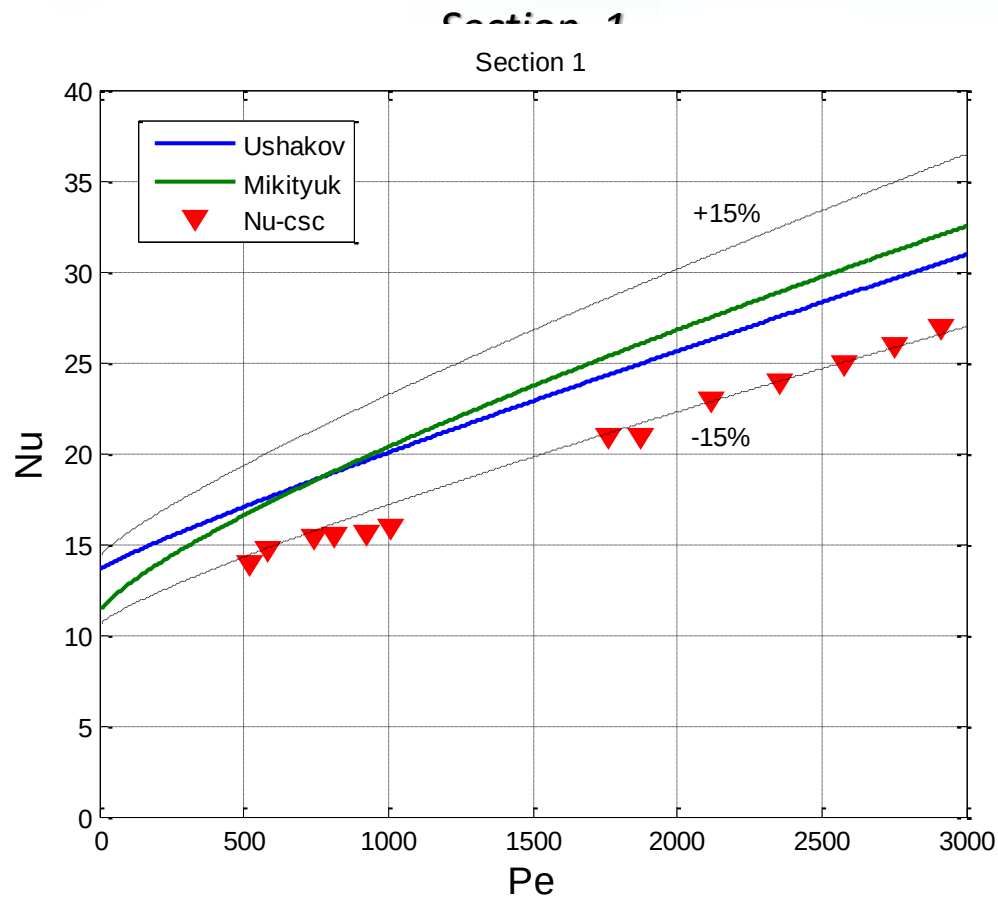
Name	LBE Mass flow rate [kg/s]	FPS Electrical Power[kW]	ΔT (outlet-inlet) FPS
1-NC	25	600	113
2-NC	23	500	101
3-NC	21	400	90
4-NC	19	300	72
5-NC	14	200	73
6-NC	12	100	37

Steady State condition

Experimental Results



Experimental Results



$$Nu = 0.047 \cdot (1 - e^{-3.8 \cdot (x-1)}) (Pe^{0.77} + 250)$$

valid for $1.1 \leq p/d \leq 1.95$ and for $30 \leq Pe \leq 5000$

$$Nu = 7.55 \cdot (p/d) - 20 \cdot (p/d) - 0.041 \cdot (p/d)^{-2} \cdot Pe^{(0.56 + 0.19 \cdot p/d)}$$

valid for $1.2 \leq p/d \leq 2$ and for $1 \leq Pe \leq 4000$

@Test #1

- @ Full Power steady state circulation by gas Lift (800 kW)
- @ PLOFA transition
- @ Mixing & stratification and FPS data
- @ No long run (20 h)

@Test #2

- @ Full Power steady state circulation by gas Lift (600 kW)
- @ PLOFA transition
- @ Mixing & stratification and FPS data
- @ No long run (6 h)

TEST 1

Nominal Steady State	PLOH+LOF transient
HS Thermal Power ~800 kW	Isolation of the main HX (isolating the feed water)
HLM flow rate: 60-70 kg/s (by gas lift)	Core "scram" at about 30 kW (decay power)
Argon mass flow rate ~3NI/s	Start-up of the DHR-system (air mass flow rate 0.24 kg/s)
Average velocity into the HS:1m/s	DHR air inlet @ room temperature
Pool LBE initial temperature ~314°C (Vertical gradient in the pool of 3°C 316 T-MS-001, 312 °C T-MS-119)	"Main pump" turn-off (the gas injection is interrupted)
Vessel heating system: not active	Vessel heating system: not-active
HX water flow rate ~ 0.6 kg/s	
HX thermal power removed ~750 kW	
DHR: not active	
HX inlet Water @ room temperature	

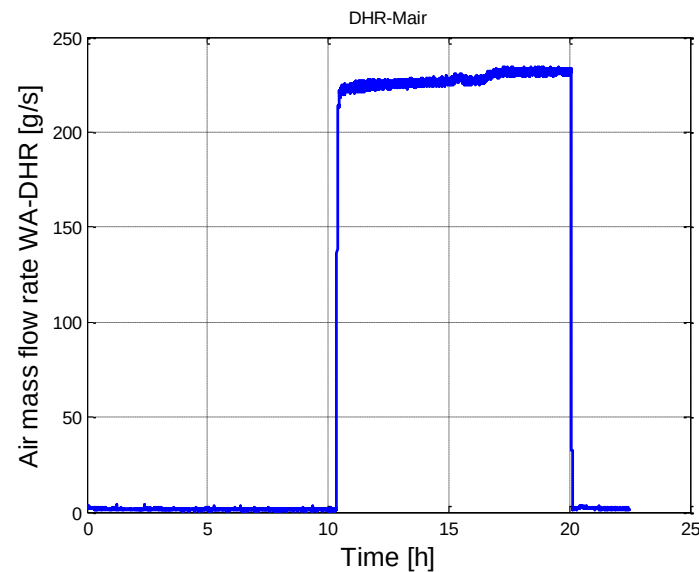
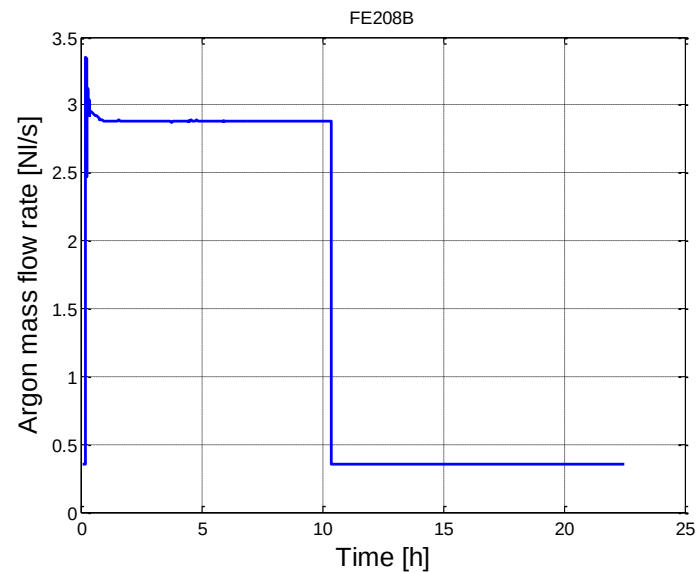
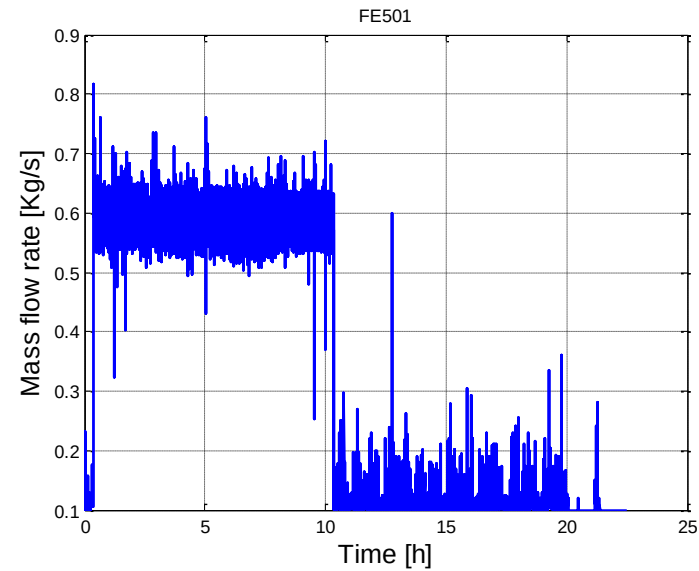
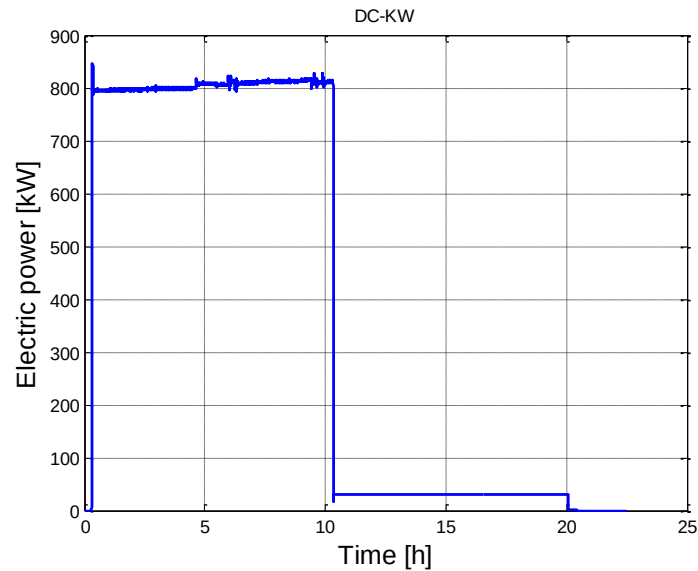
FULL POWER RUN

<u>EVENT</u>	TIME
Power ramp (0-800 kW)	0.3h → 0.35h
Full power (800kW)	0.35 h → 10.3 h
Water injection (main HX)	0.35 h → 10.35 h
Argon Injection	0.17 h → 10.35 h

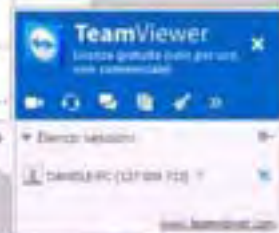
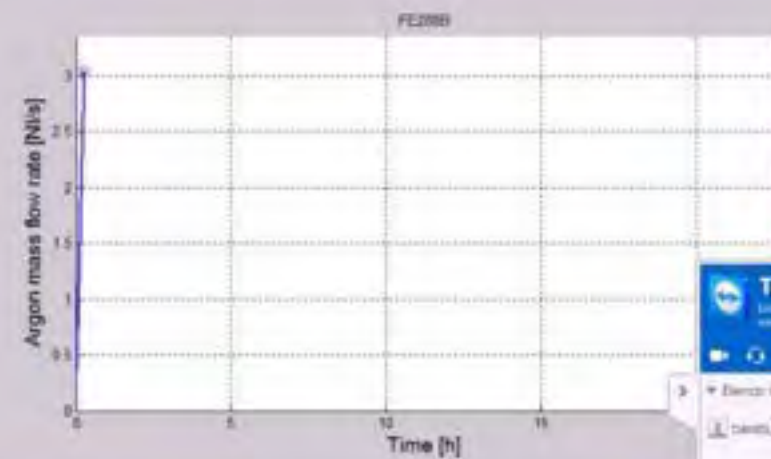
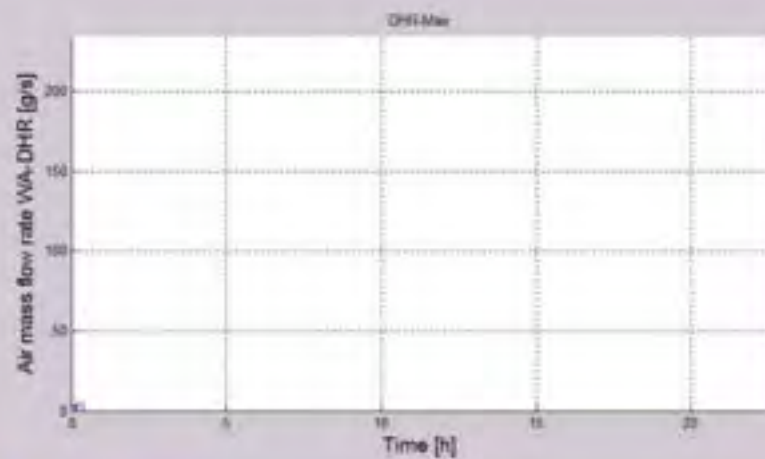
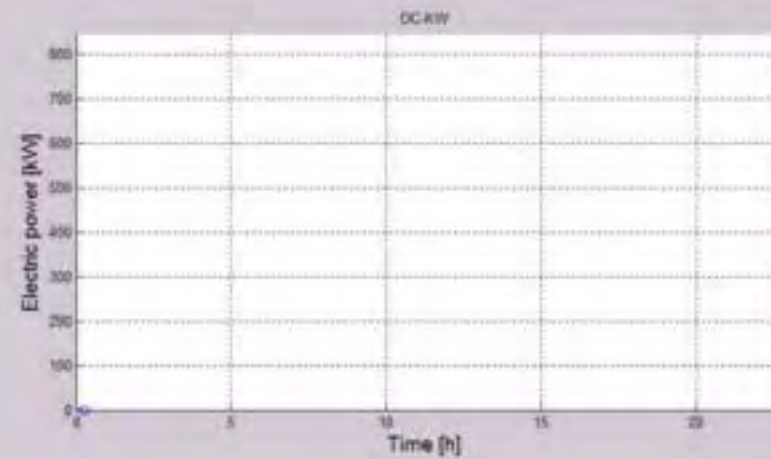
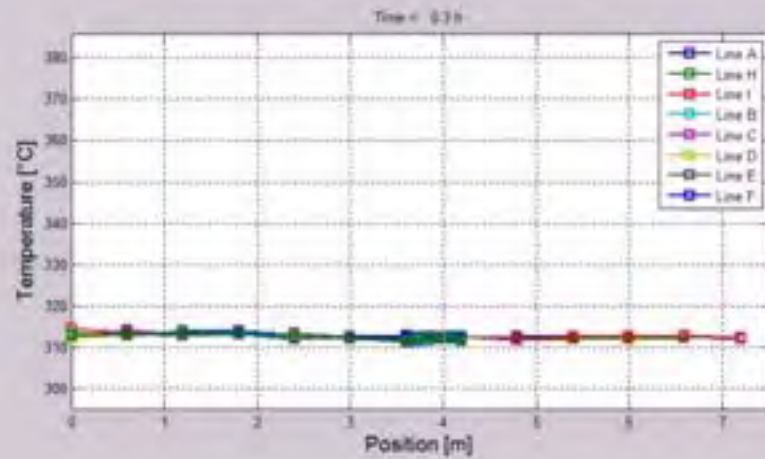
TRANSITION

<u>EVENT</u>	TIME
Power ramp (800-30 kW)	10.3 h → 10.35 h
Air Injection (DHR)	10.35 h → 20.09 h

TEST 1: Boundary conditions



TEST 1



TEST 2

Nominal Steady State	PLOH+LOF transient
HS Thermal Power ~800 kW	Isolation of the main HX (isolating the feed water)
HLM flow rate: 60-70 kg/s (by gas lift)	Core “scram” at about 30 kW (decay power)
Argon mass flow rate ~2.7 NI/s	Start-up of the DHR-system (air mass flow rate $\dot{m} \sim 0.325 / 0.22 \text{ kg/s}$)
Average velocity into the HS:1m/s	DHR air inlet @ room temperature
Pool LBE initial temperature ~280°C (Vertical gradient in the pool of 4°C 282 T-MS-001, 278 °C T-MS-119)	“Main pump” turn-off (the gas injection is interrupted)
Vessel heating system: not active	Vessel heating system: not-active
HX water flow rate ~ 0.6 kg/s	
HX thermal power removed ~750 kW	
DHR: not active	
HX inlet Water @ room temperature	

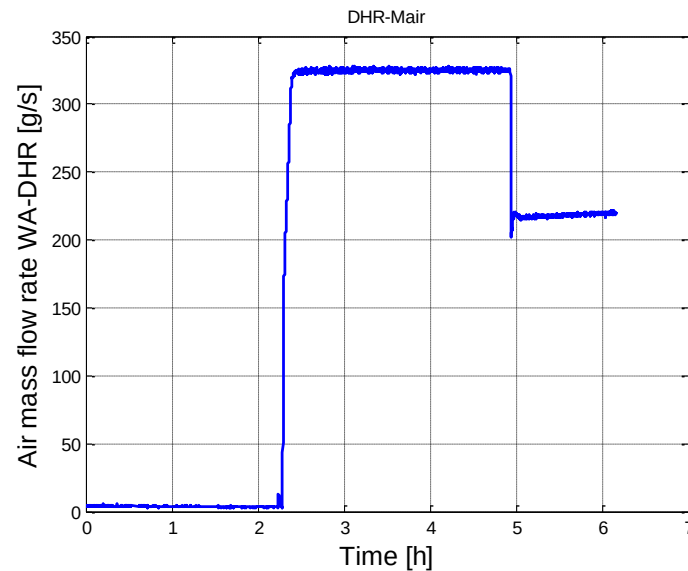
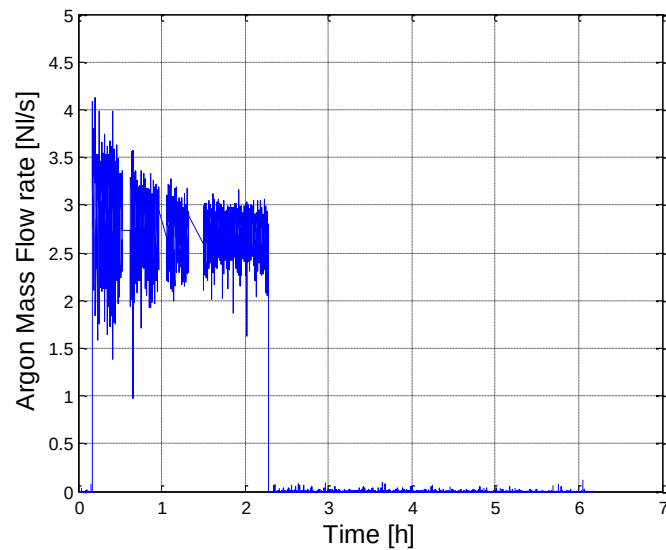
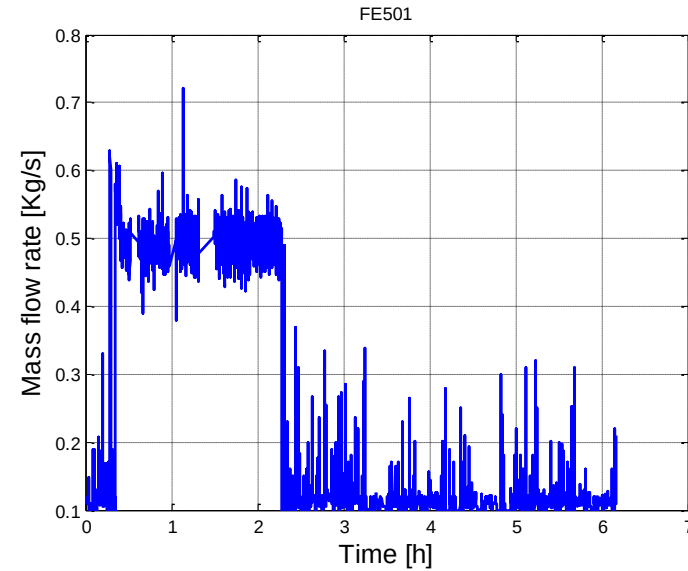
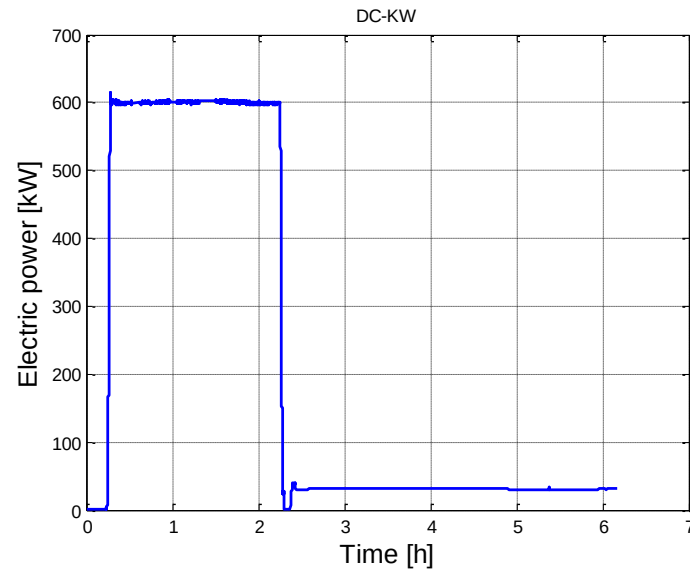
FULL POWER RUN

<u>EVENT</u>	TIME
Power ramp (0-600 kW)	0.24h → 0.28h
Full power (600kW)	0. 28h → 2.28 h
Water injection (main HX)	0.35 h → 2.28 h
Argon Injection	0.16 h → 2.28 h

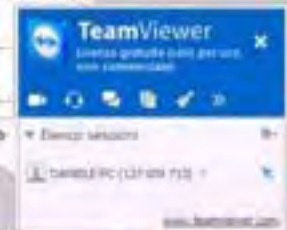
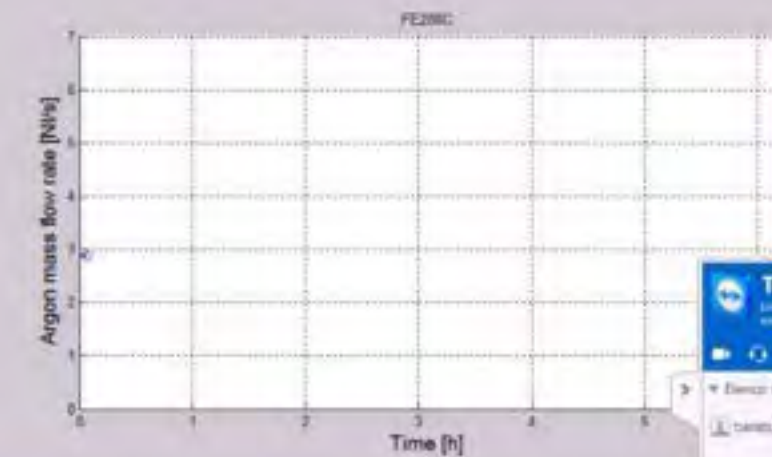
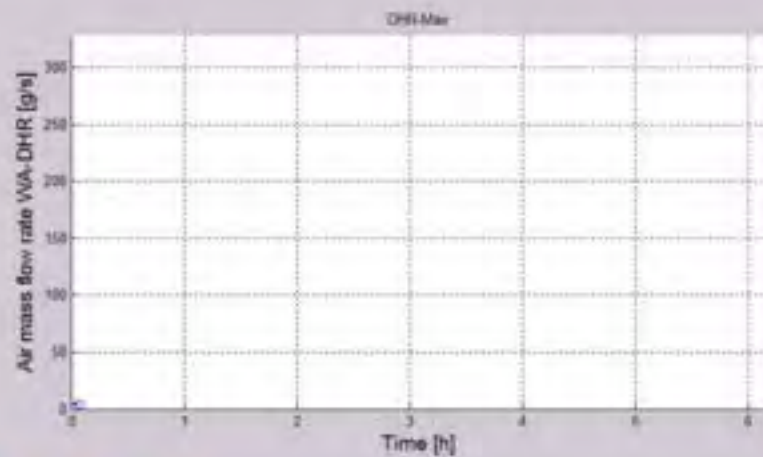
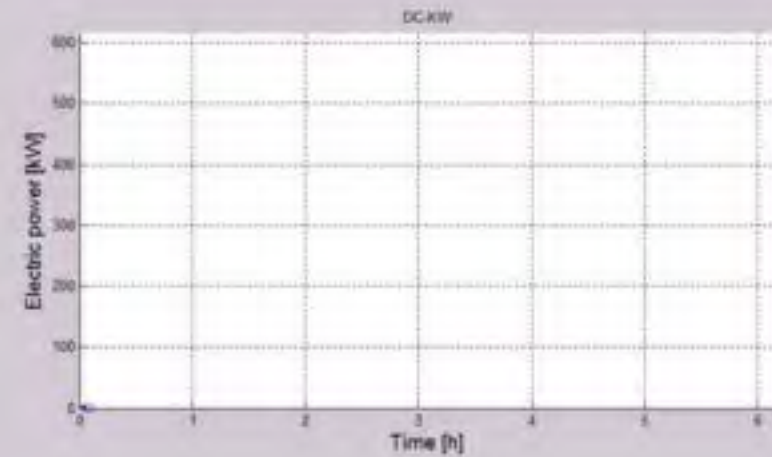
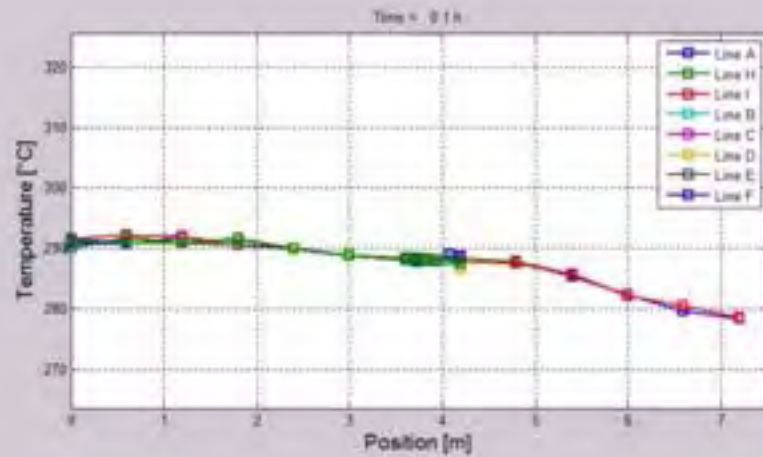
TRANSITION

<u>EVENT</u>	TIME
Power ramp (600-30 kW)	2.25 h → 2.28 h
Air Injection (DHR)	2.28 h → 4.9 h (0.325 kg/s) 4.9 h → 6.15 h (0.22 kg/s)

TEST 2: Boundary conditions



TEST 2



- Nu has been calculated considering the **average cladding temperature** and the **central sub-channel temperature** consistently with the measuring technique.
- Results carried out showed that the **LFR primary system is technological feasible**. Nu in the FPS has been computed, ($Pe \sim 500-3000$) results are in good agreement with correlations justifying their use for HLM fuel pin bundle design ($\pm 15\%$).
- Results showed that Nu is slightly lower in the middle section (Section 1) if compared with the ones into the upper section (section 3).
- Thermal Stratification happens in the pool, **up to 40°C in forced circulation regime**, and **10°C in natural circulation regime**.
- Thermal stratification takes place in the downcomer, being localized at the outlet section on the main heat exchanger / decay heat removal



UNIVERSITY OF PISA

Dipartimento di Ingegneria Civile e Industriale (DICI)

PRELIMINARY ANALYSIS OF CIRCE FACILITY BY CFD CODES

Daniele Martelli
Nicola Forgione
Francesco Andreoli
Gemma Damiani

ADP ENEA-MSE (PAR 2014-LP2)
C.R. ENEA Brasimone 19-20 Nov. 2015

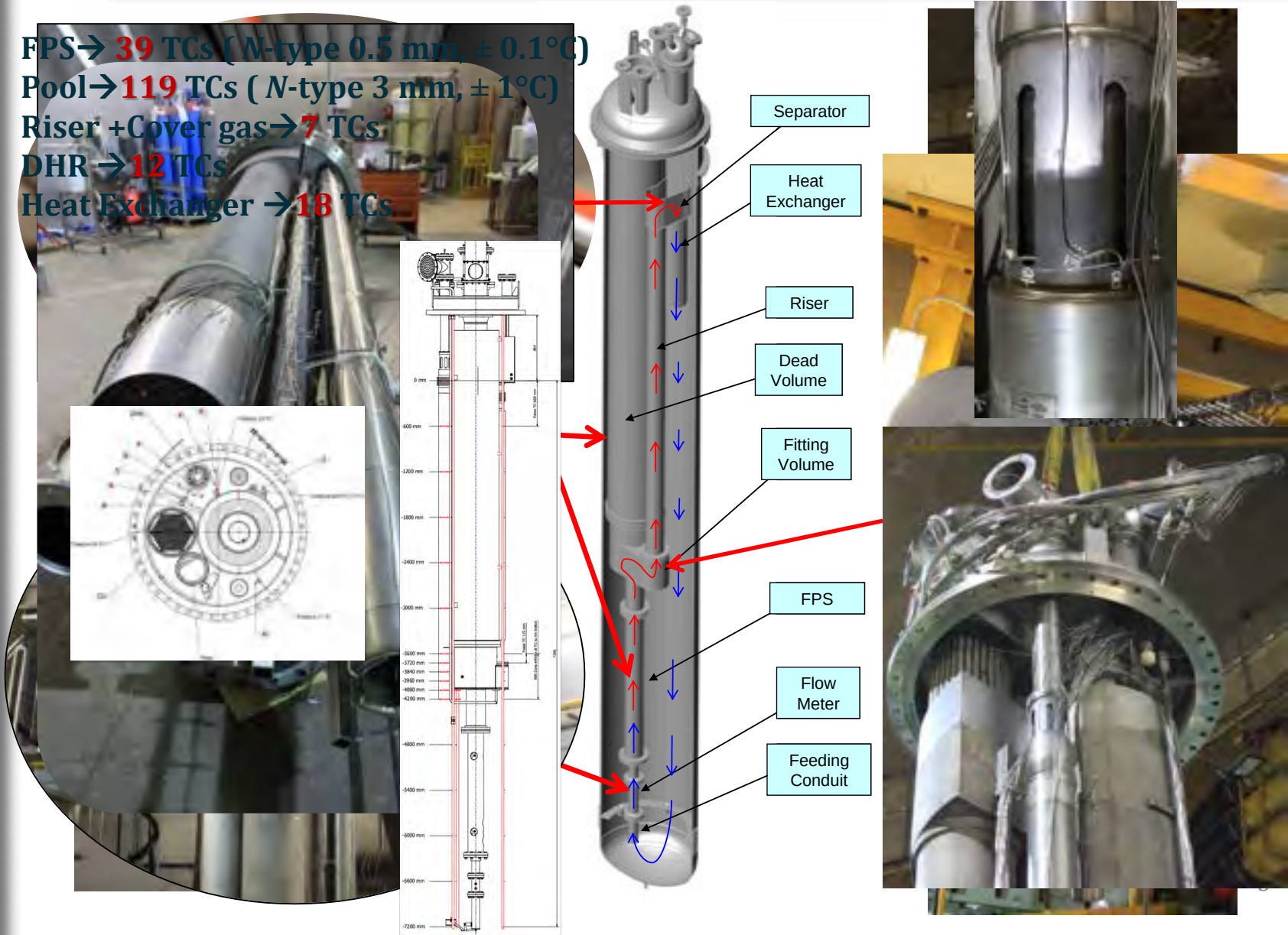
Outline

- **CIRCE Experimental facility**
- **Geometrical model**
- **CFD Simulations**
- **Obtained results**
- **Pool thermal Stratification**
- **CIRCE post-test simulation**
- **CIRCE HERO experimental facility**
- **CIRCE-HERO 3D model**
- **Conclusions**

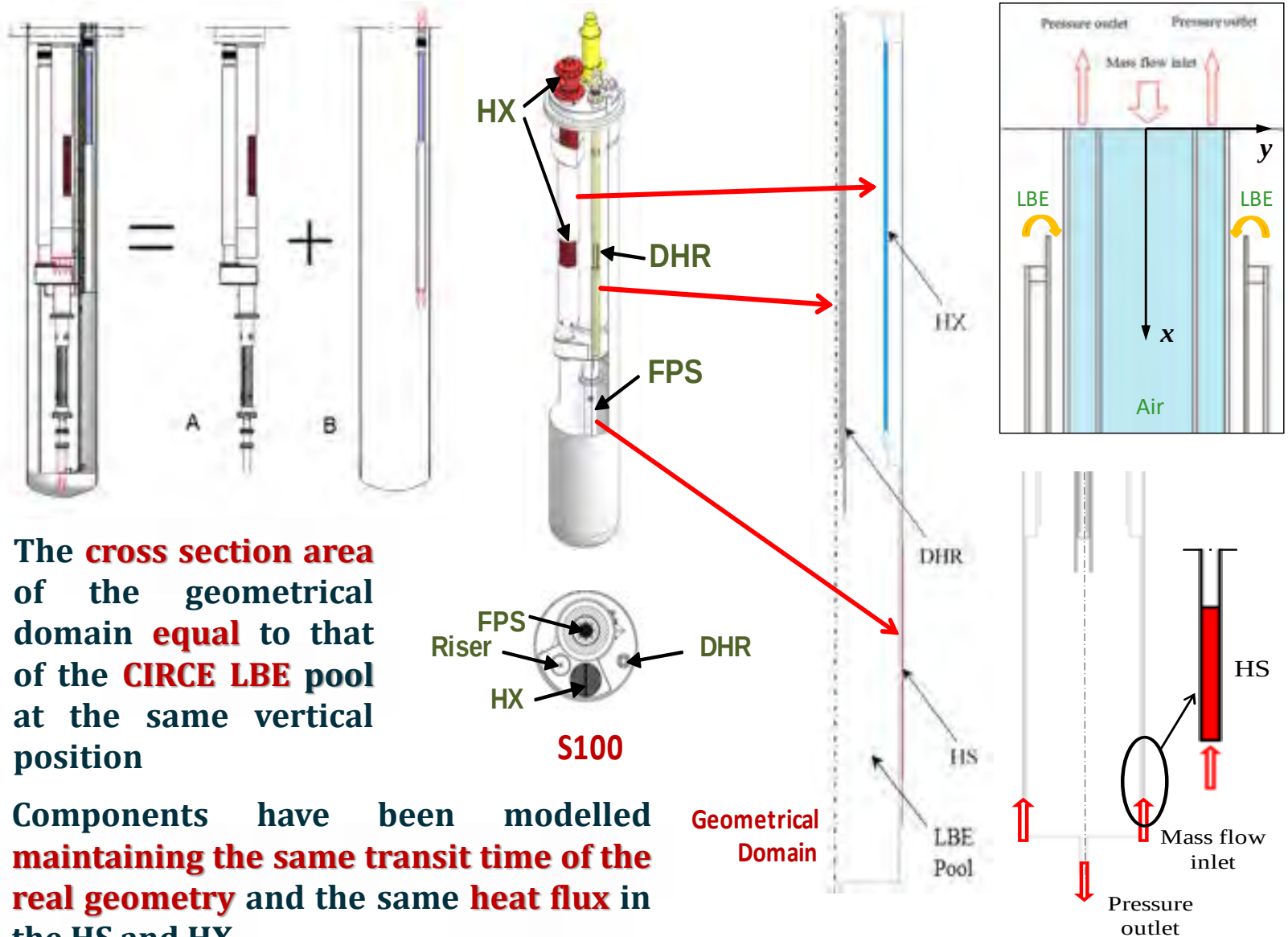
CIRCE Experimental facility

Geometrical
model

FPS → **39** TCs (N-type 0.5 mm, $\pm 0.1^{\circ}\text{C}$)
 Pool → **119** TCs (N-type 3 mm, $\pm 1^{\circ}\text{C}$)
 Riser + Cover gas → **7** TCs
 DHR → **12** TCs
 Heat Exchanger → **18** TCs

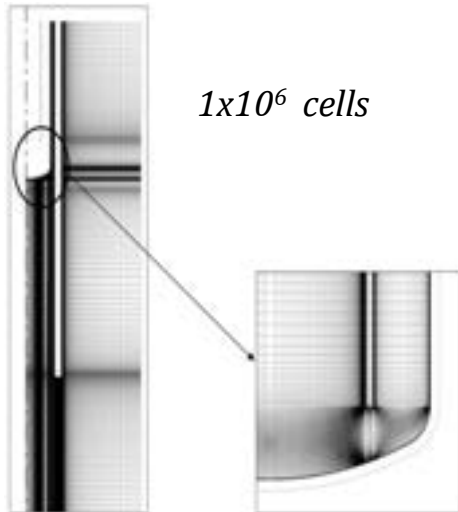


Geometrical model



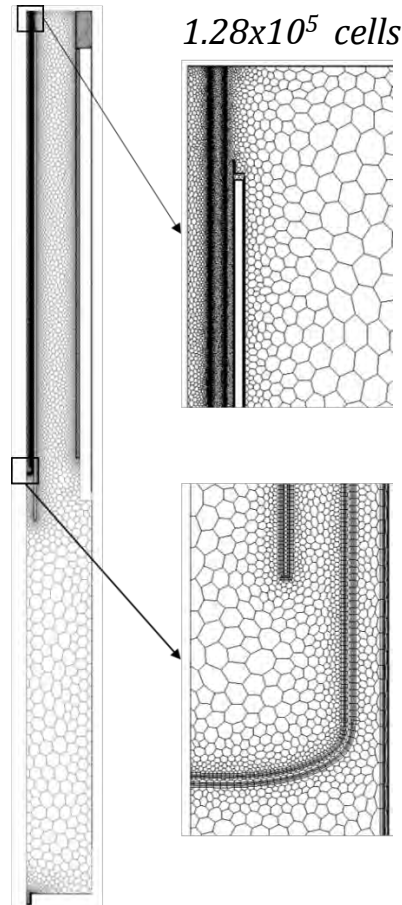
CFD simulations

Obtained
results

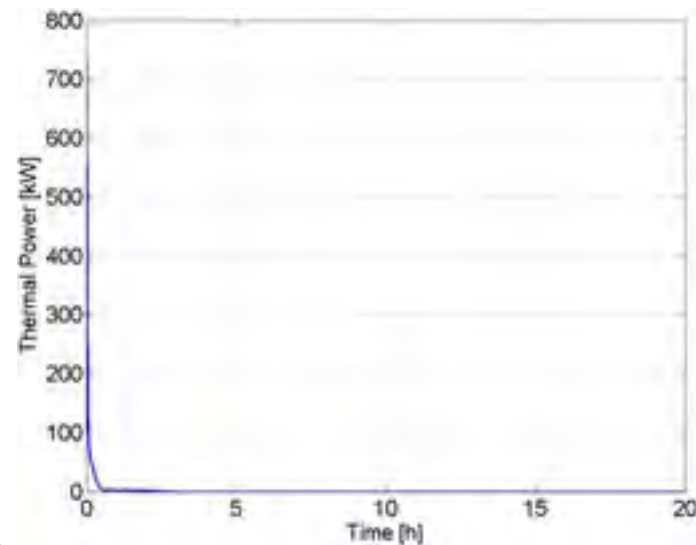
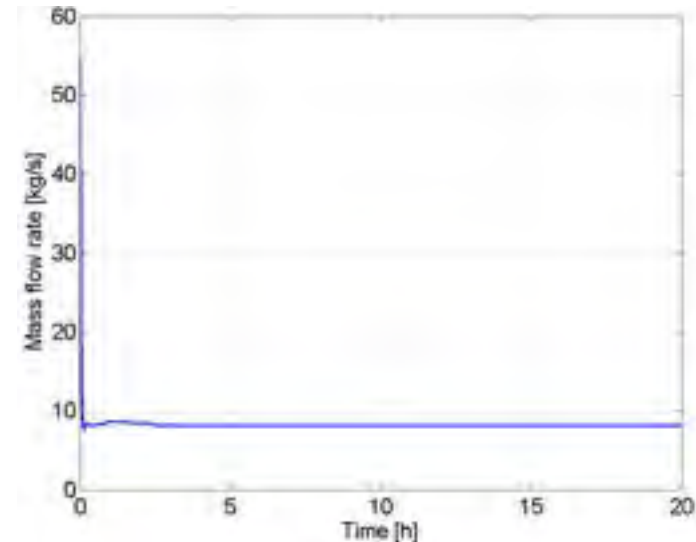


k-ε standard RNG with enhanced wall treatment
First order UPWIND scheme
Adiabatic External walls

Air mass flow rate 0.3 kg/s
Air inlet temperature 20°C



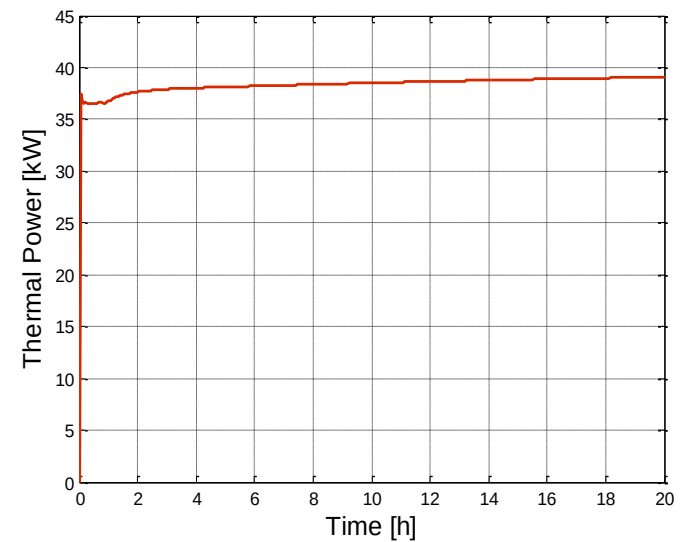
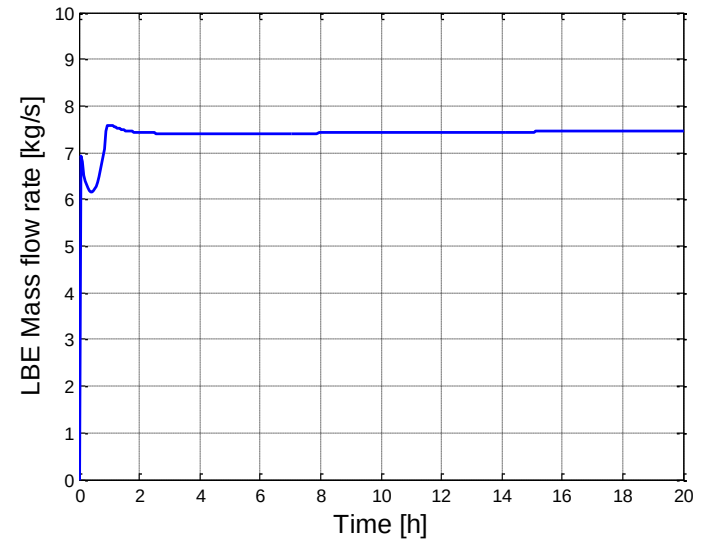
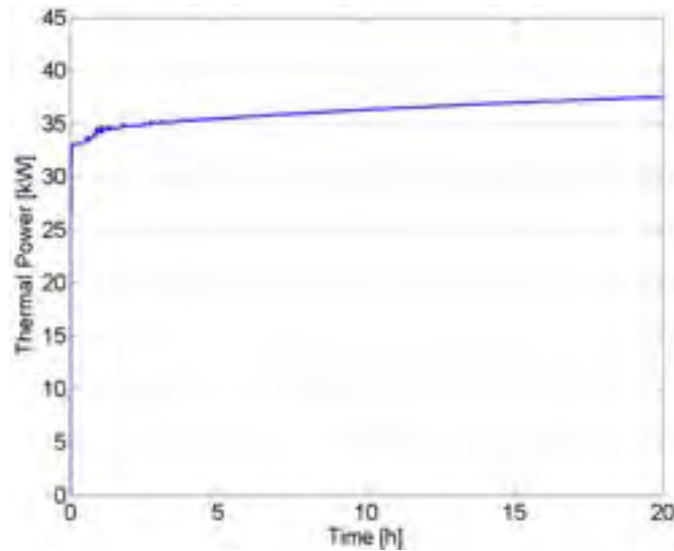
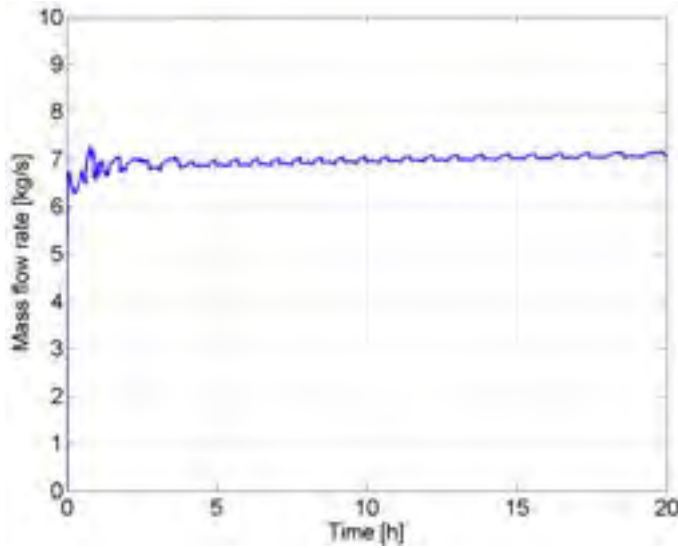
SST k-ω with y+ wall treatment
First order UPWIND scheme
Adiabatic External walls



Obtained
results
(1 di 2)

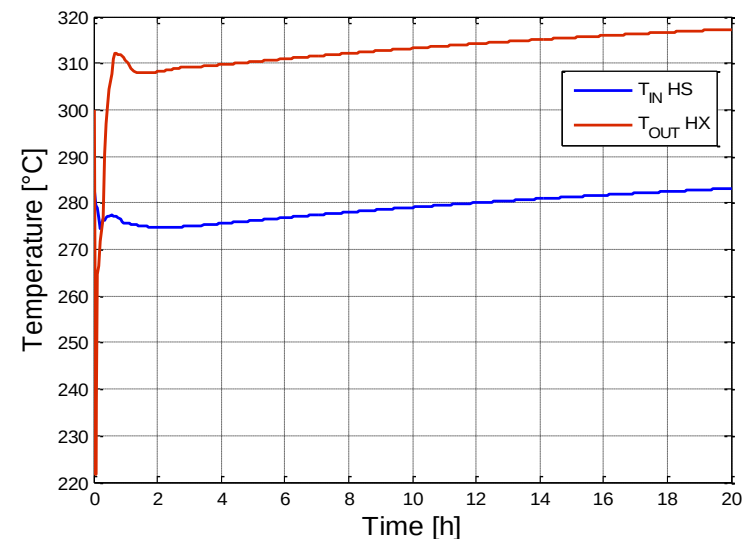
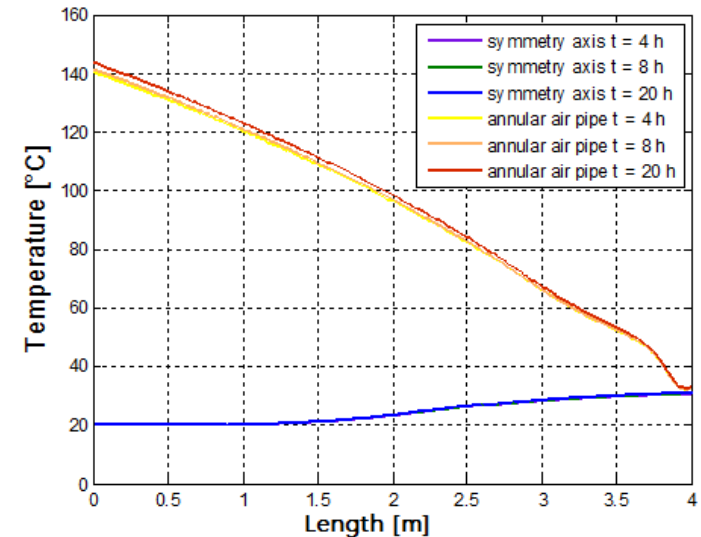
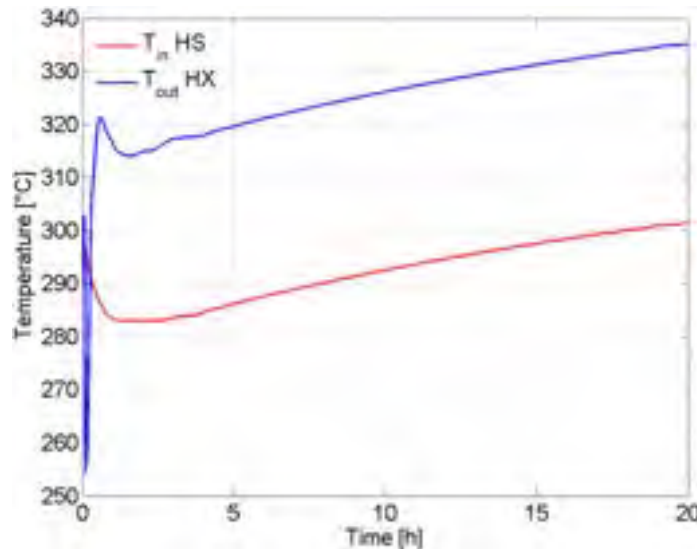
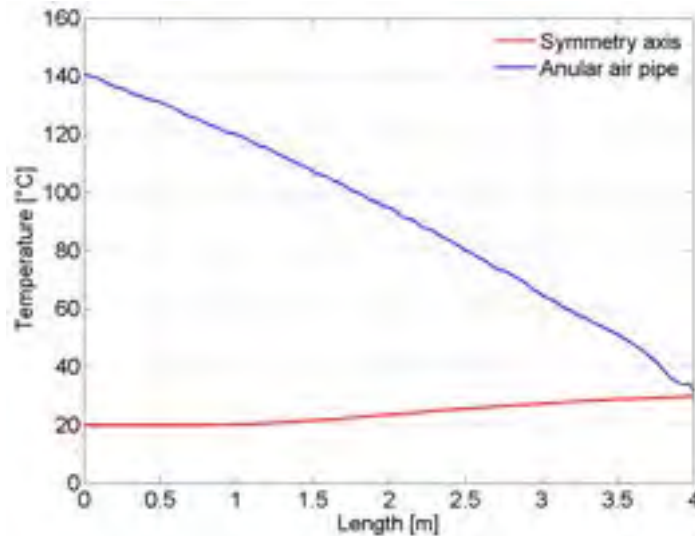
Obtained Results 1 of 2

Obtained
results
(2di 2)

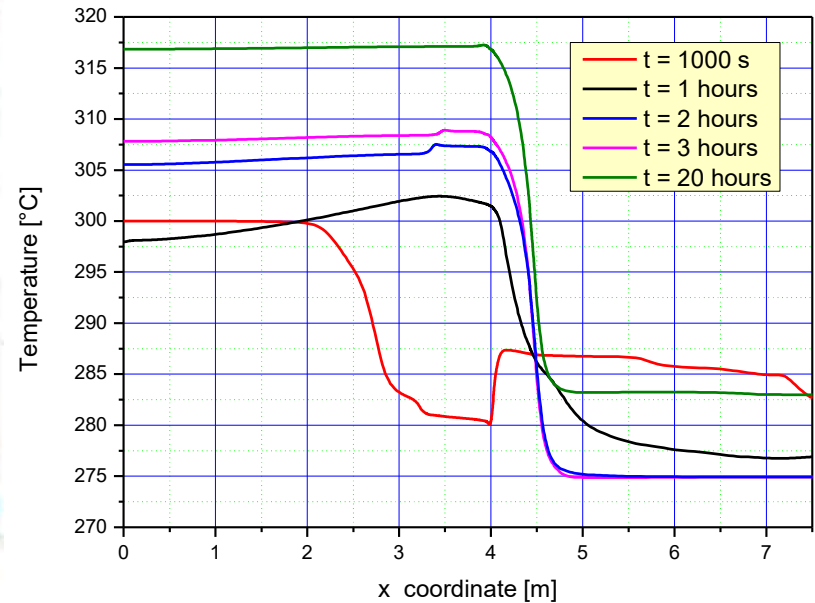
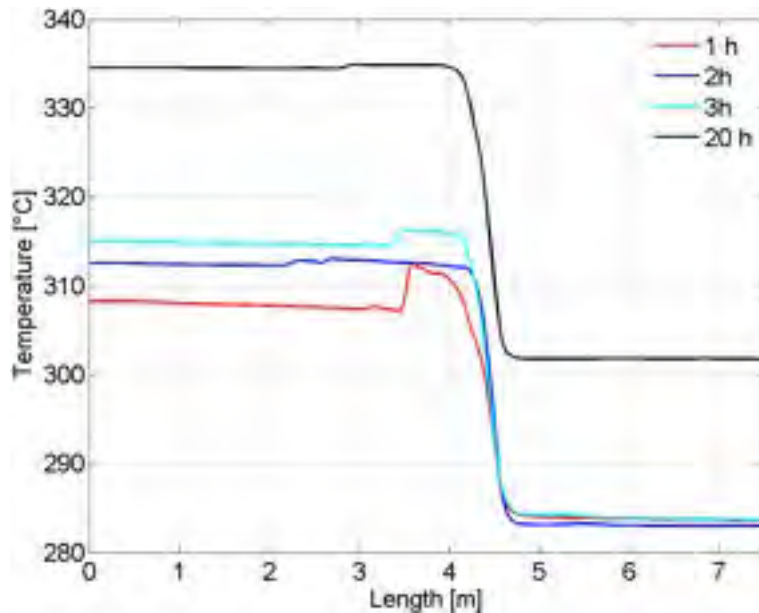


Obtained Results 2 of 2

Pool thermal
stratification

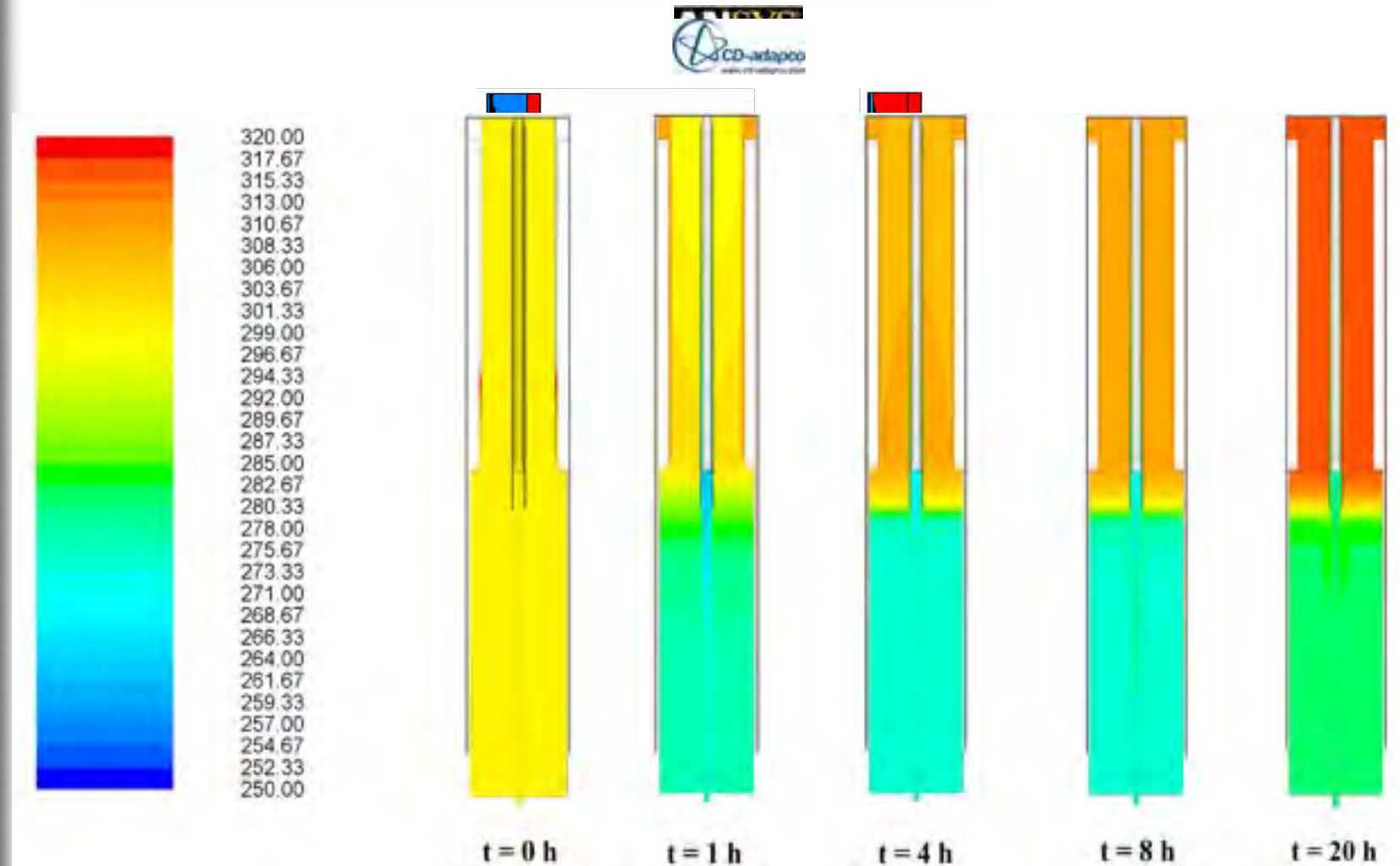


Pool Thermal Stratification 1 of 2



Pool Thermal Stratification 2 of 2

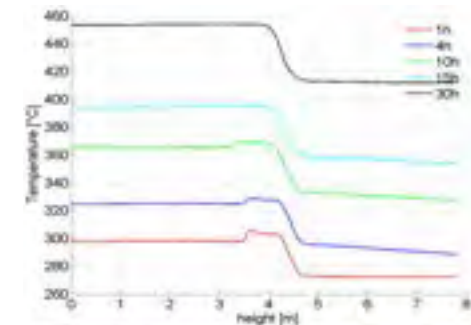
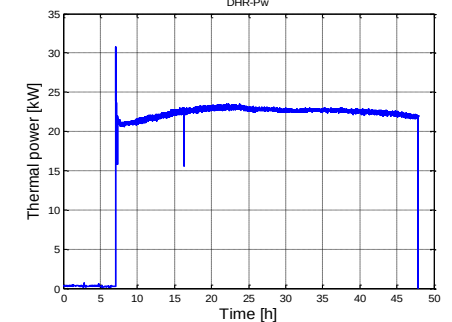
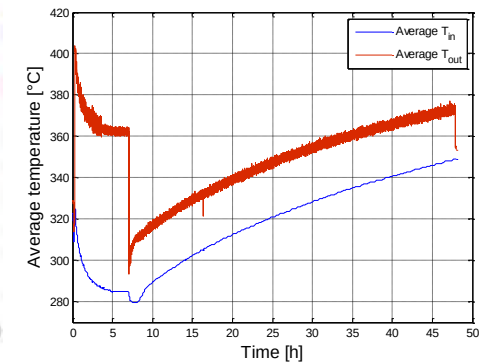
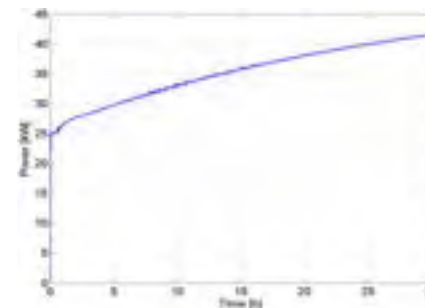
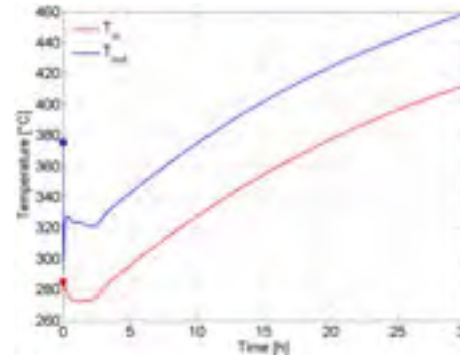
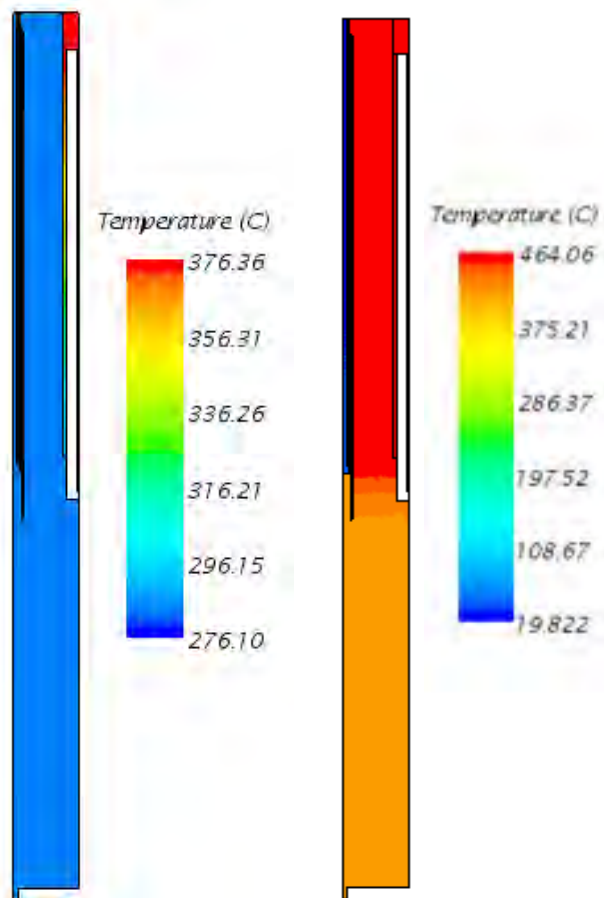
CIRCE
Post-test
simulation



CIRCE Post-test Simulation

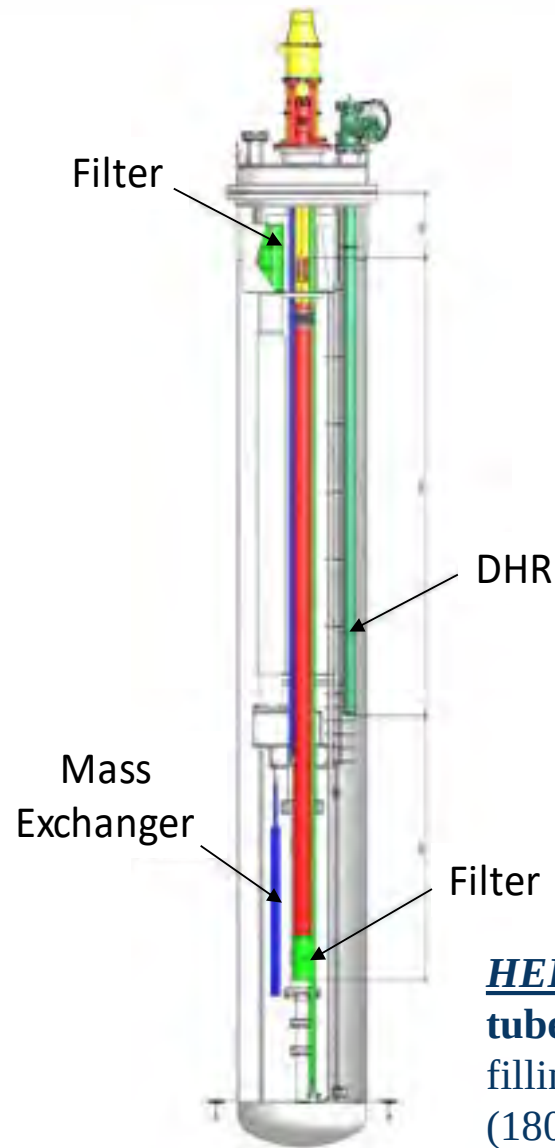
Post Test simulation performed with STAR CCM+ according to the PLOHS+LOF accident experimentally reproduced in CIRCE (TEST IV)¹

BC full power run: $M_{fr} \rightarrow 56 \text{ kg/s}$; $T \rightarrow 258^\circ\text{C}$; $Q \rightarrow 730 \text{ kW}$



¹ ADPFISS-LP2-027 "Circe Experimental Report" D. Martelli et al. 2013

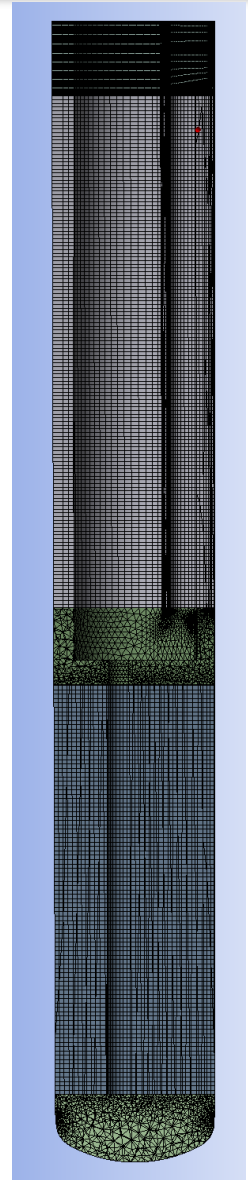
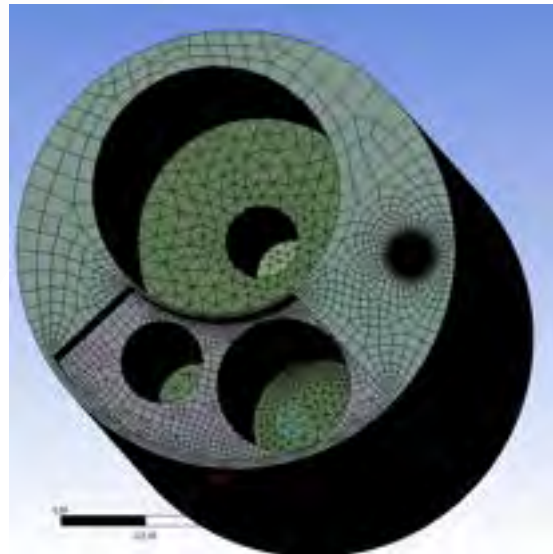
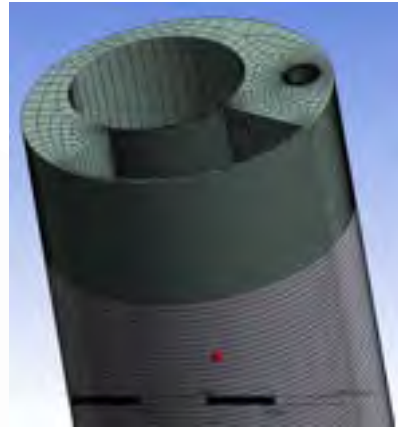
CIRCE-HERO Experimental facility



Filter

HERO-SGBT: seven double-walls bayonet tubes (with stainless steel powder filling the gap) fed by pressurized water (180 bar). It has a thermal duty of about **500 kW**

NEXT → CIRCE-HERO 3D model



Conclusions

- A simplified **2D CIRCE ICE-DHR numerical model** was **developed** adopting both Ansys Fluent & STAR-CCM+
- **RNG $k-e$** (FLUENT) & **$k-\omega$ SST** (STAR-CCM+) turbulent model were adopted
- External losses were **neglected**
- Boundary conditions of **LBE mass flow rate** passing through the FPS and the **thermal power removed by the HX** after the transition to natural circulation **obtained from a previous RELAP5 simulation**
- Numerical simulation highlighted that **long calculation time is required** to reach a steady state condition due to the high thermal inertia of the pool
- Comparison between **FLUENT & STAR-CCM+** shows a **good agreement**
- After 20 h the thermal stratification is foreseen with a **thermal gradient concentrated between the exit section of the DHR and of the HX**
- Both codes predict a temperature difference of **about 34 °C between the upper and lower plenum**
- A **three-dimensional** calculation model of the **CIRCE –HERO** is under development

Thank you for the attention

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ADP ENEA-MSE (PAR 2014-LP2)
C.R. ENEA Brasimone 19-20 Nov. 2015



PRE-TEST CFD ANALYSIS OF THE ROD BUNDLE EXPERIMENT IN THE HEAVY LIQUID METAL FACILITY NACIE-UP

Ranieri Marinari (UniPi / ENEA), Ivan Di Piazza (ENEA)



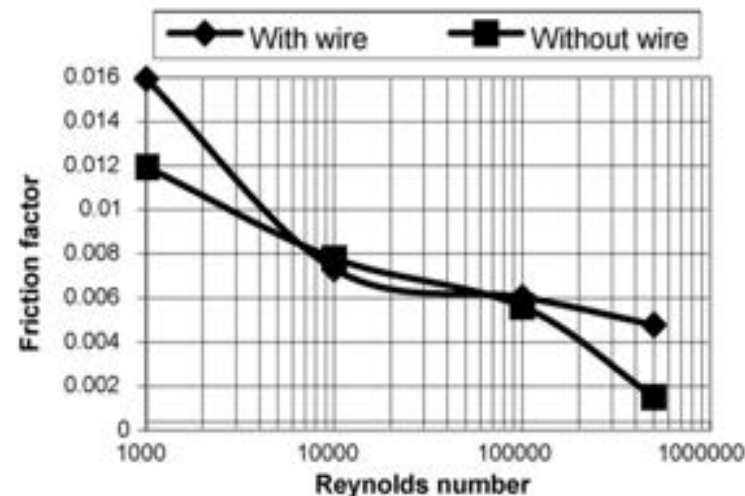
CONTENTS

- Introduction
- Literature review on HLM cooled wire-wrap bundles
- The NACIE-UP facility
- Code validation
- Development of the CFD model
- Sensitivity analysis
- Results
- Highlights for the experimental activity
- Conclusions

WIRE WRAPPED PINS VS. GRID SPACERS

Advantages :

- Easy to fabricate
- Less expensive
- Mechanical vibrations problems reduced
- Reactivity oscillations reduced
- Higher mixing of the coolant



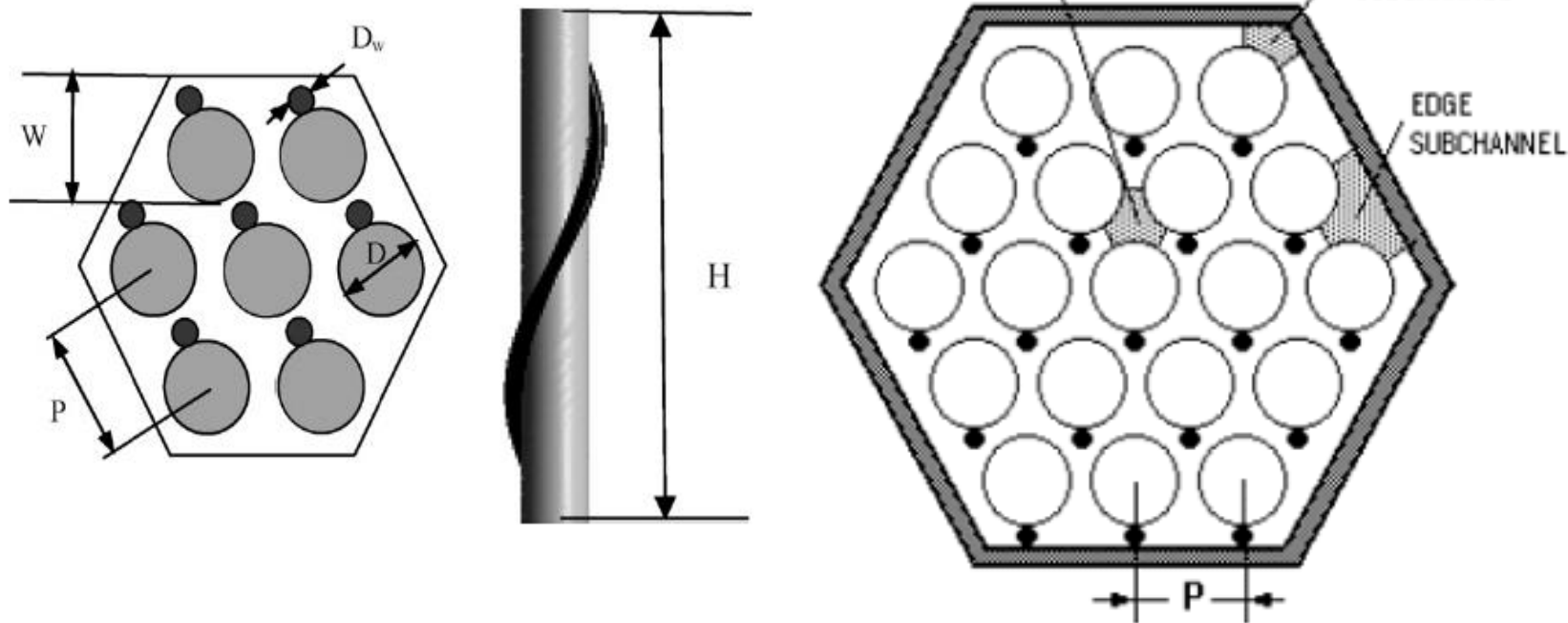
Disadvantages :

- Higher steel volume into the core
- Lower breeding ratio
- Higher pressure loss
- Complex geometrical features (subch)
- Complex velocity and temperature fields
- Lower 'computability', loss of symmetry

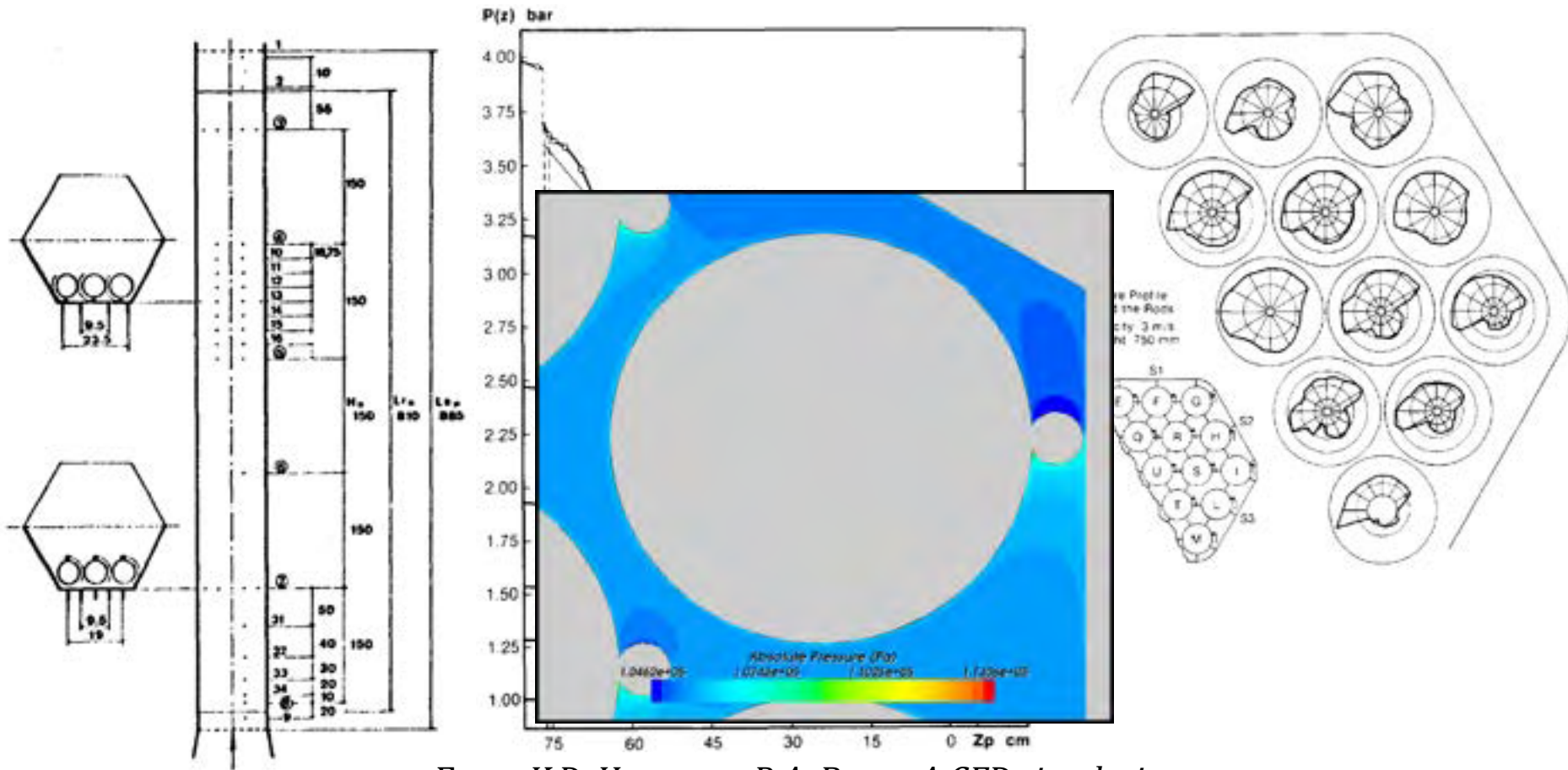




DEFINITIONS



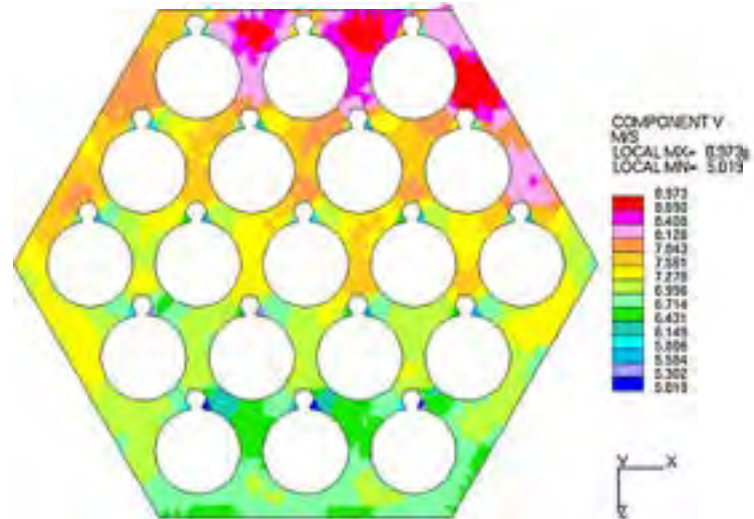
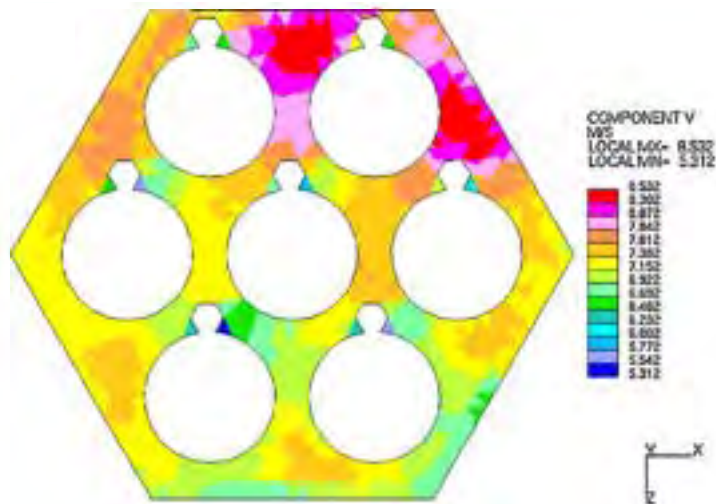
PRESSURE FIELD IN THE PIN BUNDLE



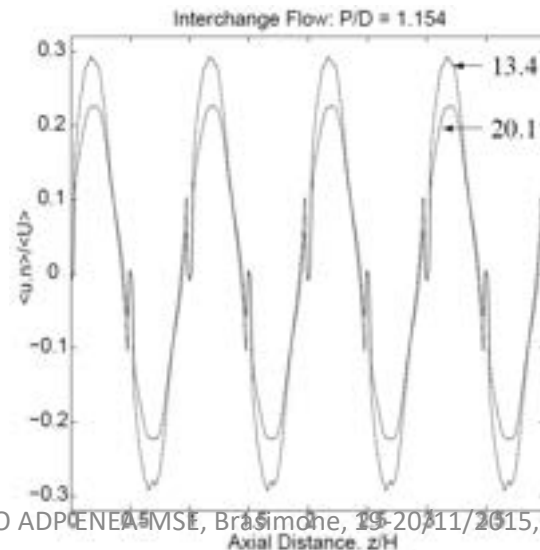
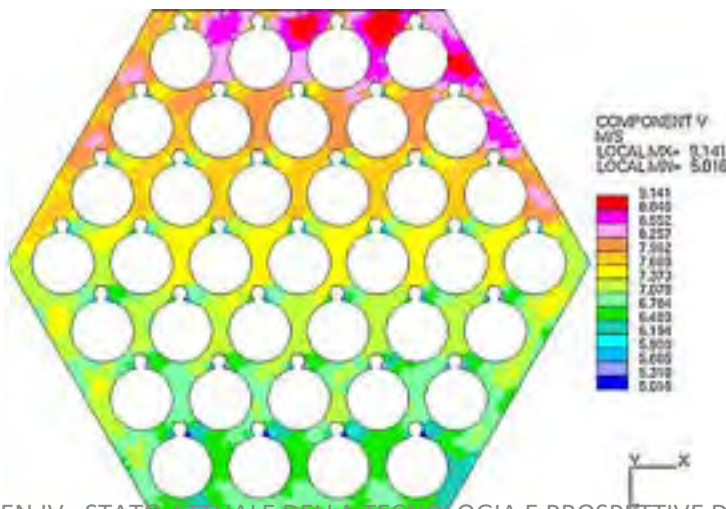
From: K. J. Henrich, ASME, Paper, 75 QFD-21 (1975) on
process for fast reactor fuel assemblies, NED, 2010.



VELOCITY FIELDS IN THE PIN BUNDLE

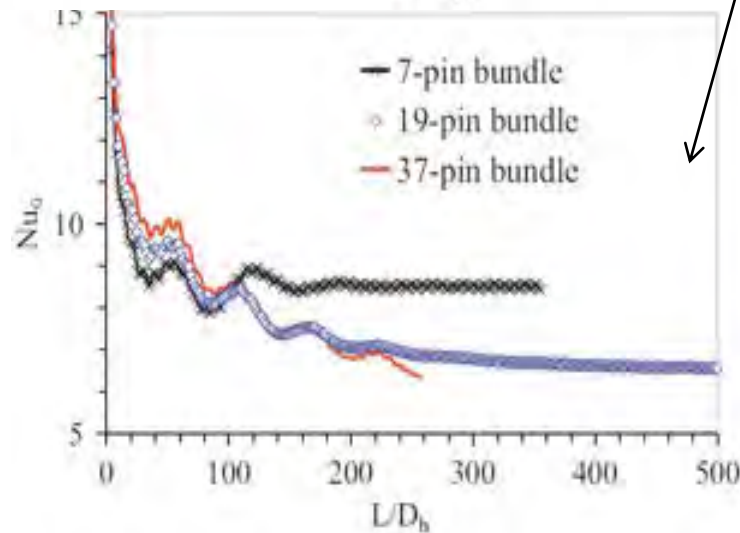
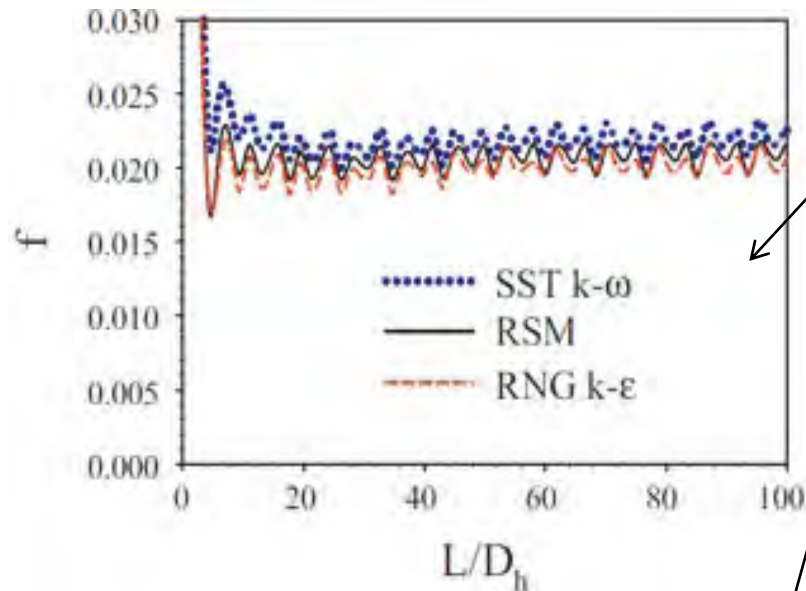


From: R. Gajapathy, K. Velusamy, *A comparative CFD investigation of helical wire-wrapped 7, 19 and 37 fuel pin bundles and its extendibility to 217 pin bundle*, NED, 2009.

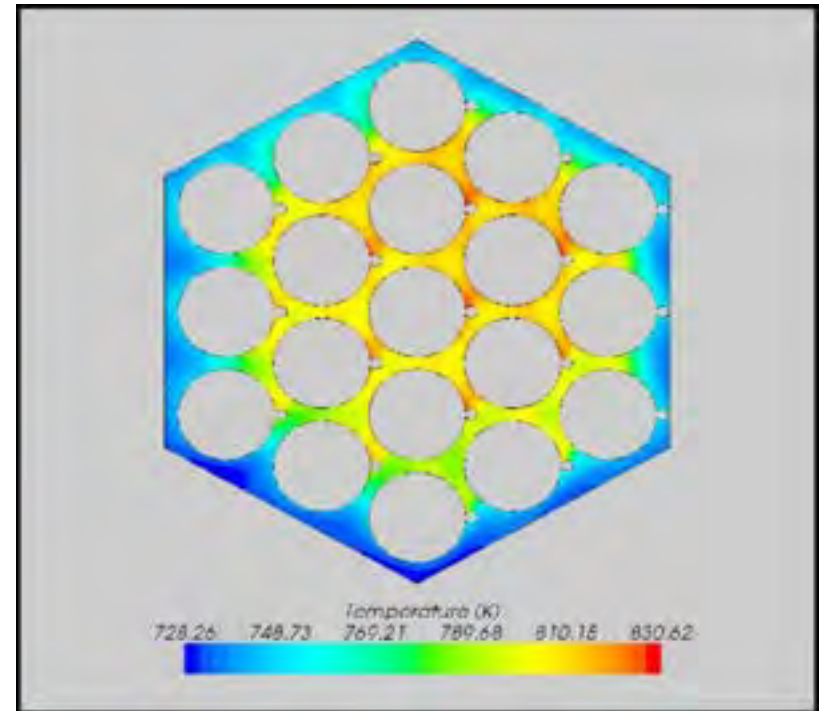




PRESSURE LOSS AND HEAT TRANSFER IN THE PIN BUNDLE



From
N.G. Rasu, K. Velusamy, Simultaneous development of flow and temperature fields in wire-wrapped fuel pin bundles of sodium cooled fast reactor, NED,2014.



From *K.D. Hamman, R.A. Berry, A CFD simulation process for fast reactor fuel assemblies, NED,2010.*

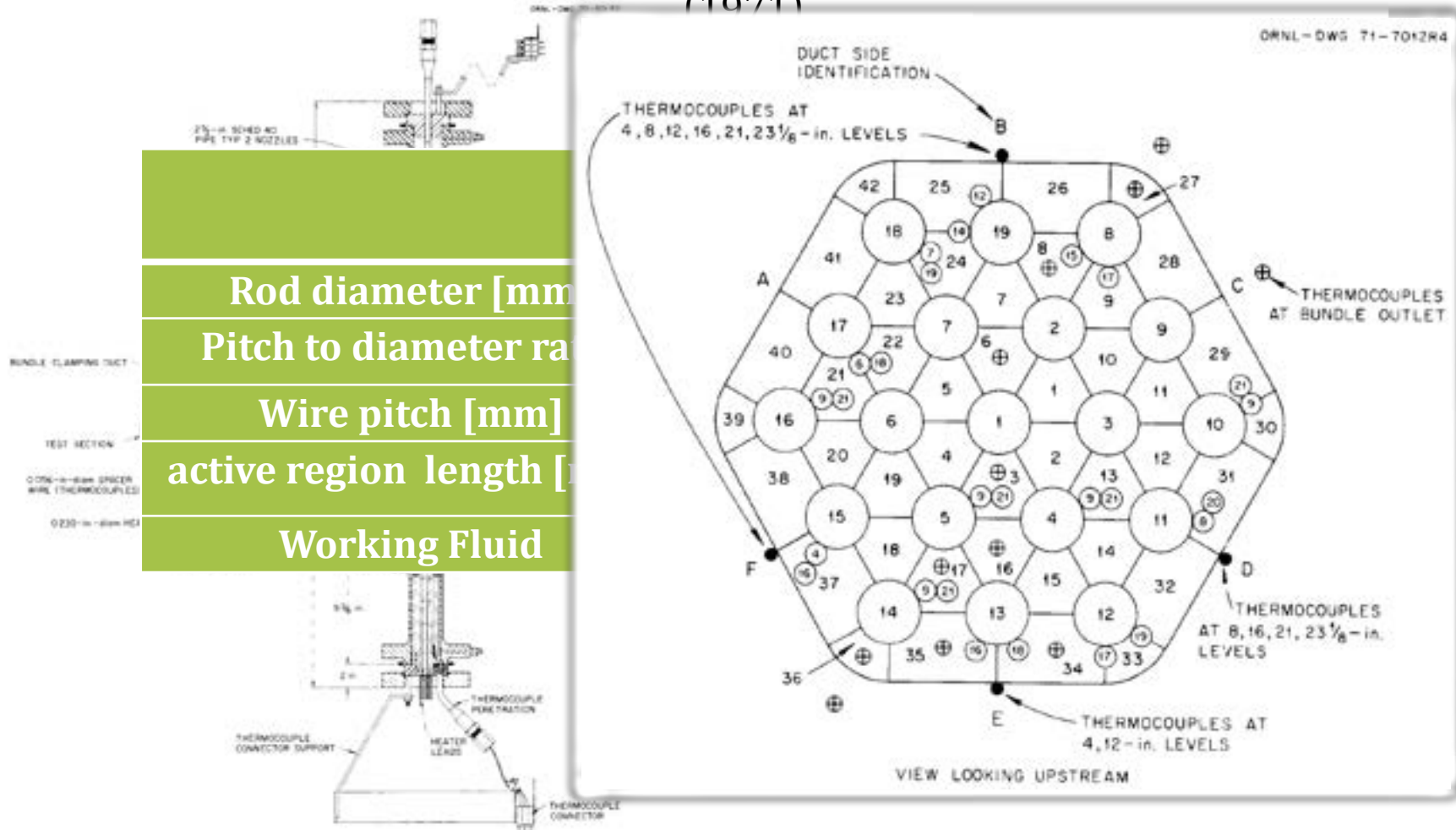




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CODE VALIDATION

Fuel Failure Mockup (FFM) , sodium test facility, Oak-Ridge National Laboratory
(1971)



From M.H. Fontana, *Temperature Distribution in the Duct Wall and at the Exit of a 19-Rod Simulated LMFBF Fuel Assembly (FFM-2A)*. ORNL-4852, Oak Ridge National



CODE VALIDATION: CFD MODEL AND TEST MATRIX

ANSYS
R15.0

Hex

Case number	G (gpm) [kg/s]	Bundle power [kW]	Cable power [kW]	Re [-]	T _{inlet} [K]
TEST4 - RUN102	2.03 [0.11]	12.67	3.8	1841	590
TEST4 - RUN105	4.97 [0.27]	31.13	5.95	8380	587
TEST4 - RUN202	2.12	22.15	0.65	1841	602.52
TEST4 - RUN205	5.13	58.61	0.44	8381	595.48
TEST6 - RUN103	30.36 [1.62]	117.14	0.67	50927	590.77
TEST6 - RUN103' (Finer mesh)	30.36 [1.62]	117.14	0.67	50927	590.77
TEST6 - RUN103'' (Second order turbulence model)	30.36 [1.62]	117.14	0.67	50927	590.77



100.00

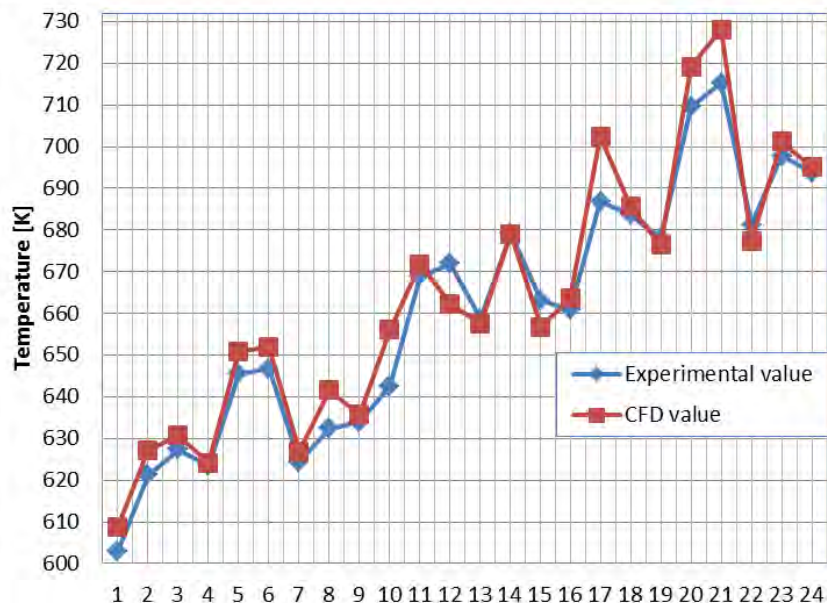
300.00



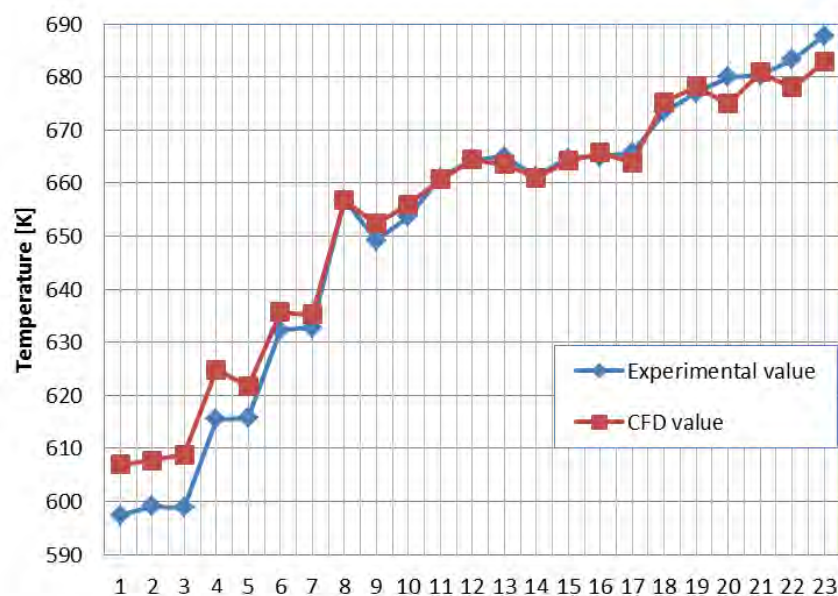
CODE VALIDATION : RESULTS

TEST4 - RUN105

Mass Flow Rate [gpm]	4.97 (0.27 kg/s)
Power [kW]	31.13
u_{sc} [m/s]	0.78
Re_{sc}	8380
Pe_{sc}	33.65



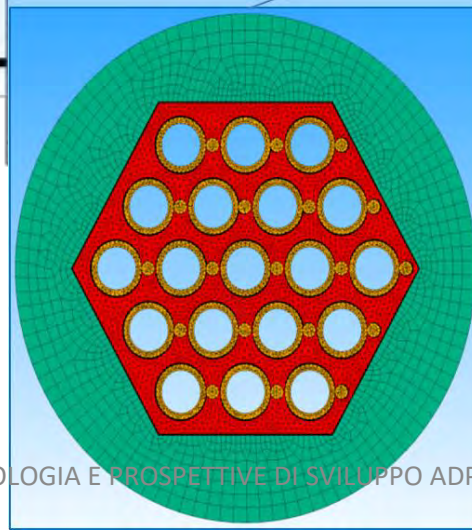
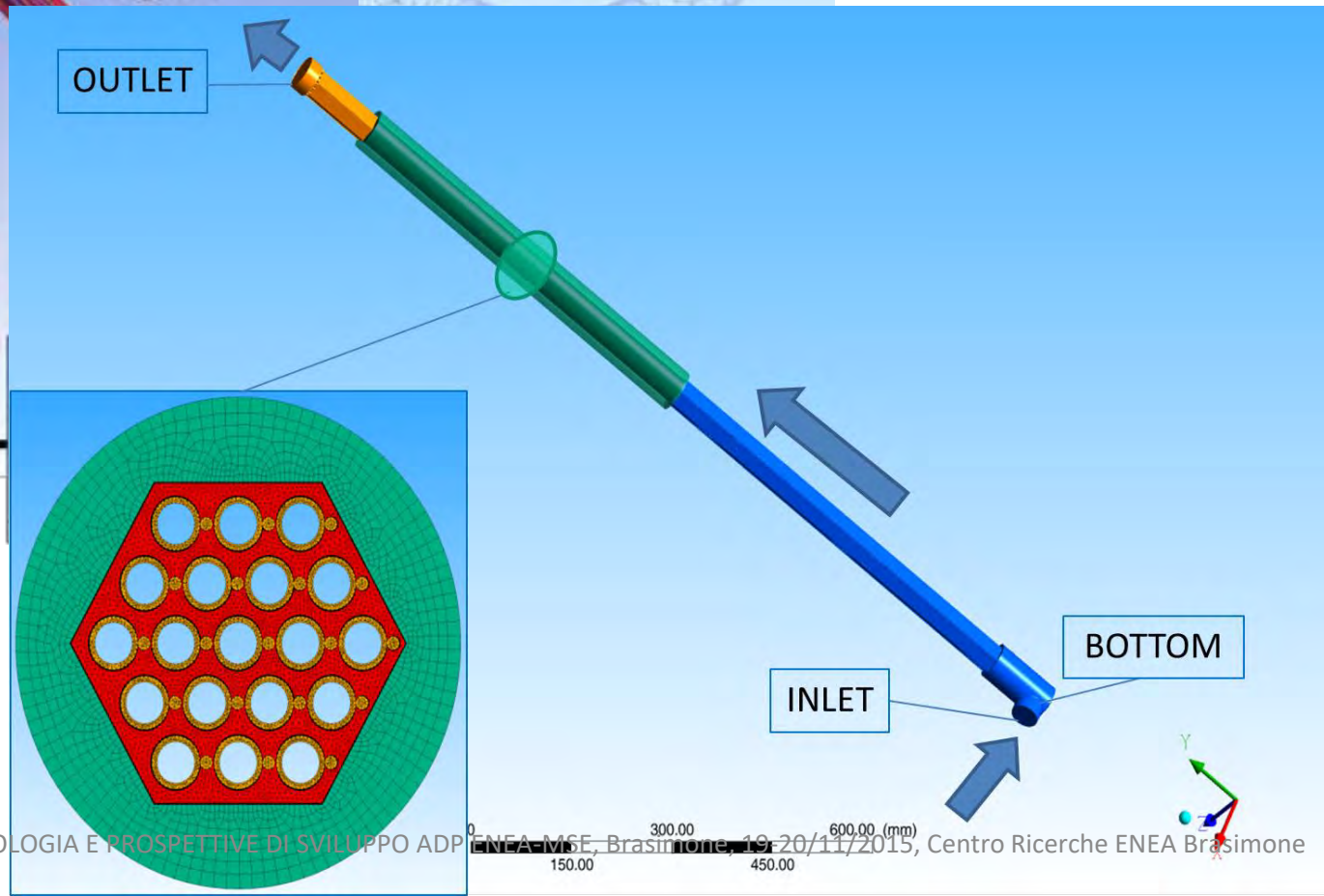
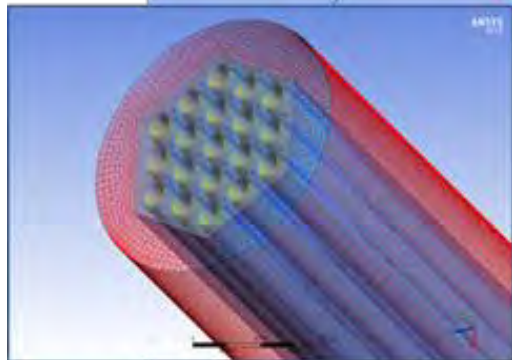
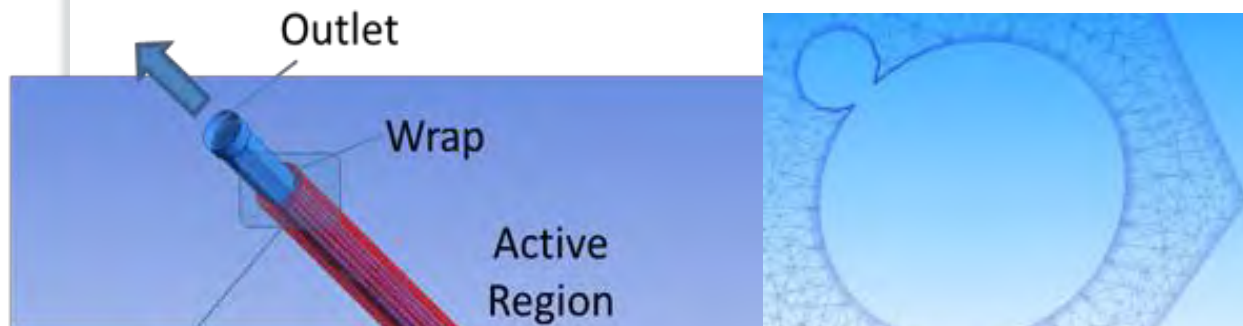
Pin temperatures



Duct wall
temperatures



NACIE-UP FPS: THE CFD MODEL



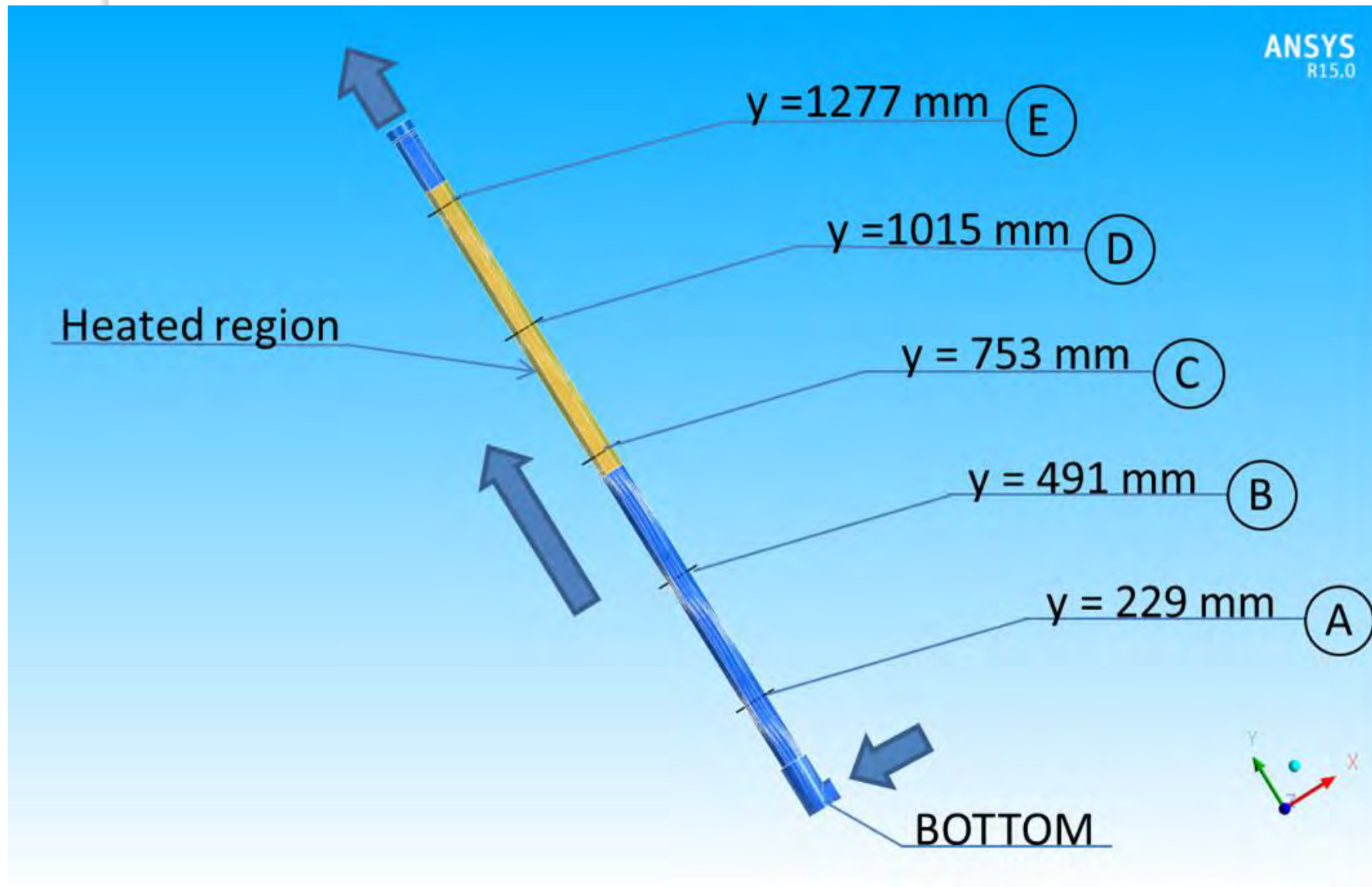


COMPUTATIONAL SETUP

Code	ANSYS CFX 15.0
Analysis method	RANS (Stationary)
Turbulence model	Standard SST k- ω (Menter)
	All y+ wall treatment
Numerical scheme for convective terms	High Resolution (second order)
Working fluid	Lead Bismuth Eutectic (LBE) (Constant Properties)
Inlet	473 K mfr (according to the test matrix)
Outlet	Zero pressure



SENSITIVITY ANALYSIS



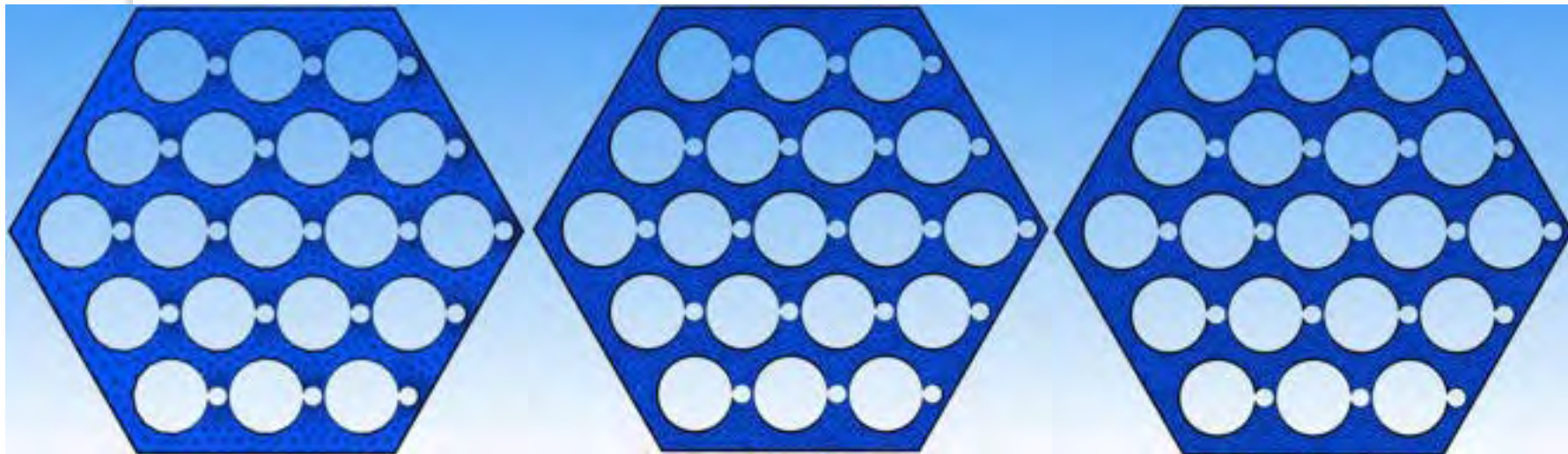


MESH INDEPENDENCE

Coarse mesh
($\sim 8.5 \cdot 10^6$ nodes)

Medium mesh
($\sim 22 \cdot 10^6$ nodes)

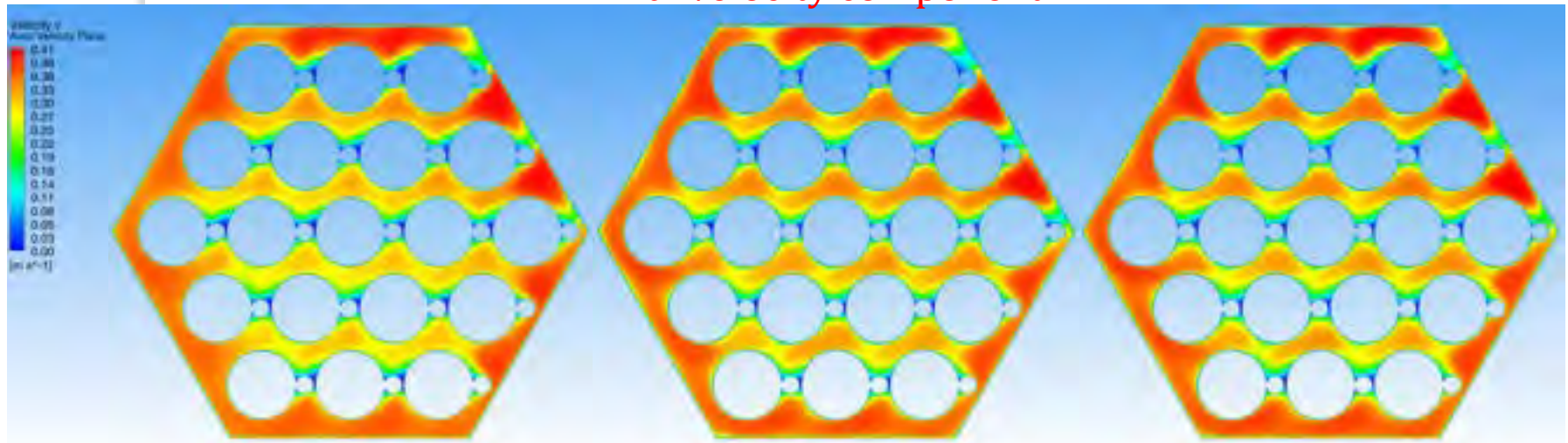
Fine mesh
($\sim 28.3 \cdot 10^6$ nodes)



G [kg/s]	u_{sc} [m/s]	Re_{sc} [-]	Thermal power [kW]
2.032	0.29	6162	32.52

MESH INDEPENDENCE: VELOCITY FIELD

Axial velocity component

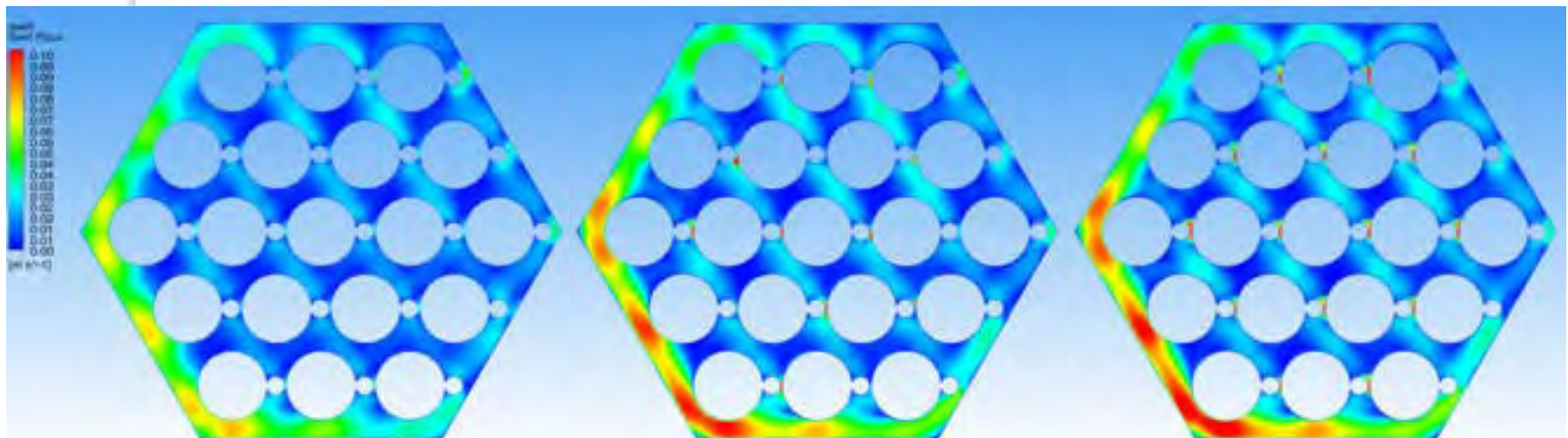


Coarse mesh

Medium mesh

Fine mesh

Swirl velocity component

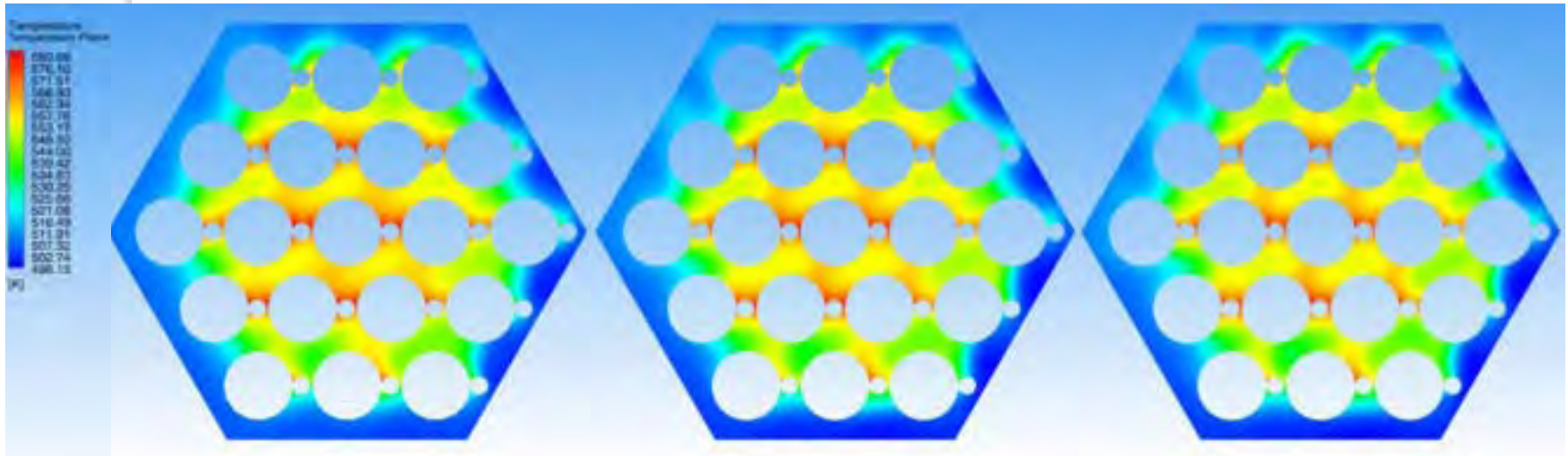


MESH INDEPENDENCE: TEMPERATURE FIELD

Coarse mesh
($\sim 8.5 \cdot 10^6$ nodes)

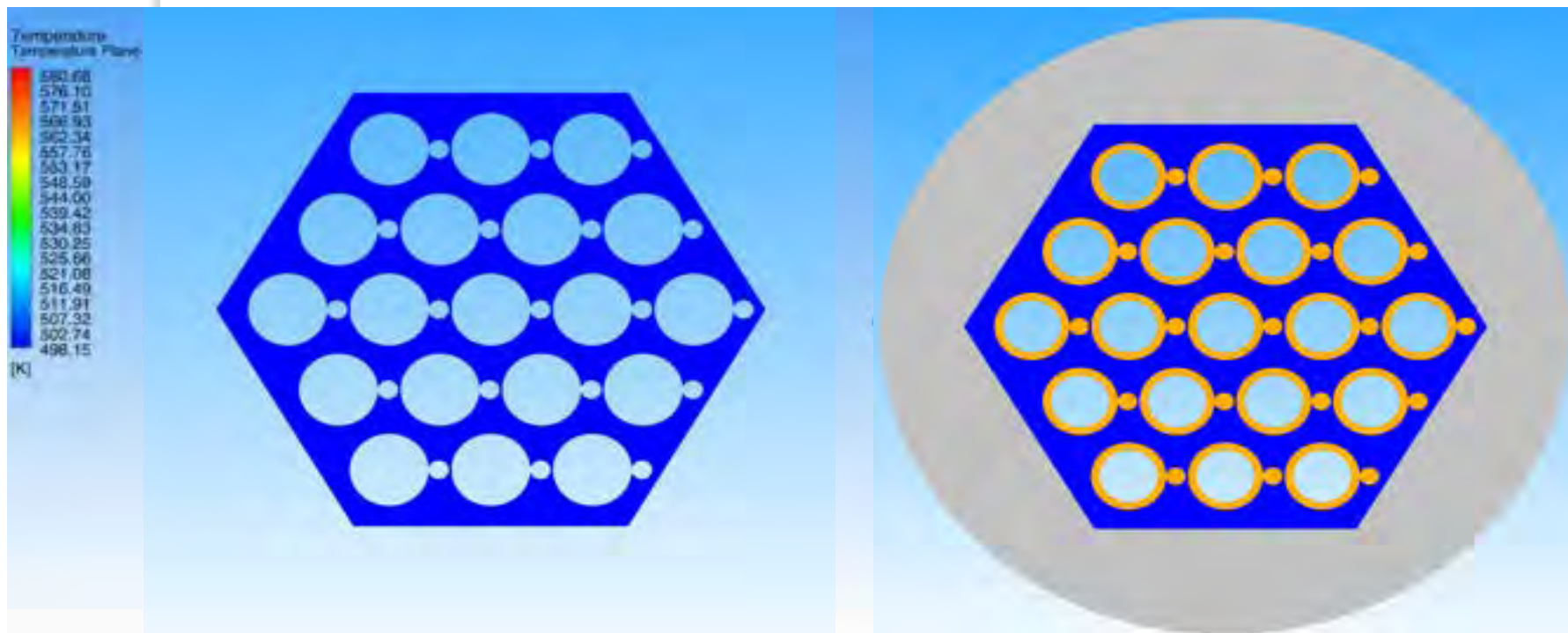
Medium mesh
($\sim 22 \cdot 10^6$ nodes)

Fine mesh
($\sim 28.3 \cdot 10^6$ nodes)



The medium size mesh has been chosen for the simulations

THE INFLUENCE OF THE SOLID STRUCTURES



CFD model (only fluid)

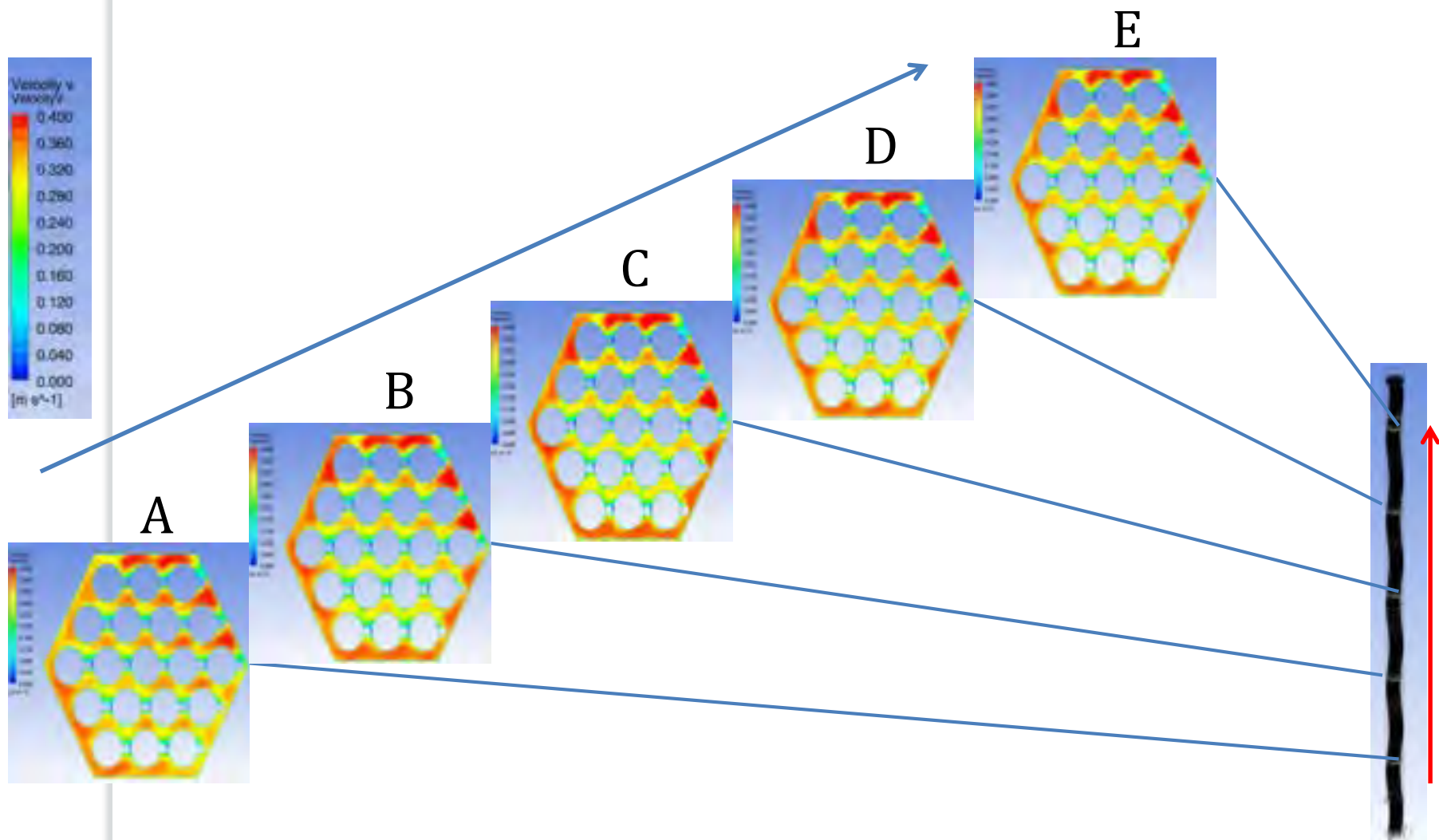
CFD model with solid structures

CFD TEST MATRIX ($\Delta T_{IO}=110$ K)

Preliminary model cases	Complete model cases	mfr [kg/s]	Q [kW]	Re _{sc}	Pe _{sc}
OF05	SS05	0.5	8.07	1516	41.0
OF10	SS10	1	16.14	3032	81.9
OF20	SS20	2.032	32.52	6162	166.5
OF30	SS30	3	48.42	9097	245.8
OF40	SS40	4	64.56	12130	327.7
OF50	SS50	5	80.70	15162	409.6
OF60	SS60	6	96.84	18195	491.5
OF70	SS70	7	112.97	21227	573.5

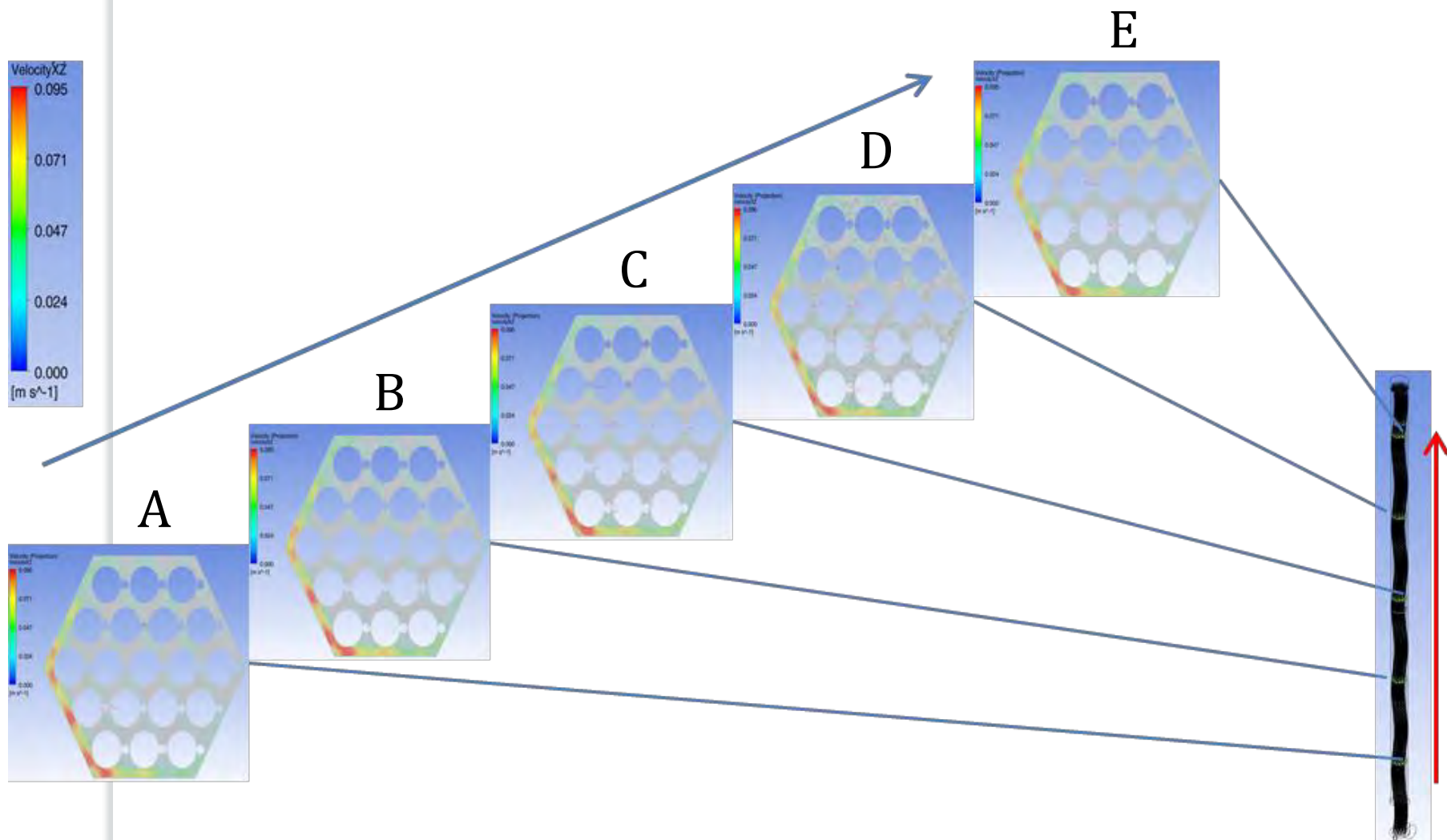


CASE SS20 : AXIAL VELOCITY DEVELOPMENT



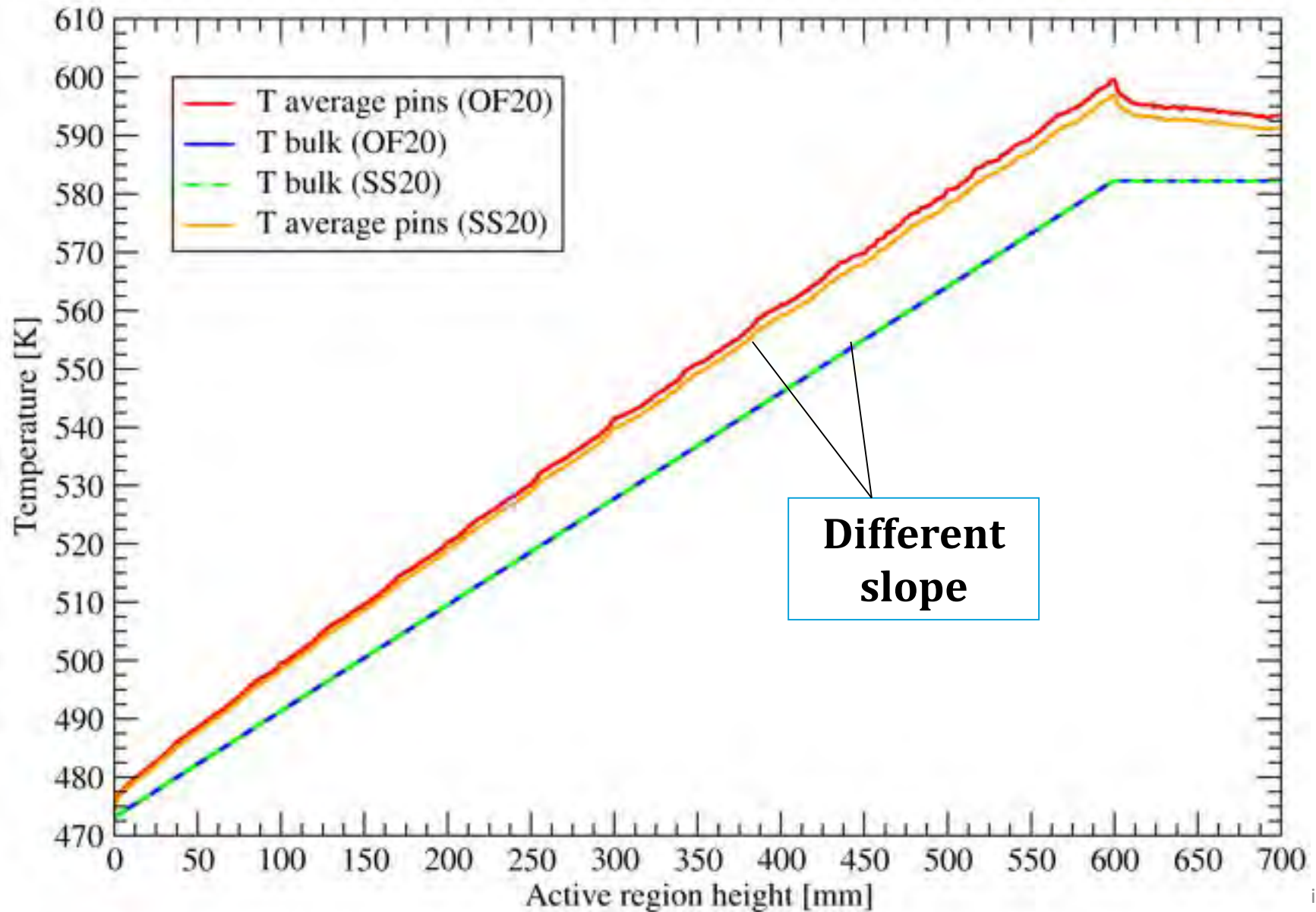


CASE SS20 : SWIRL VELOCITY DEVELOPMENT





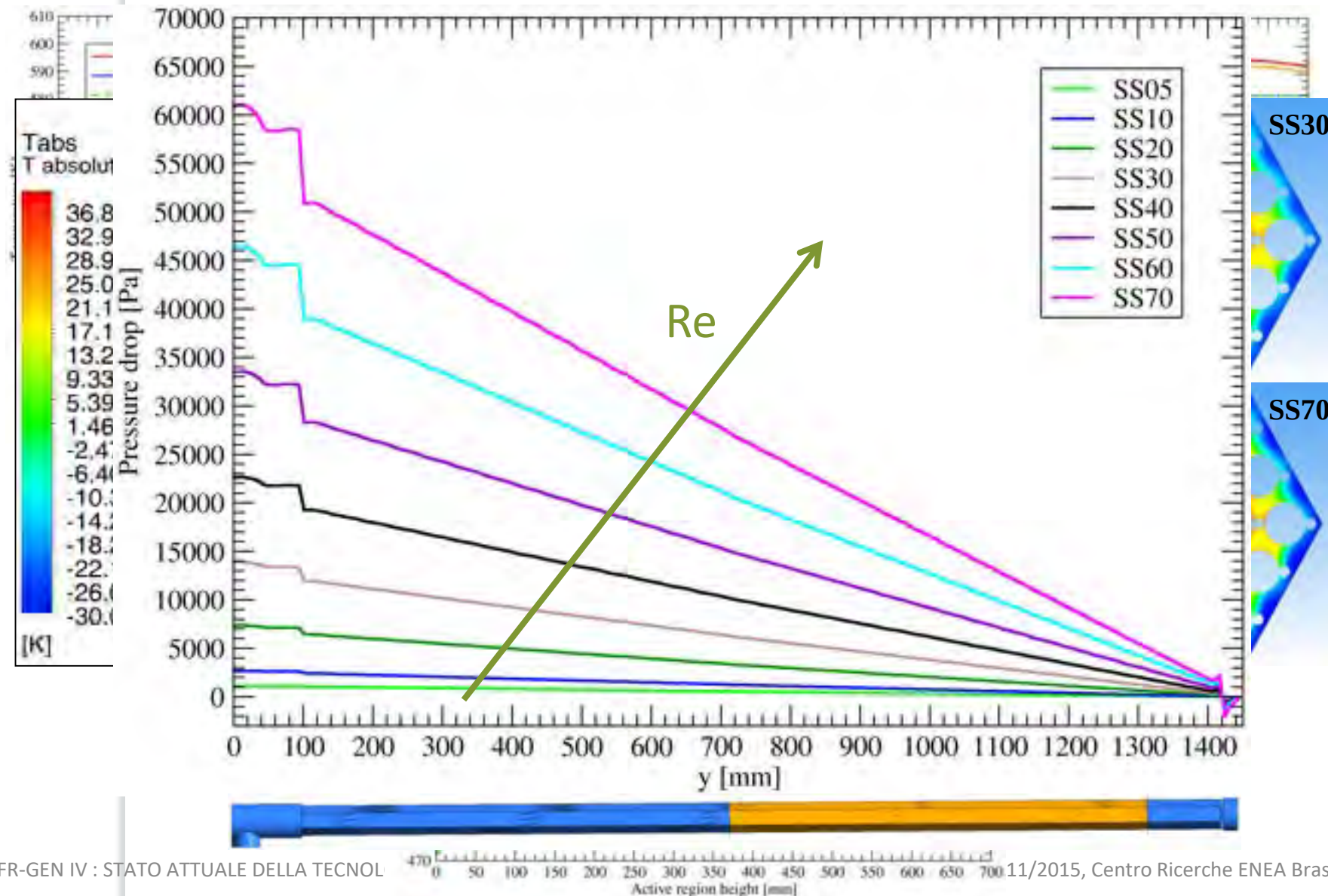
CASE OF20-SS20 : TEMPERATURE FIELD DEVELOPMENT



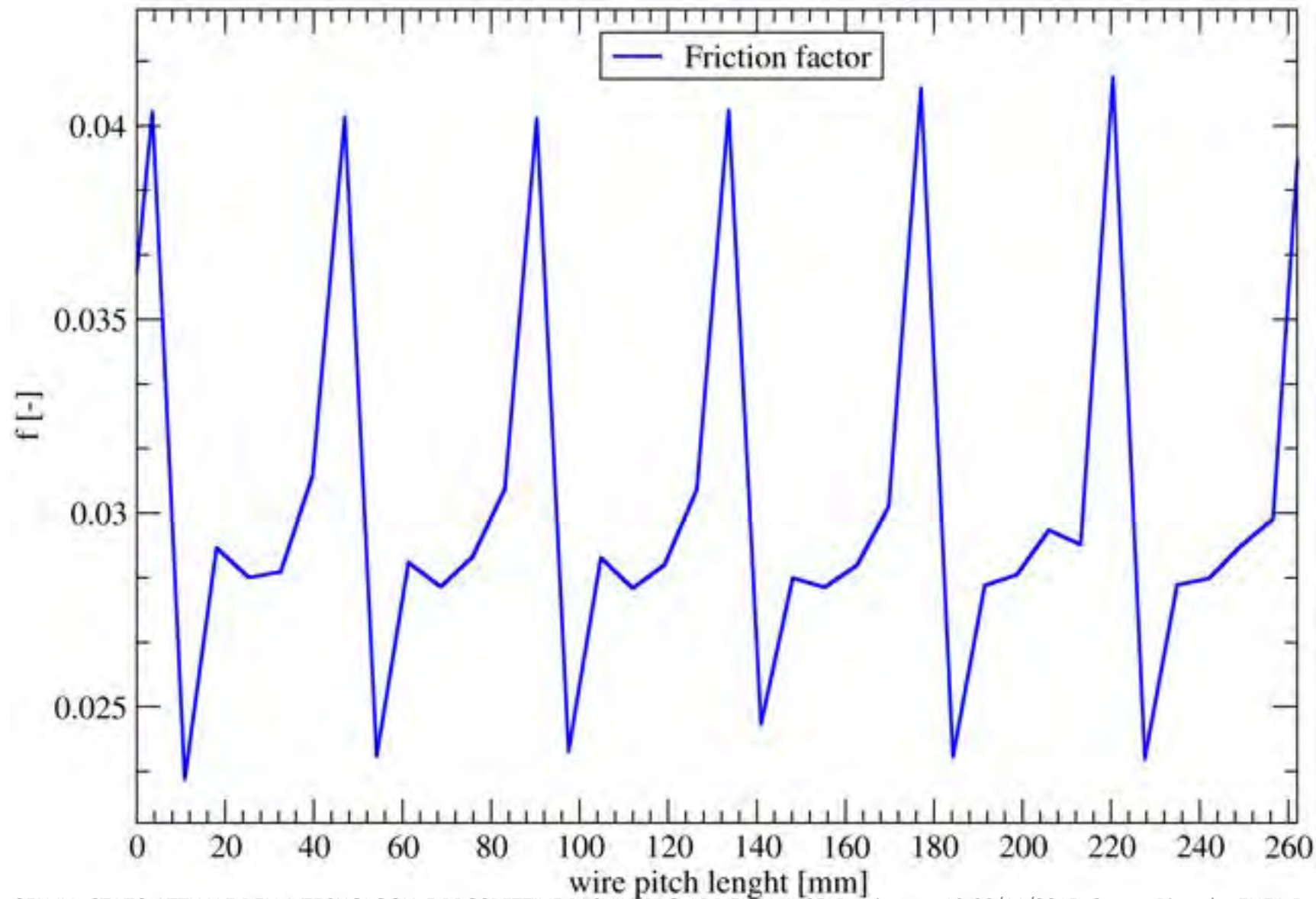


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INFLUENCE OF REYNOLDS NUMBER

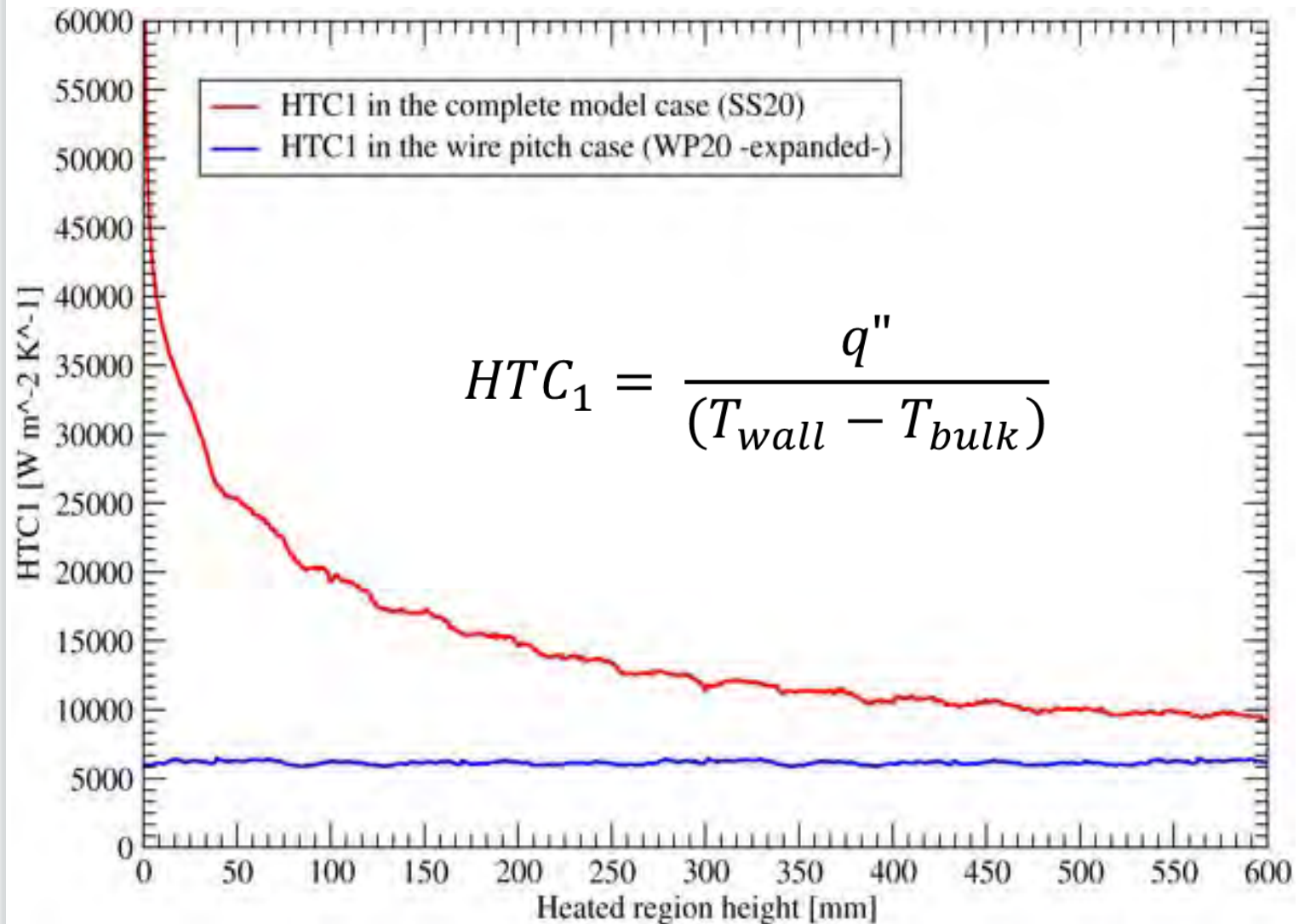


COMPARISON WITH CORRELATIONS: PRESSURE LOSSES IN THE ACTIVE REGION



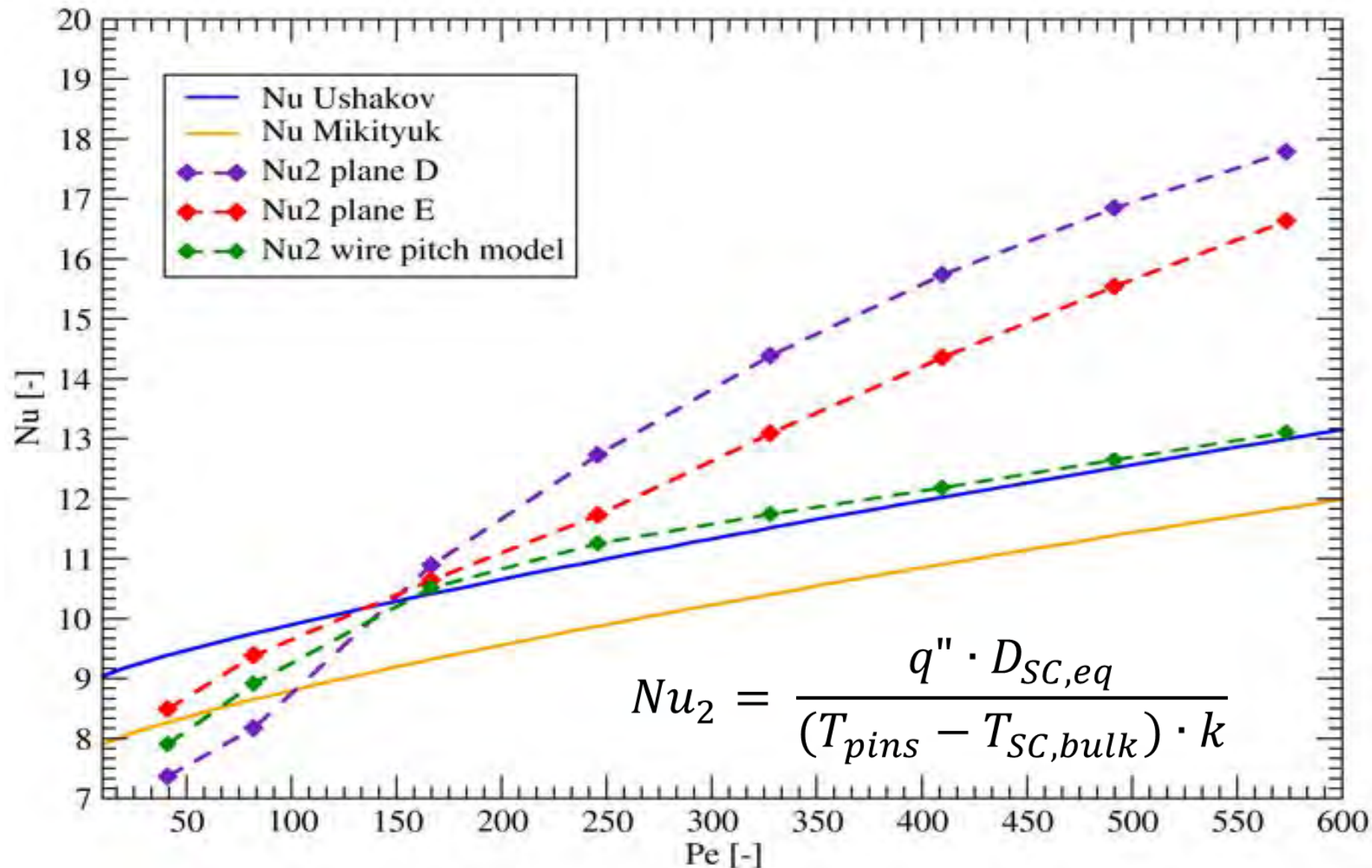


COMPARISON WITH THE CORRELATIONS: HEAT TRANSFER COEFFICIENT (HTC)





COMPARISON WITH CORRELATIONS: HTC “EXPERIMENTAL DEFINITION”



HIGHLIGHTS FOR THE EXPERIMENTAL ACTIVITY

The pre-test CFD analysis of the NACIE-UP FPS shows some interesting features of the experimental test section and provided **highlights** on the experimental test matrix itself.

In particular the following points can be stressed:

1. The considerable effect of the **conjugate heat transfer** on the LBE thermal field in particular for the lower mass flow rate cases: *hexagonal pipe* creates a thermal bridge between the hot and the cold region of the fluid;
2. The **small difference between the pin temperature and the sub-channel temperature** that can be attained in the inner sub-channels especially at the lower mass flow rates of the experimental range (as the 0.5 and 1.0 kg/s results) (HTC experimental impact);
3. The **thermal field does not reach a fully developed** and stable **condition** in the heated/instrumented region and this phenomenon was predicted by other authors.



NEW EXPERIMENTAL TEST MATRIX

TEST	mNACIE[kg/s]	mMYRRHAFA[kg/s]	usc[m/s]	Resc	Pesc	Nu Ushakov	Nu Mik	h[W/m ² K]	Q[W]	Q[kW]	DT IOBulk	DT_wallBulk	Tmaxclad[°C]	Regime	HX	TRANSITION	V142[°]
T101	1.37	7.9023717	0.203366	4.20E+03	113.541	10.00552033	8.914783	27351	1.08E+04	10.8	53.85	1.69	255.54	NAT CIRC	LOW	STATIONARY	X*
T102	1.08	6.201861334	0.159604	3.30E+03	89.108	9.80879592	8.713497	26813	1.08E+04	10.8	68.61	1.72	270.34	NAT CIRC	LOW	STATIONARY	X*
T103	0.83	4.801441033	0.123564	2.55E+03	68.987	9.638683124	8.537978	26348	1.08E+04	10.8	88.63	1.75	290.38	NAT CIRC	LOW	STATIONARY	X*
T104	0.66	3.801140818	0.097822	2.02E+03	54.614	9.511171137	8.405321	25999	1.08E+04	10.8	111.95	1.78	313.73	NAT CIRC	LOW	STATIONARY	X*
T105	0.50	2.900870624	0.074653	1.54E+03	41.679	9.390623258	8.278847	25670	1.08E+04	10.8	146.69	1.80	348.49	NAT CIRC	LOW	STATIONARY	X*
T106	0.40	2.300690495	0.059208	1.22E+03	33.056	9.306173402	8.18949	25439	1.08E+04	10.8	184.96	1.82	386.78	NAT CIRC	LOW	STATIONARY	X*
T107	1.75	10.10303217	0.26	5.37E+03	145.159	10.24819026	9.161047	28014	2.17E+04	21.7	84.32	3.30	287.62	NAT CIRC	LOW	STATIONARY	X*
T108	1.37	7.9023717	0.203366	4.20E+03	113.541	10.00552033	8.914783	27351	2.17E+04	21.7	107.80	3.38	311.18	NAT CIRC	LOW	STATIONARY	X*
T109	1.08	6.201861334	0.159604	3.30E+03	89.108	9.80879592	8.713497	26813	2.17E+04	21.7	137.36	3.45	340.81	NAT CIRC	LOW	STATIONARY	X*
T110	0.83	4.801441033	0.123564	2.55E+03	68.987	9.638683124	8.537978	26348	2.17E+04	21.7	177.42	3.51	380.93	NAT CIRC	LOW	STATIONARY	X*
T111	0.66	3.801140818	0.097822	2.02E+03	54.614	9.511171137	8.405321	25999	2.17E+04	21.7	224.11	3.56	427.67	NAT CIRC	LOW	STATIONARY	X*
T112	2.03	11.70351252	0.301188	6.22E+03	168.155	10.41809953	9.332352	28478	3.25E+04	32.5	109.01	4.86	313.88	GAS LIFT	LOW	STATIONARY	X*
T113	1.58	9.102731958	0.234257	4.84E+03	130.787	10.1393271	9.050822	27716	3.25E+04	32.5	140.16	5.00	345.16	NAT CIRC	LOW	STATIONARY	X*
T114	1.23	7.102131528	0.182772	3.78E+03	102.043	9.914104125	8.82145	27101	3.25E+04	32.5	179.64	5.11	384.75	NAT CIRC	LOW	STATIONARY	X*
T115	0.97	5.601681205	0.144158	2.98E+03	80.484	9.736927036	8.639527	26616	3.25E+04	32.5	227.76	5.21	432.96	NAT CIRC	LOW	STATIONARY	X*
T201	0.5	2.87985	0.074113	1.53E+03	41.377	9.38772769	8.275795	25662	2.17E+04	21.7	296.39	3.61	500.00	NAT CIRC	LOW	STATIONARY	X*
T202	0.75	4.319775	0.111169	2.30E+03	62.066	9.578010697	8.474987	26182	3.24E+04	32.4	294.72	5.28	500.00	NAT CIRC	LOW	STATIONARY	X*
T203	1	5.7597	0.148225	3.06E+03	82.755	9.755989672	8.659172	26668	4.30E+04	43.0	293.13	6.87	500.00	NAT CIRC	HIGH	STATIONARY	X*
T204	1.25	7.199625	0.185281	3.83E+03	103.444	9.925345542	8.832946	27131	5.35E+04	53.5	291.60	8.40	500.00	NAT CIRC	HIGH	STATIONARY	X*
T205	1.5	8.63955	0.222338	4.59E+03	124.132	10.08813226	8.998849	27576	6.39E+04	63.9	290.13	9.87	500.00	NAT CIRC	HIGH	STATIONARY	X*
T206	1.75	10.079475	0.259394	5.36E+03	144.821	10.24565164	9.158481	28007	7.41E+04	74.1	288.72	11.28	500.00	NAT CIRC	HIGH	STATIONARY	X*
T207	2	11.5194	0.29645	6.13E+03	165.510	10.39879793	9.312934	28426	8.43E+04	84.3	287.35	12.65	500.00	GAS LIFT	HIGH	STATIONARY	X*
T208	2.5	14.39925	0.370563	7.66E+03	206.887	10.69441181	9.609265	29234	1.04E+05	104.5	284.77	15.23	500.00	GAS LIFT	HIGH	STATIONARY	X*
T209	3	17.2791	0.444675	9.19E+03	248.265	10.97859911	9.892175	30010	1.24E+05	124.3	282.35	17.65	500.00	GAS LIFT	HIGH	STATIONARY	X*
T210	3.5	20.15895	0.518788	1.07E+04	289.642	11.25351216	10.16439	30762	1.44E+05	143.8	280.07	19.93	500.00	GAS LIFT	HIGH	STATIONARY	X*
T211	4	23.0388	0.5929	1.23E+04	331.019	11.52083192	10.42777	31493	1.63E+05	163.1	277.92	22.08	500.00	GAS LIFT	HIGH	STATIONARY	X*
T212	4.5	25.91865	0.667013	1.38E+04	372.397	11.78165227	10.68367	32206	1.82E+05	182.2	275.89	24.11	500.00	GAS LIFT	HIGH	STATIONARY	X*
T213	5	28.7985	0.741125	1.53E+04	413.774	12.03683153	10.9331	32903	2.01E+05	201.0	273.96	26.04	500.00	GAS LIFT	HIGH	STATIONARY	X*
T214	5.5	31.67835	0.815238	1.68E+04	455.152	12.28704034	11.17684	33587	2.20E+05	219.6	272.13	27.87	500.00	GAS LIFT	HIGH	STATIONARY	X*
T215	6	34.5582	0.88935	1.84E+04	496.529	12.53281602	11.41554	34259	2.35E+05	235.0	266.95	29.24	496.19	GAS LIFT	HIGH	STATIONARY	X*
T216	6.5	37.43805	0.963463	1.99E+04	537.907	12.774598	11.64969	34920	2.35E+05	235.0	246.41	28.69	475.10	GAS LIFT	HIGH	STATIONARY	X*
T217	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	STATIONARY	0
T301	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	PLOFA	0
	1.20	6.91164	0.17787	3.68E+03	99.306	9.892051612	8.798884	27040	1.18E+04	11.8	66.74	1.85	268.59	NAT CIRC	LOW		
T302	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	PLOFA	0
	1.70	9.79149	0.251983	5.21E+03	140.683	10.21452198	9.126999	27922	2.35E+04	23.5	94.22	3.59	297.80	NAT CIRC	LOW		
T303	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	PLOFA	0
	2.00	11.5194	0.29645	6.13E+03	165.510	10.39879793	9.312934	28426	3.53E+04	35.3	120.13	5.29	325.41	NAT CIRC	LOW		
T304	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	PLOFA	0
	2.40	13.82328	0.35574	7.35E+03	198.612	10.63629662	9.551181	29075	4.70E+04	47.0	133.47	6.89	340.37	NAT CIRC	HIGH		
T305	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	PLOFA	0
	2.60	14.97522	0.385385	7.96E+03	215.163	10.75207223	9.666817	29391	5.88E+04	58.8	154.01	8.52	362.53	NAT CIRC	HIGH		
T306	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	PLOFA	0
	2.70	15.55119	0.400208	8.27E+03	223.438	10.80929873	9.723861	29548	7.05E+04	70.5	177.97	10.17	388.14	NAT CIRC	HIGH		
T401	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	1.00E+05	100.0	97.37	11.98	309.35	GAS LIFT	HIGH	STATIONARY	0,10,20,30,40
T402	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	FBLOCKAGE	0
	2.60	14.97522	0.385385	7.96E+03	215.163	10.75207223	9.666817	29391	5.88E+04	58.8	154.01	8.52	362.53	GAS LIFT	HIGH		X*(da T401)
T403	7	40.3179	1.037575	2.14E+04	579.284	13.01275178	11.87974	35571	2.35E+05	235.0	228.81	28.16	456.98	GAS LIFT	HIGH	FBLOCKAGE	0
	4.00	23.0388	0.5929	1.23E+04	331.019	11.52083192	10.42777	31493	5.88E+04	58.8	100.11	7.95	308.06	GAS LIFT	HIGH		X*(da T401)

CONCLUSIONS

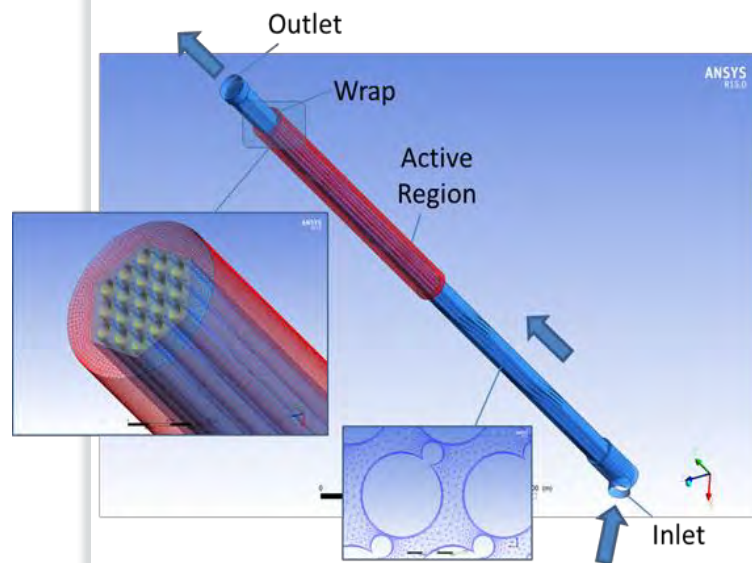
- ✓ A CFD pre-test analysis was carried out on the NACIE-UP fuel pin bundle simulator (FPS) placed at the ENEA Brasimone Research Centre. The FPS has 19-pins, it is wire-wrapped and it is cooled with liquid Lead Bismuth Eutectic (LBE) and the study is in the context of GEN.-IV nuclear reactors research.
- ✓ **An experimental campaign will be carried out in 2014** on the bundle coolability in the context of the SEARCH FP7 EU project to support the MYRRHA design. The thesis documents the code assessment for the wire wrap bundle geometry, the CFD model developed to describe the experimental test section, the sensitivity analysis developed on the model, model validations and pre-test results.
- ✓ The whole FPS test section was modelled including the inlet region, the entry region, the active region, the outlet region with the upper grid, and the hexagonal wrap. The total number of nodes and elements in the model was $3.5 \cdot 10^7$ and $9.7 \cdot 10^7$ respectively, with wall resolution $y^+ = 1 - 4$ in the range of interest. Stationary RANS computations were performed for the whole experimental range with mass flow rates from 0.5 to 7 kg/s and with a corresponding Reynolds number from $1.5 \cdot 10^3$ to $2.1 \cdot 10^4$.
- ✓ **A CFD code validation was carried out** on experimental data by ORNL in a similar geometry cooled by sodium. Results showed a global coherence of the results and a correct description of the conjugate heat transfer effects. **A good agreement was found** between numerical and experimental data, although the RANS approach showed some limitations for the central sub-channel temperature distributions at high mass flow rates.
- ✓ The **velocity field** in the wire-wrapped assembly of NACIE-UP shows **complex features** and **a strong secondary fluid flow** due to the swirl. Results show that the **hydrodynamic field is fully developed well before the beginning of the active region** after one wire pitch about. Nevertheless, **the thermal field is not fully developed in the active region** and the slopes of the wall and bulk temperatures are different.
- ✓ A **good agreement** was obtained by comparing CFD results with **existing pressure drop correlations** Chen & Todreas .
- ✓ Regarding the **conjugate heat transfer effect**, from numerical simulations it is clear that the conduction in the wrap pipe structure and in the wire is **very important** to correctly capture the temperature gradients, the local temperature maxima close to the wire and temperature minima in the edge sub-channels, especially for the lower Reynolds number cases.
- ✓ Several **highlights for the experimental activity** emerged by the pre-test CFD analysis. In particular, the fuel bundle **power should be increased** as much as possible **in the low mass flow rate range** to improve the accuracy on the heat transfer coefficient measurement. Moreover, the numerical evidence of the not fully developed thermal field in the bundle, implies that experimental results must be released with details on the experimental test facility and boundary conditions.
- ✓ The **developed CFD model will be used for pre and post test analysis of PLOFA and foot flow blockage experiments.**



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PRE-TEST CFD ANALYSIS OF THE ROD BUNDLE EXPERIMENT IN THE HEAVY LIQUID METAL FACILITY NACIE-UP

Thanks you for your attention





Pre-Test Analysis of SGTR Event on Large Scale Experimental facility by SIMMER-IV code

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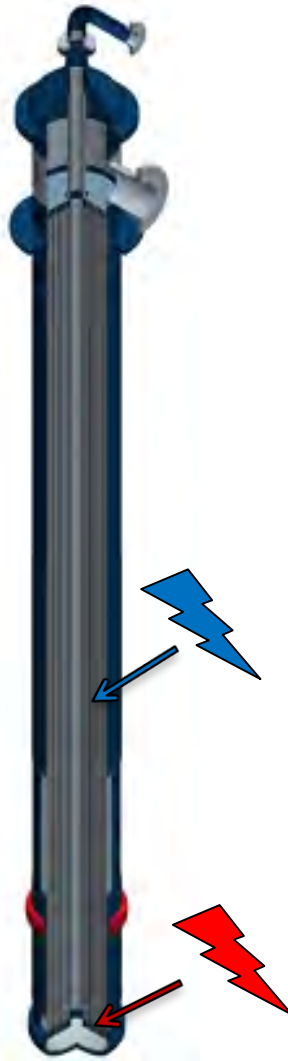
- ❑ Introductory remarks
- ❑ MYRRHA-PHX
- ❑ CIRCE facility (ENEA Brasimone CR)
- ❑ Preliminary pre-test analysis by SIMMER-III (2D) code
- ❑ Test Section design, components and instrumentation
- ❑ Detailed pre-test analysis by SIMMER-IV (3D) code
- ❑ Test Section assembly
- ❑ Conclusive remarks and future work

Introductory remarks

- ❑ The **SGTR scenario** needs to be analysed in the integrated **pool type HLMFR** configuration, aiming to predict the hazardous **consequences** of the SG/PHX tube rupture taking place in the HLM pool (pressure wave propagation and cover gas pressurization, domino effect, steam dragged into the core, primary system pollution and slug formation)
- ❑ The **SGTR** event will be experimentally investigated on the large scale **CIRCE** facility, implementing a test section oriented to simulate a **portion of full scale SG tube bundle** of MYRRHA reactor
- ❑ The **design** of the test section, the **instrumentation** foreseen to be implemented, the preliminary **numerical study** performed by **SIMMER-III** (2D), the **pre-test** analysis by **SIMMER-IV** (3D) codes and the **test section assembly** are presented

MYRRHA-PHX

- ❑ In the CIRCE facility a portion of the full scale bundle of the MYRRHA PHX will be host, with LBE inlet and outlet regions
- ❑ Two rupture positions will be experimentally investigated: **Middle** and **Bottom** positions
- ❑ The main parameters of the MYRRHA PHX are listed in the table



Parameter	Unit	Value
Power of one HX	MW	27.5
Shroud external diameter	mm	~850
Shroud internal diameter	mm	~800
Feed water pipe external diameter	mm	~200
Number of water tubes	-	684
Pitch of water tubes	mm	26
External diameter of water tubes	mm	16
Internal diameter of water tubes	mm	14
Thickness of water tubes	mm	1
Length of water tubes	mm	~8500
HX LBE inlet temperature	° C	350
HX LBE outlet temperature	° C	270
HX LBE mass flow rate	Kg/s	~2500
HX water inlet temperature	° C	200
HX water outlet temperature	° C	201.6
HX water mass flow rate	Kg/s	~47
HX water pressure	bar	16

CIRCE facility (ENEA Brasimone CR)

Main Vessel S100

→ Outside Diameter
1200 mm

→ Wall Thickness
15 mm

→ Material

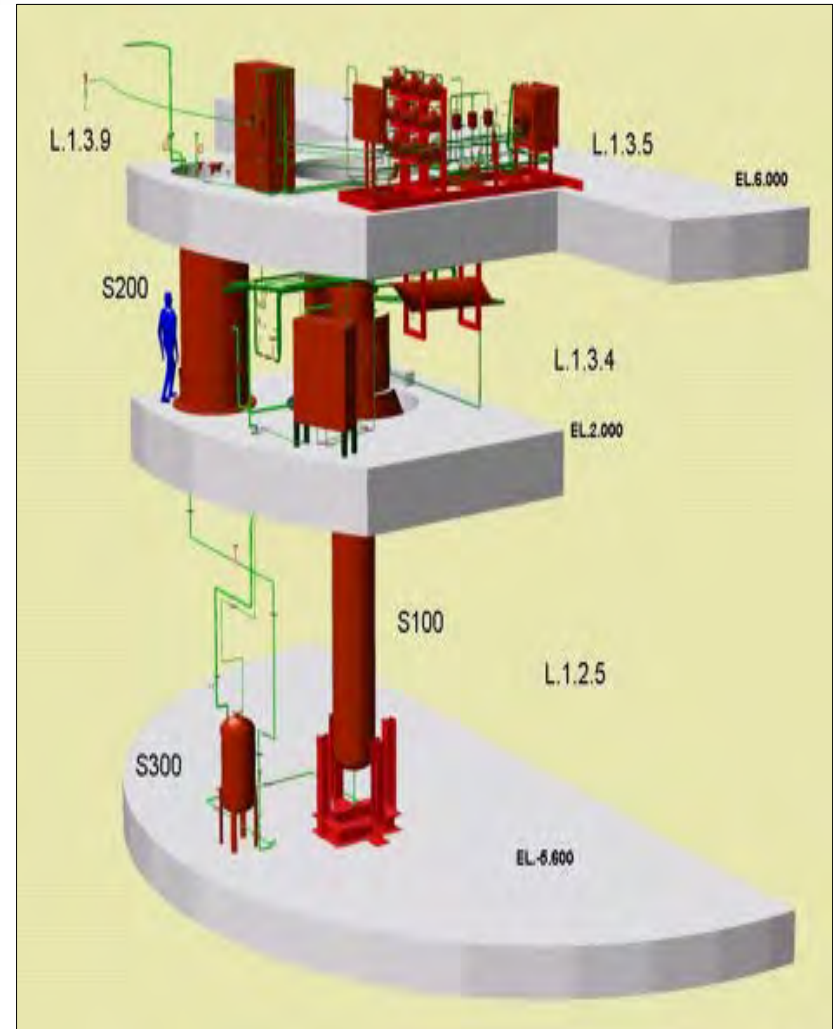
AISI 316L

→ LBE Inventory (max)
90 tons

→ Height
8-10 m

→ **Design Pressure**
16 bar

→ Design Temperature
450°C

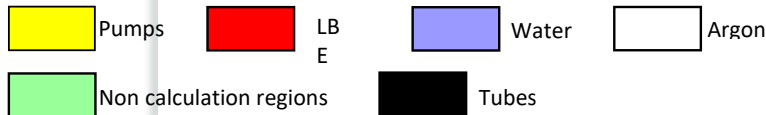
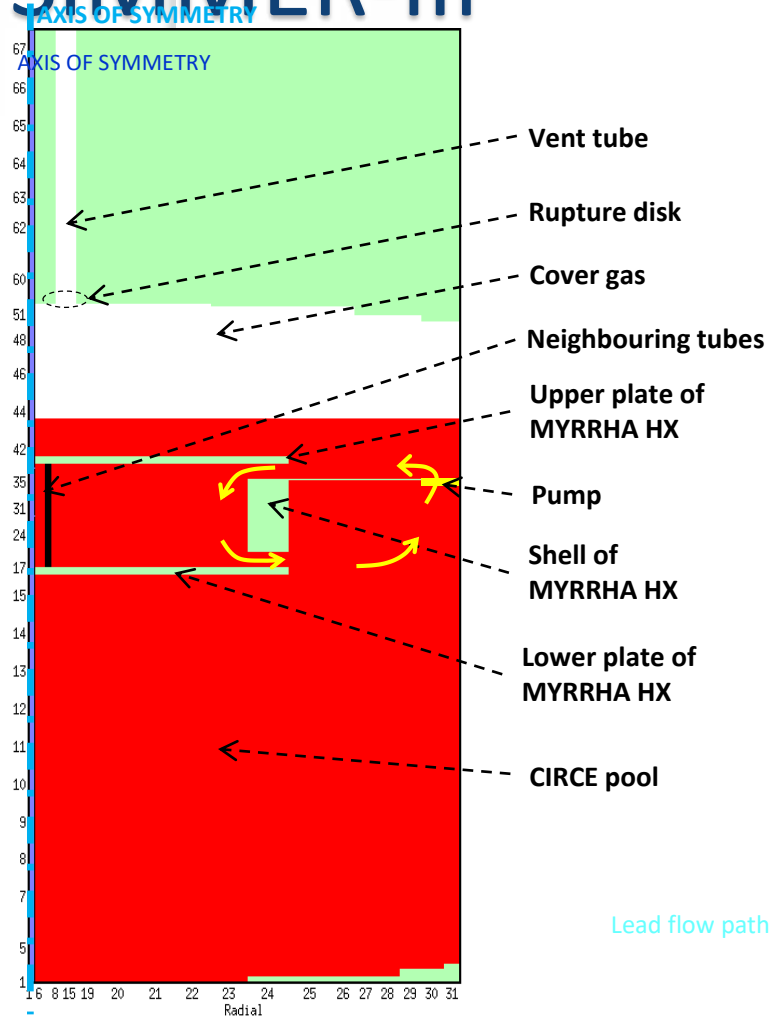


The largest LBE pool worldwide

Test section design, objectives

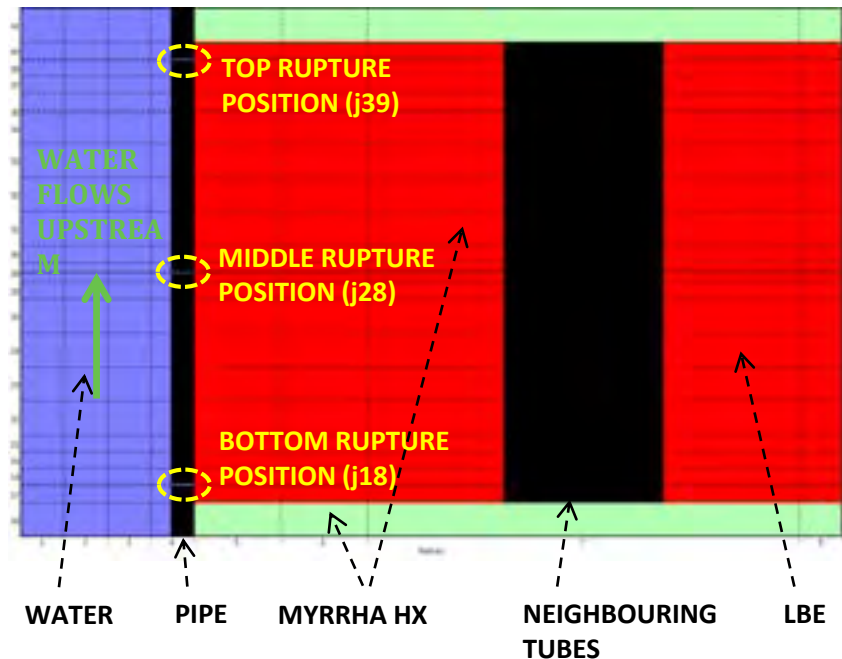
- ❑ Tube **rupture propagation** in the HX-tube bundle
- ❑ The **vapour flow path** in the tube bundle
- ❑ **Pressure waves propagation** into the HX-tube bundle and damping effect of the HX-shell towards the surrounding structures
- ❑ Assessment and performance evaluation of the **safety-guard devices** (rupture disk) aiming to mitigate the effects of the SGTR event
- ❑ Investigation on the solid **impurities formation** after the SGTR event, accompanied by a quantitative qualification of filtering performance in the pool
- ❑ Qualitative characterization of the **LBE particulate discharged** by water and rupture disk discharge lines

Preliminary pre-test analysis by SIMMER-III



SIMMER III model: 31 radial(i) and 67 axial(j) cells

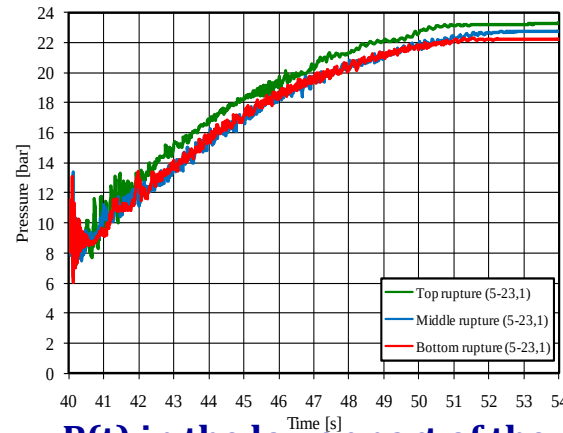
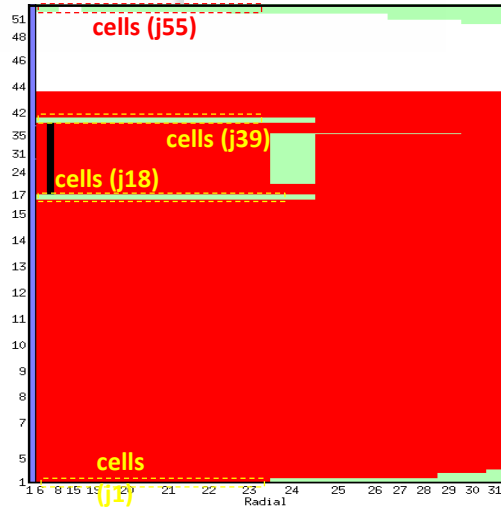
$T_{H_2O} = 200^{\circ}\text{C}$ $P_{H_2O} = 16 \text{ bar}$
 $T_{LBE} = 387^{\circ}\text{C}$ $P_{\text{ARGON}} = 1 \text{ bar}$



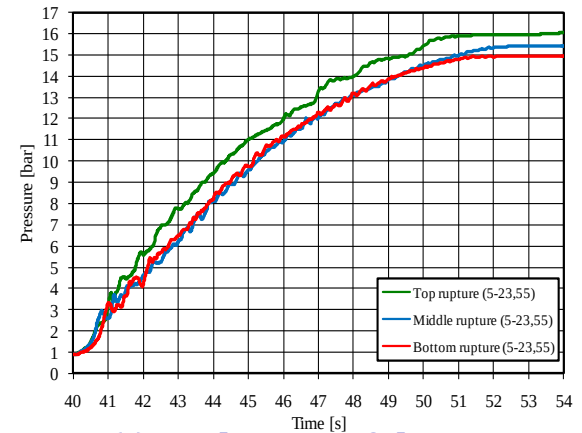
The **rupture disk** in the cover vessel is simulated to perform an assessment of the SGTR accident mitigation

Preliminary pre-test analysis by SIMMER-III

Water injection (started at 40 s) through the **top**, **middle** and **bottom** ruptures

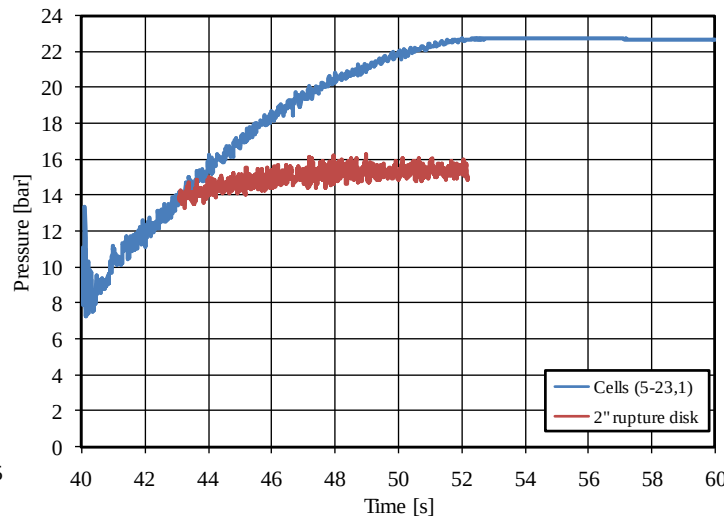
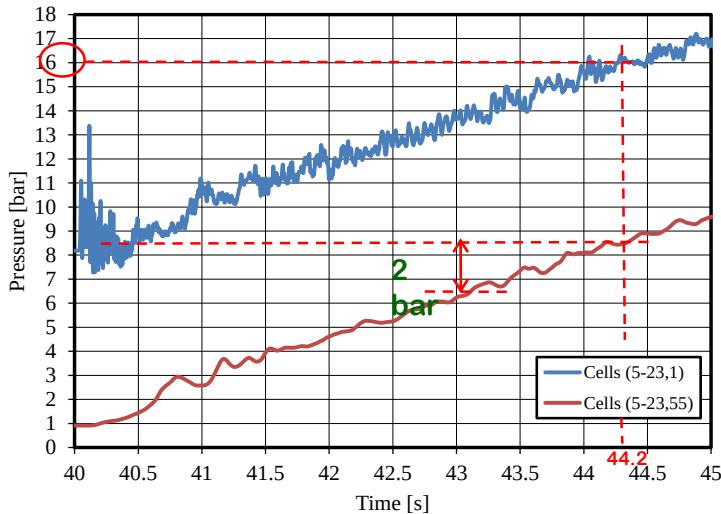


**P(t) in the lower part of the
LBE-pool into CIRCE (j1)**



**P(t) in the top of the CIRCE
cover gas (j55)**

middle rupture scenario



2 in rupture disk opening
at 6 bar (≈ 3 s)

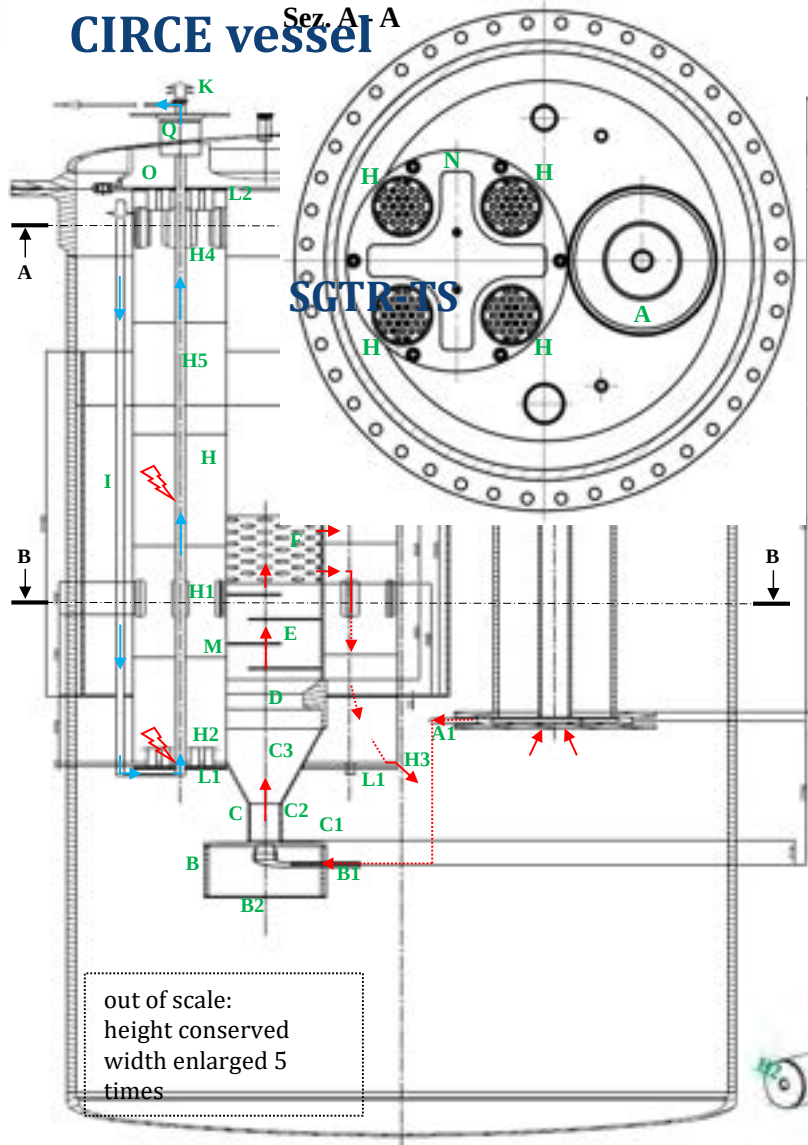
2 bar safety margin

Pressure does not reach 16
bar during **12 s** after the
water injection start

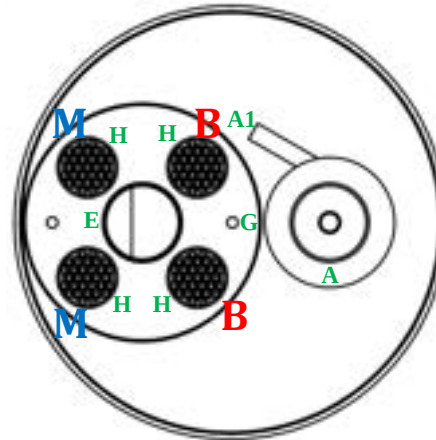
12 s are more than enough
to arrest the supply line

Test section design

CIRCE vessel

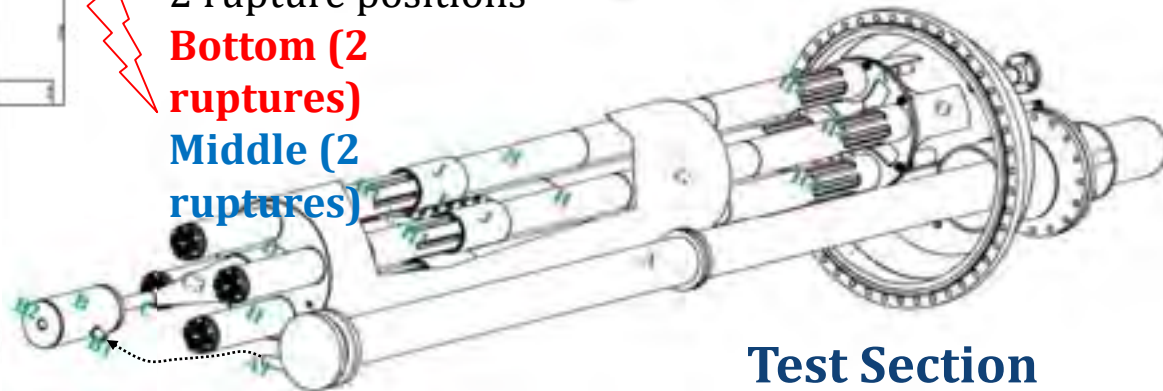


Sez. B - B

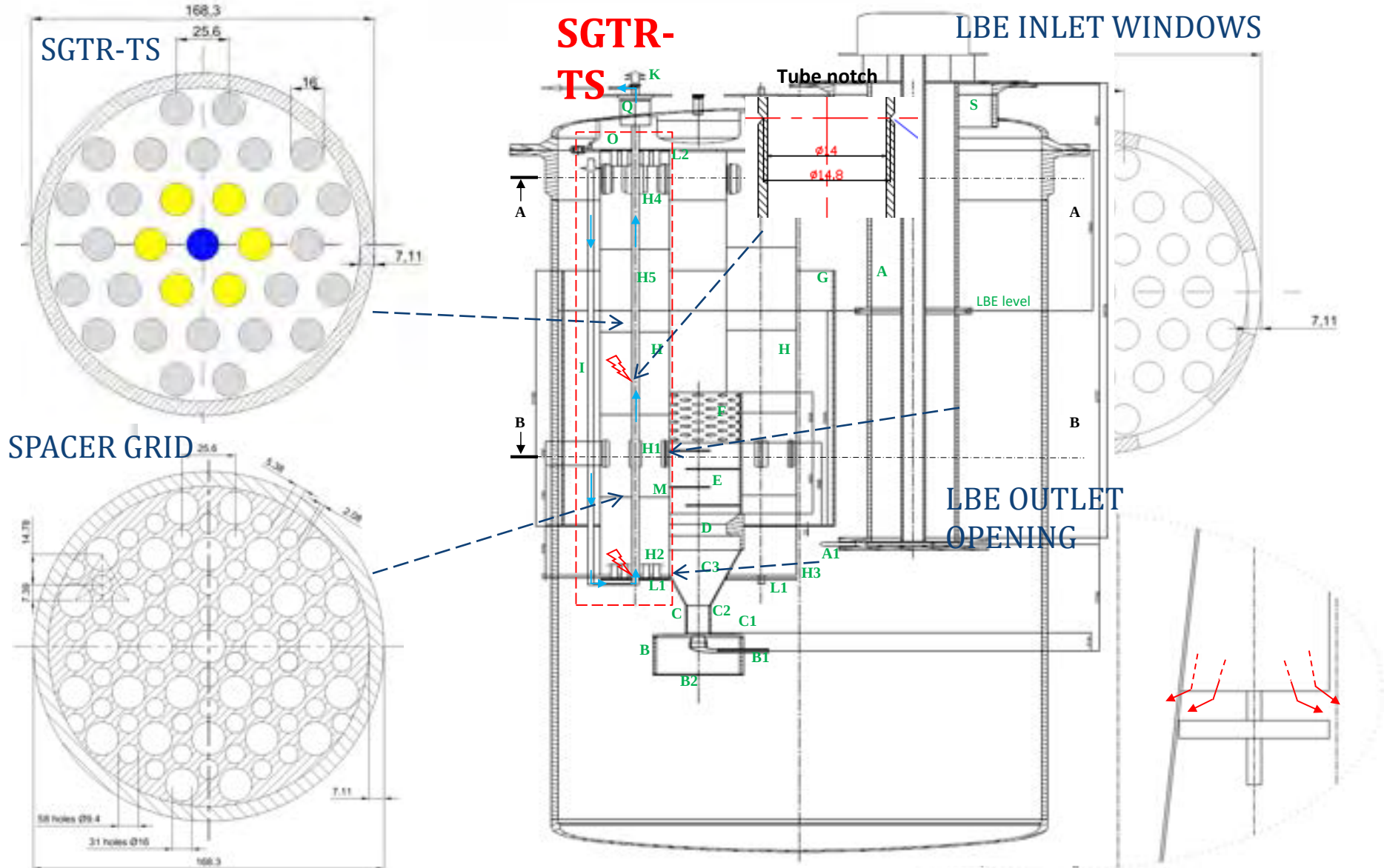


Operating conditions	Unit	Value
LBE temperature	°C	350
LBE mass flow rate (one SGTR-TS)	kg/s	~80
H ₂ O inlet temperature	°C	200
H ₂ O outlet temperature	°C	201.4
H ₂ O pressure	bar	16
H ₂ O mass flow rate (one SGTR-TS)	kg/s	~0.07
CIRCE cover gas pressure (abs)	bar	1.05
CIRCE Ar cover gas volume	m ³	~2.2
CIRCE LBE pool volume	m ³	~7
Ar monitoring tubes pressure	bar	16
Tubes length	mm	~5200

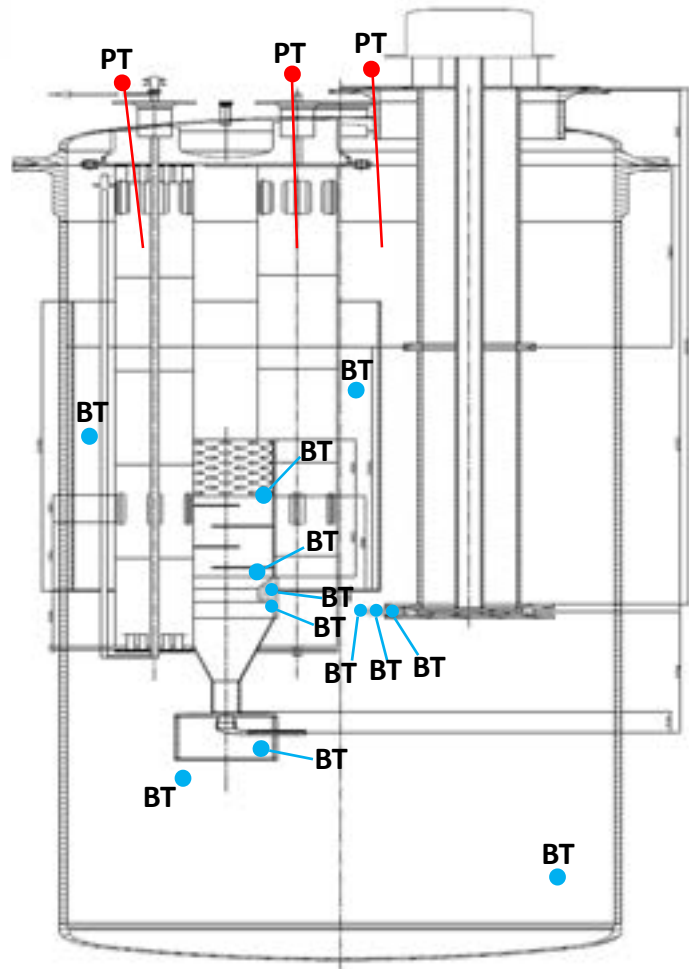
LBE flow path
 Water flow path



Test section components



Test section instrumentation



5 **fast Pressure Transducers** (transient pressure)

12 **Bubble Tubes** (level, mass flow rate and stationary pressure)

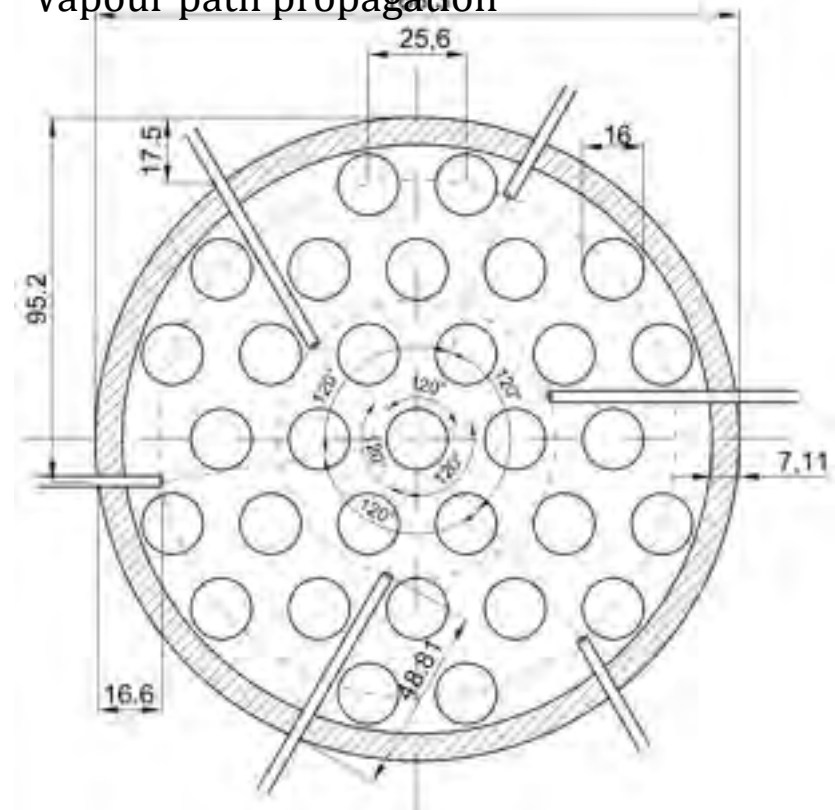
~200 **Thermocouples**

~45 in each SGTR-TS

6 TCs at level (two level below, one level at and 5-6 levels above the rupture position)

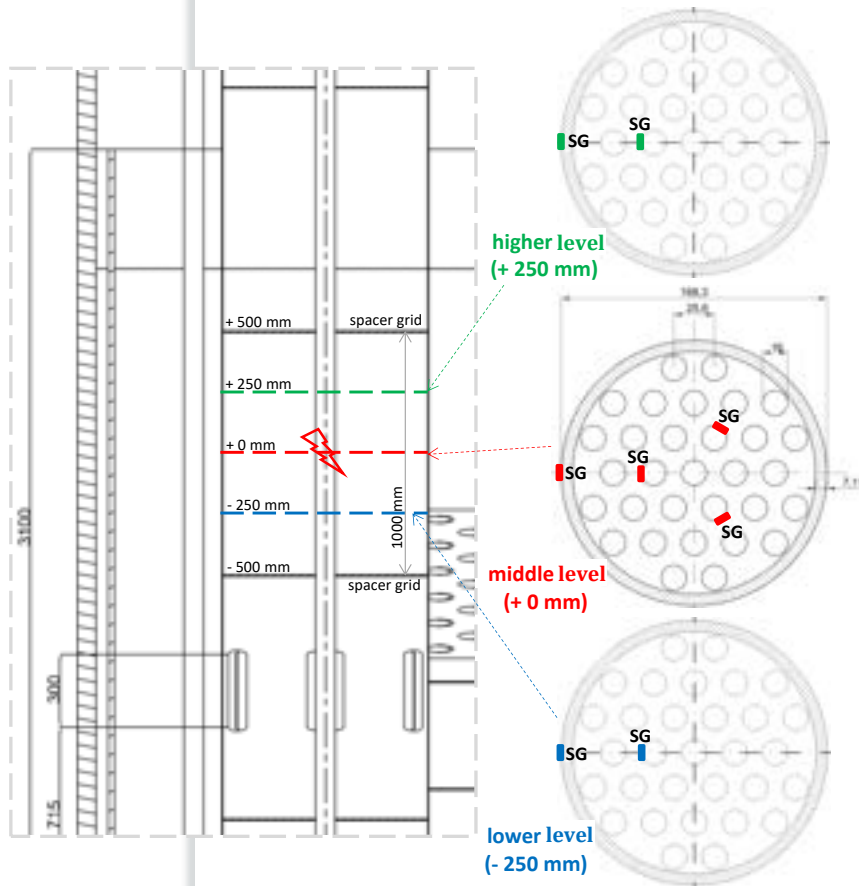
N 6 tubes 3x1 mm, 6" tube drilled

Vapour path propagation

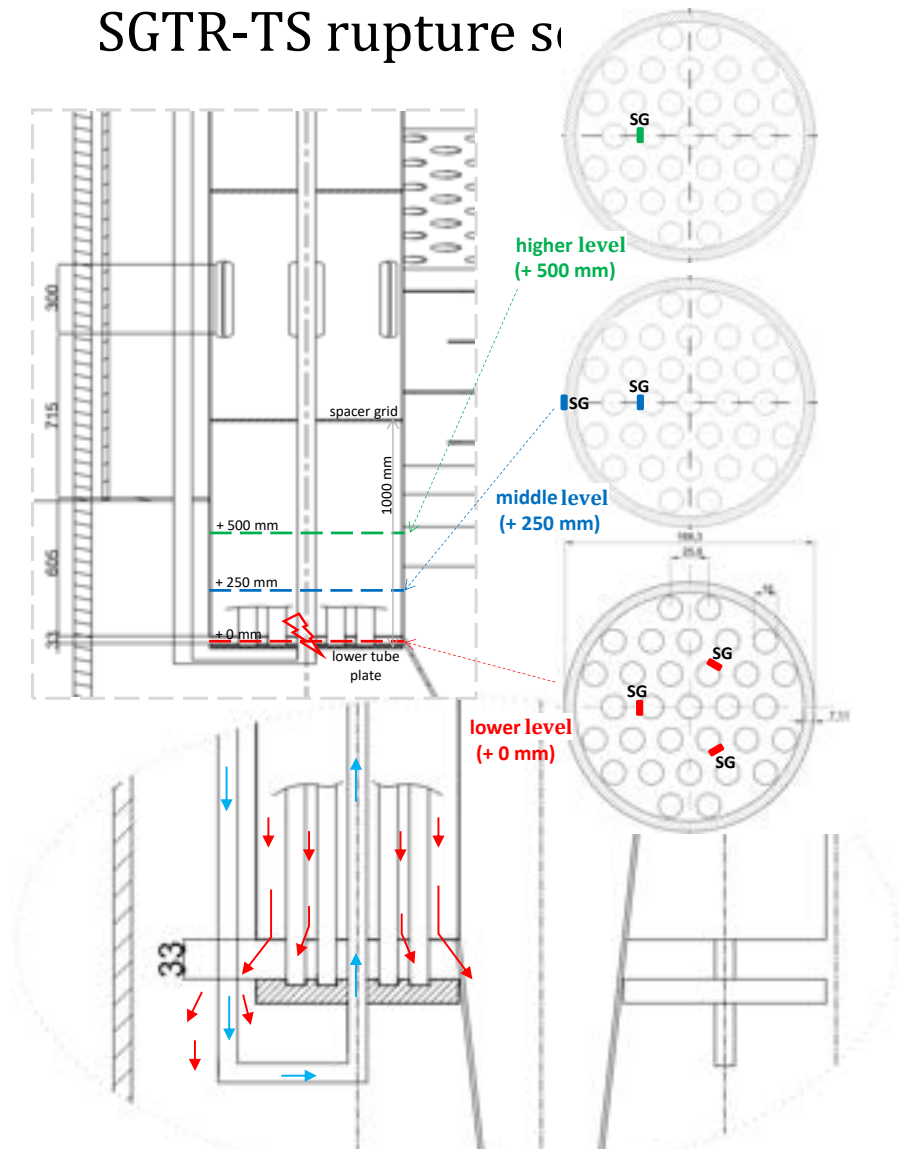


Test section instrumentation

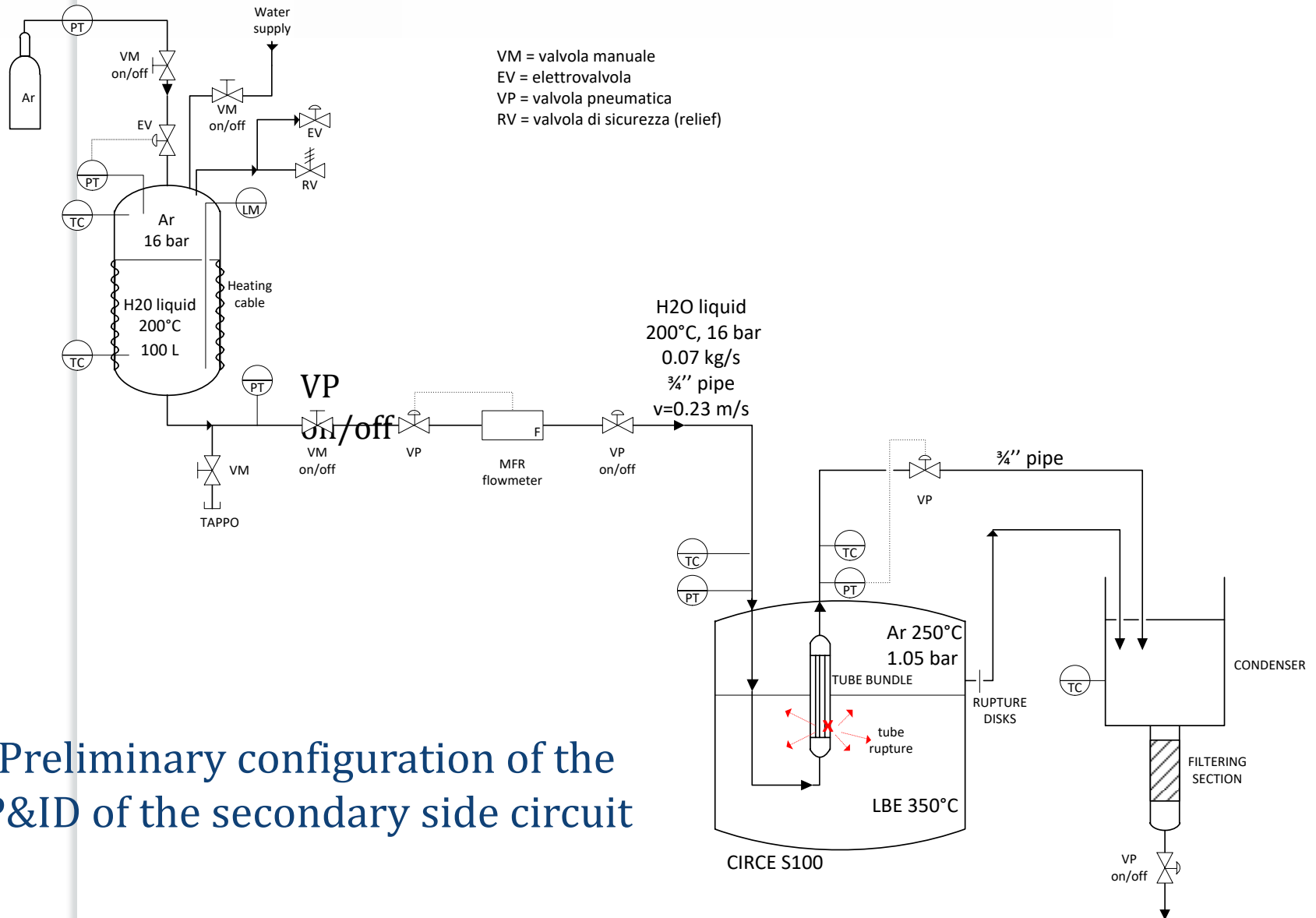
8 Strain Gages in the **middle** SGTR-TS rupture scenario



6 Strain Gages in the **bottom** SGTR-TS rupture scenario

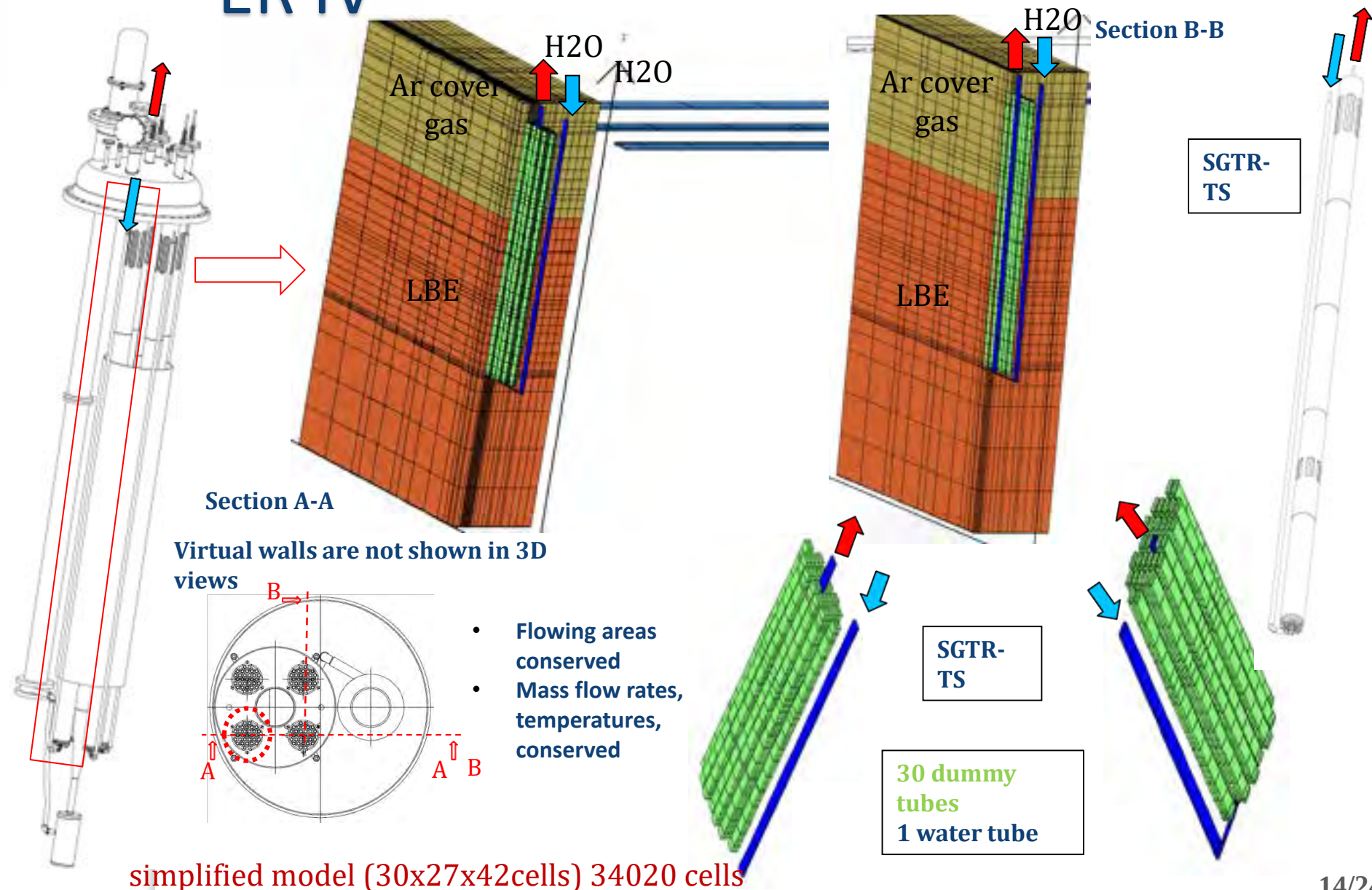


P&ID of the secondary side circuit

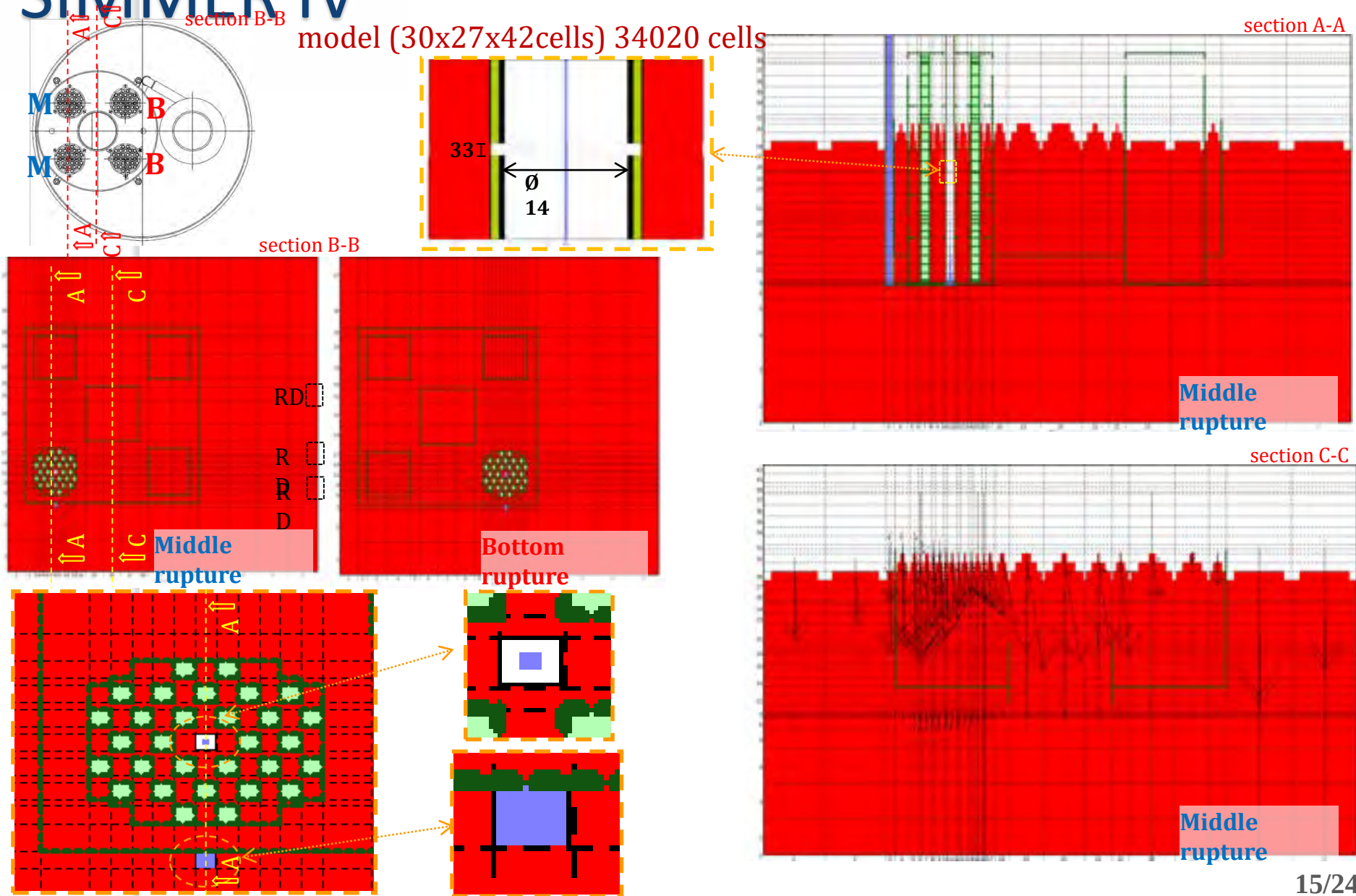


Preliminary configuration of the
P&ID of the secondary side circuit

Detailed pre-test analysis by SIMMER IV

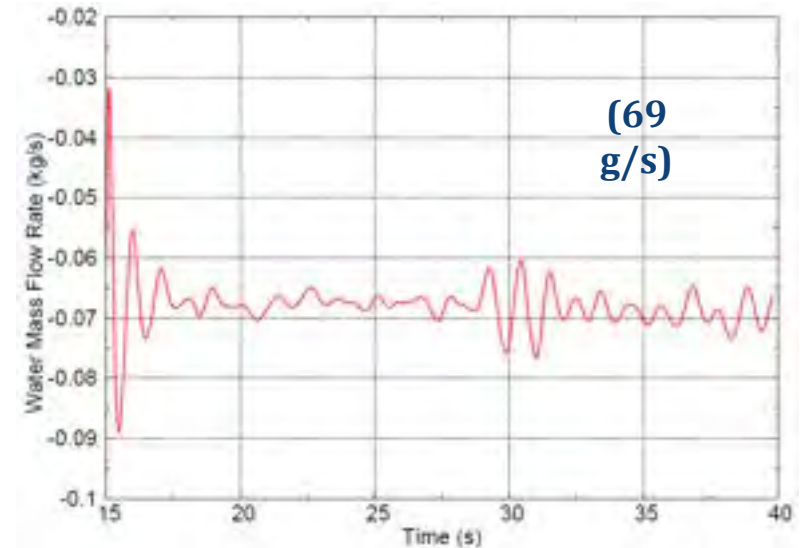
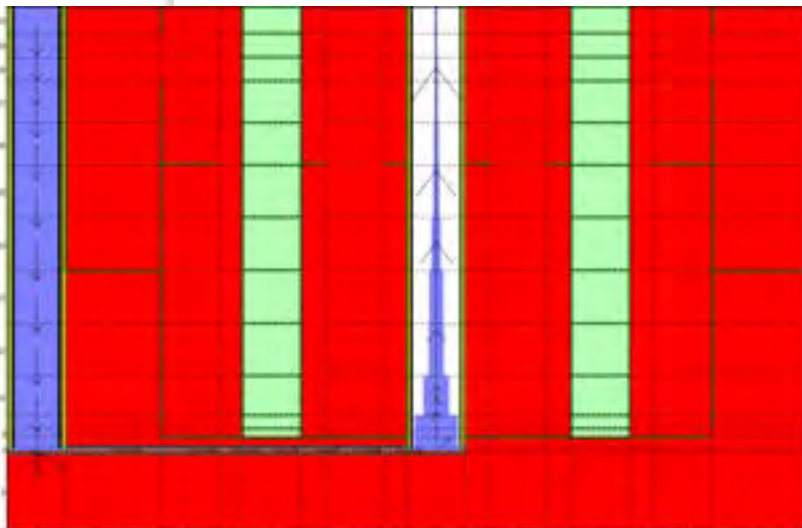
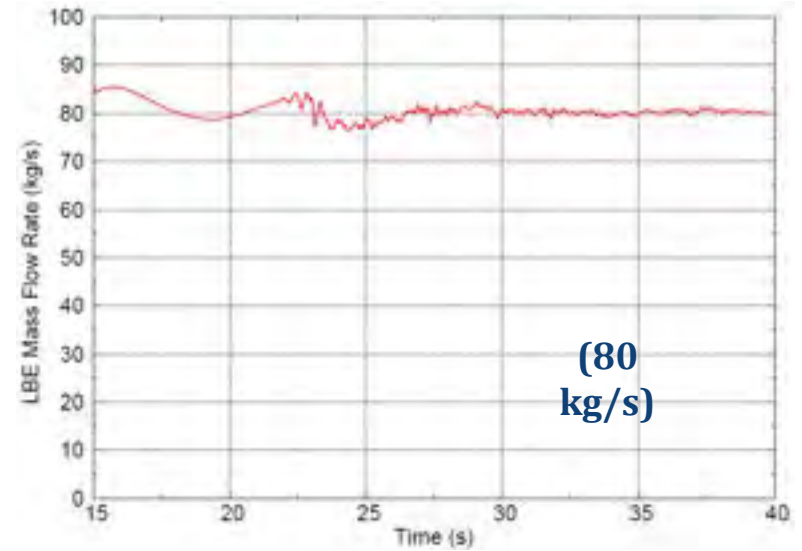
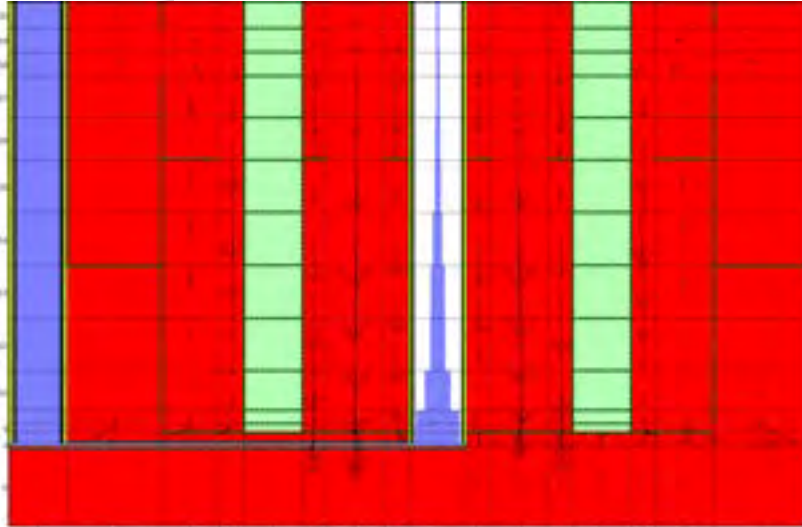


Detailed pre-test analysis by SIMMER IV



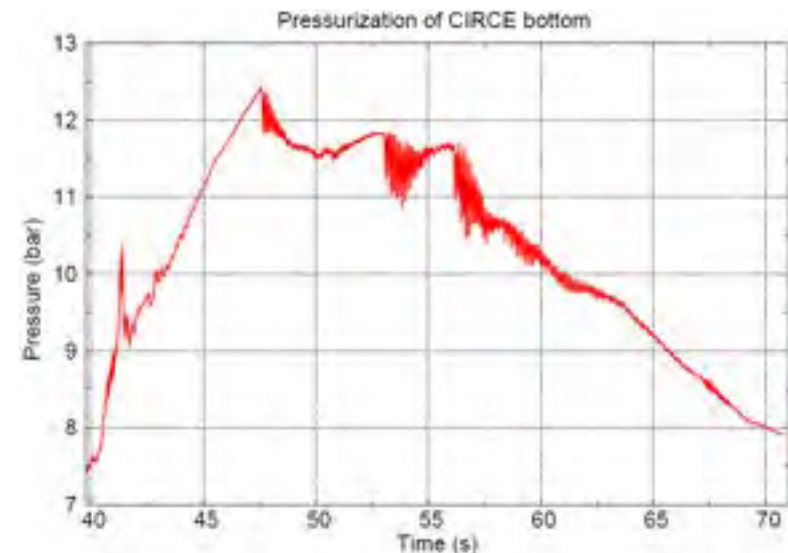
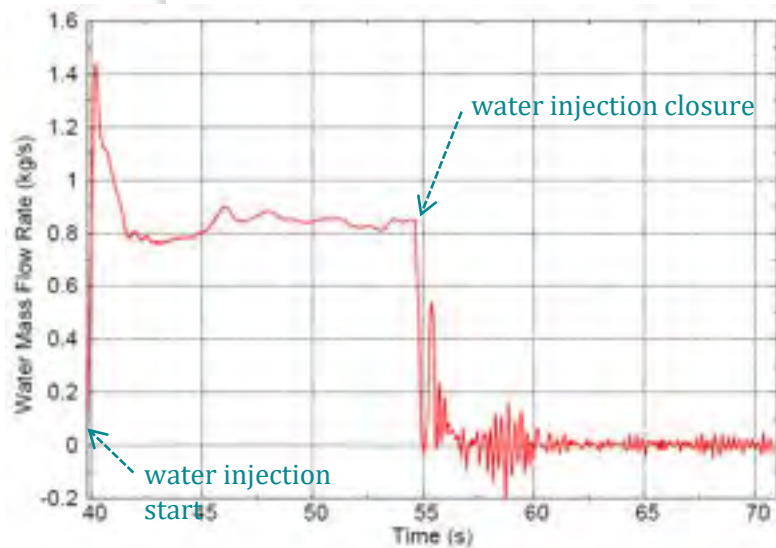
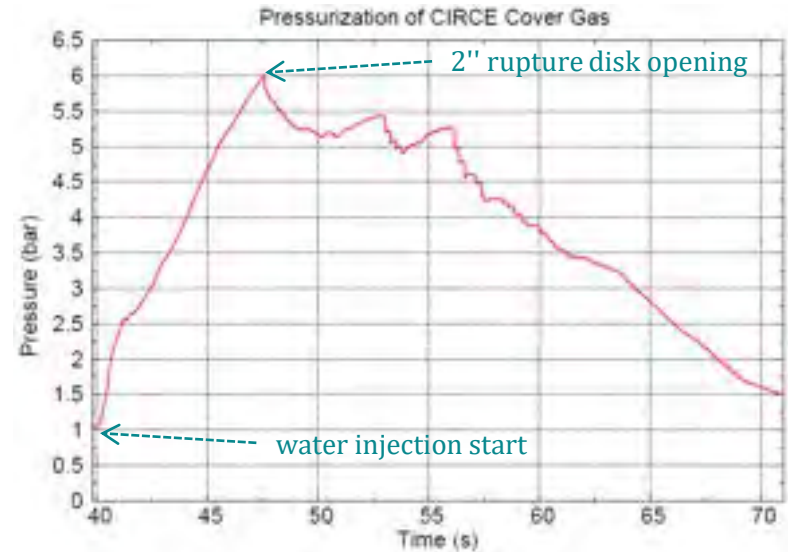
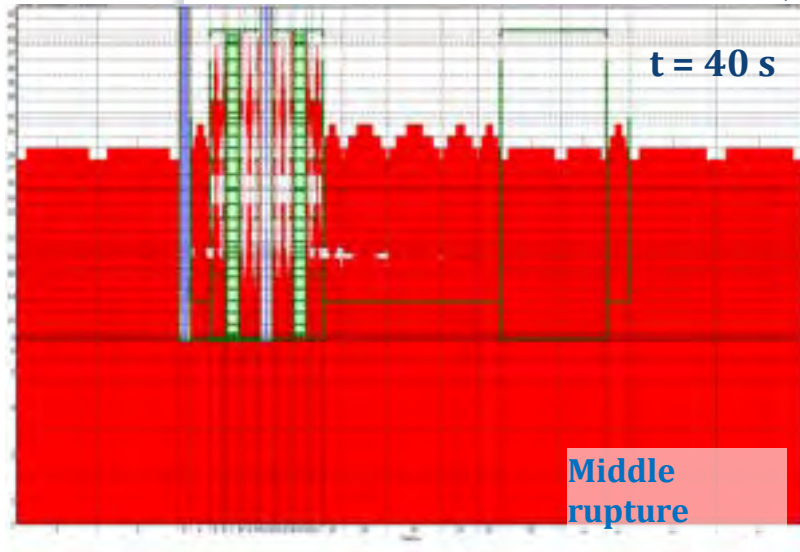
Detailed pre-test analysis by SIMMER IV

Stationary conditions before water injection



Detailed pre-test analysis by SIMMER IV

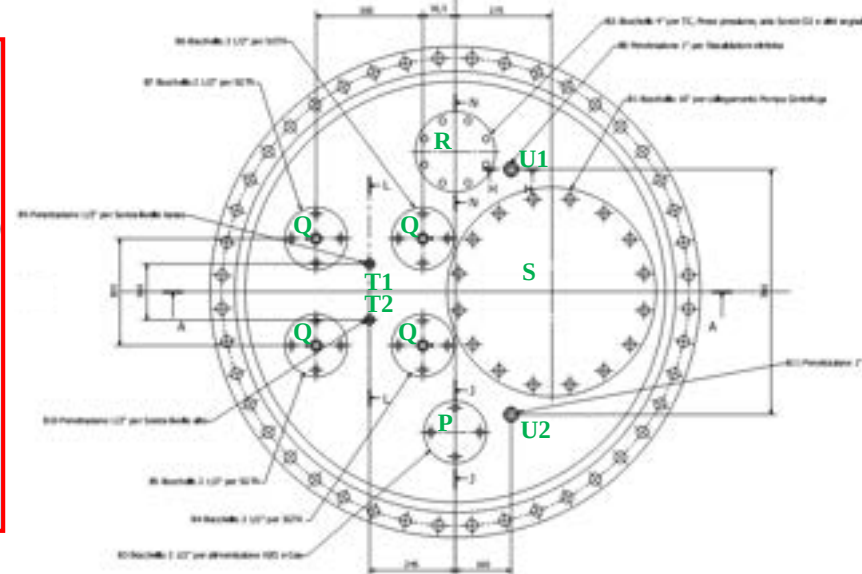
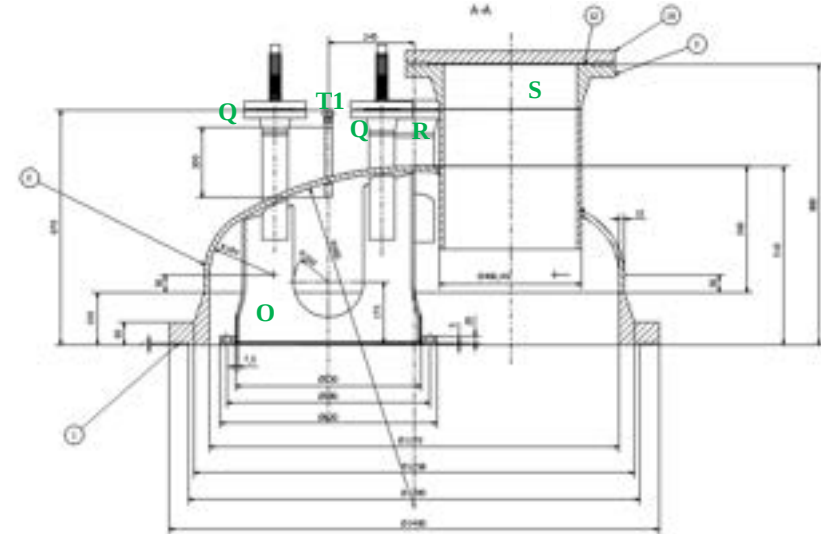
Injection start @ 39.798 s



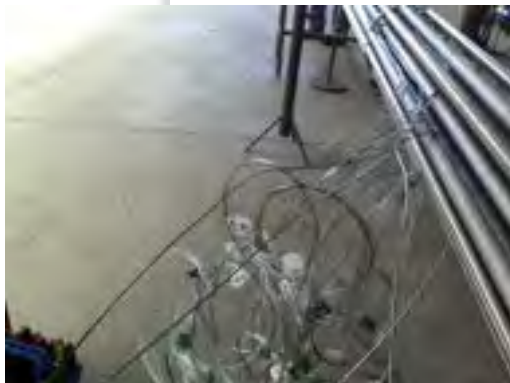
Test section components, CIRCE cover and PP



CIRCE cover vessel



Test section assembly



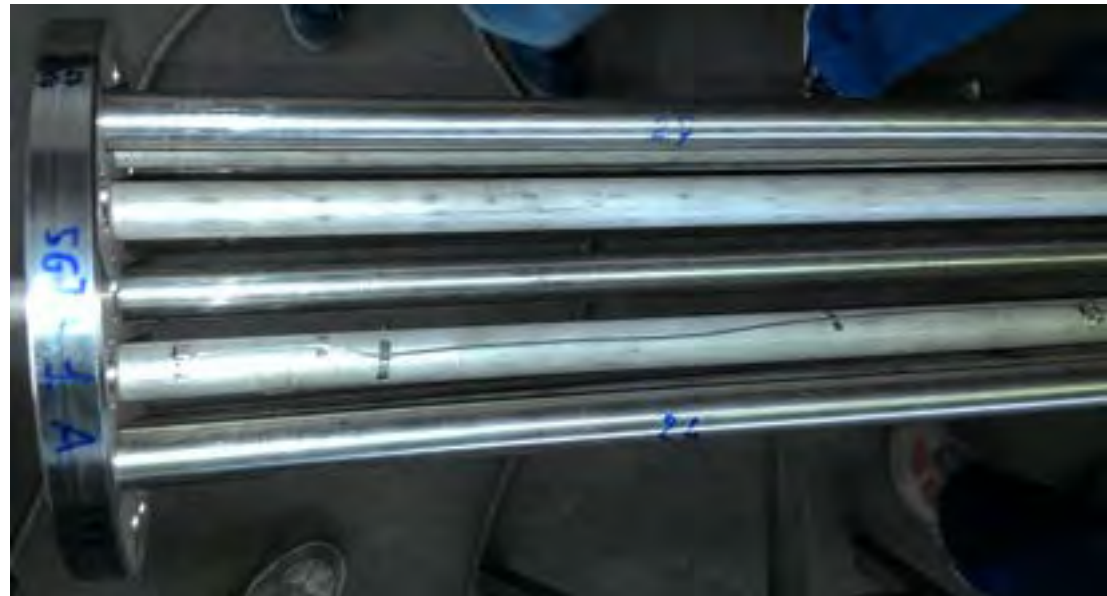
Test section assembly



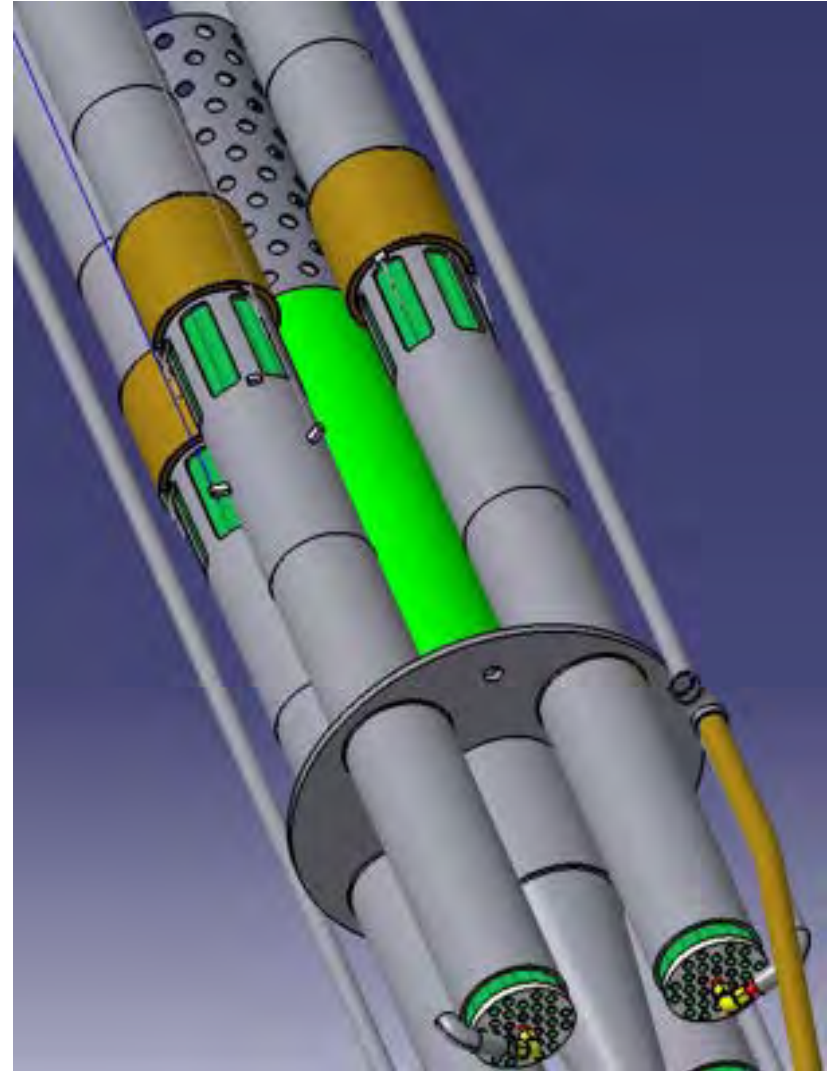
Thermocouple



Strain Gage



Test section assembly



Conclusive remarks

- ❑ Preliminary and detailed pre-test analysis by SIMMER-III and IV are carried out, respectively, the test section assembly is ongoing
- ❑ The SGTR experimental campaign is unique in the international research scenario: vertical scale 1:1 of MYRRHA in a large pool facility (Dint=1170 mm, H= 8500 mm)
- ❑ The tests will provide high quality data on SGTR event about domino effect, vessel pressurization, safe-guard devices, pressure wave propagation/strain, vapour flow path and impurities formation in a configuration relevant for HLMRs. They provide feedback for design work about such issues
- ❑ Solved criticalities: execution of more tests without TS removal (separator/sliding valves), water tubes rupture (notch/hydraulic system), B.C. of MYRRHA reactor (water, LBE), safe execution of the tests (pressurization transient/rupture disks)
- ❑ The experimental campaign will constitute a first evidence of the SGTR scenario consequences for HLMRs

Conclusive remarks

THANK YOU FOR YOUR ATTENTION

Time schedule

- ❑ The assembling of the **instrumented test section** is foreseen to be concluded by **November 2015**
- ❑ The test section is foreseen to be set in **CIRCE** facility by the **end of 2015** as well as the implementation of the secondary side (water supply line)
- ❑ The **experimental campaign** (4 tests) will be carried out by **March 2016**



Advances in the development of the FRENETIC code for the coupled dynamics of lead-cooled reactors (CERSE-POLITO RL 1572/2015)

R. Bonifetto, D. Caron, S. Dulla, P. Ravetto, L. Savoldi,
R. Zanino

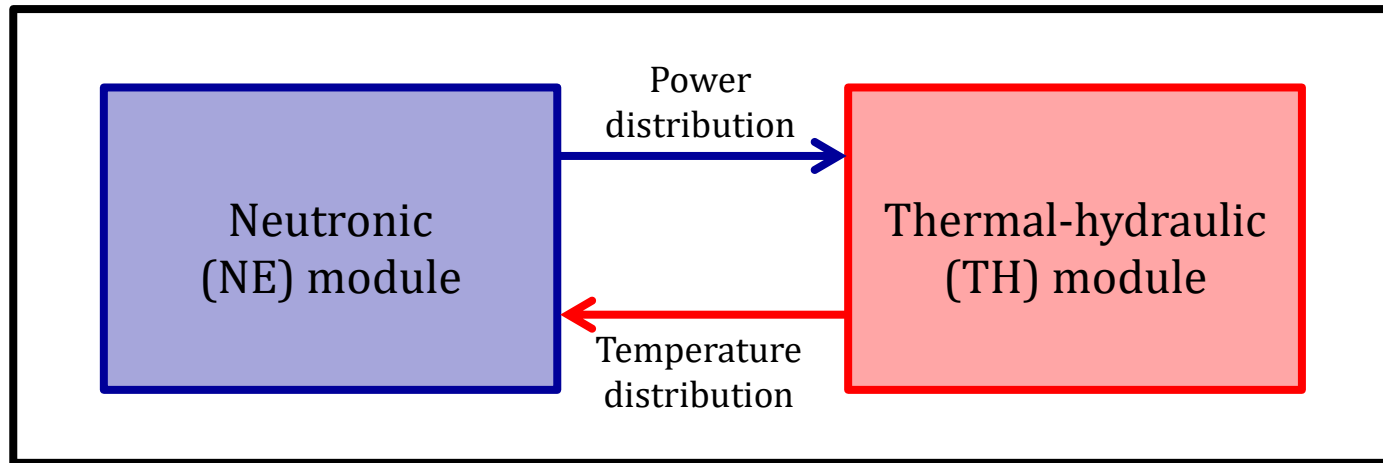
*NEMO Group, Dipartimento Energia, Politecnico di
Torino, Italy*

Contents

- The FRENETIC code
- Standalone validation of the thermal-hydraulic module
- First coupled validation of the FRENETIC code
- Conclusions and perspective

The FRENETIC code

Fast REactor NEutronics/Thermal-hydraulICS (**FRENETIC**)
code for full-core coupled analyses [R. Bonifetto et al., *Nuc. Eng. Design*, 2013]

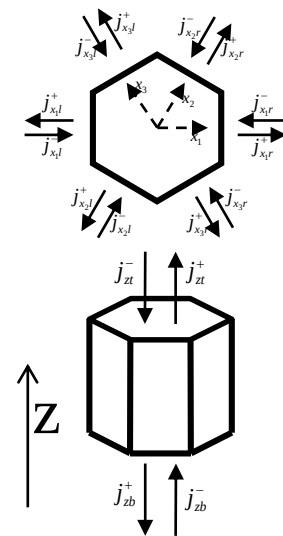


Principal objective:
computationally
efficient,
multiphysics
analyses suitable for
design and safety
studies

Preliminary validation of coupled code on EBR-II
experimental data [R. Bonifetto et al., presented at ICENES, 2015]

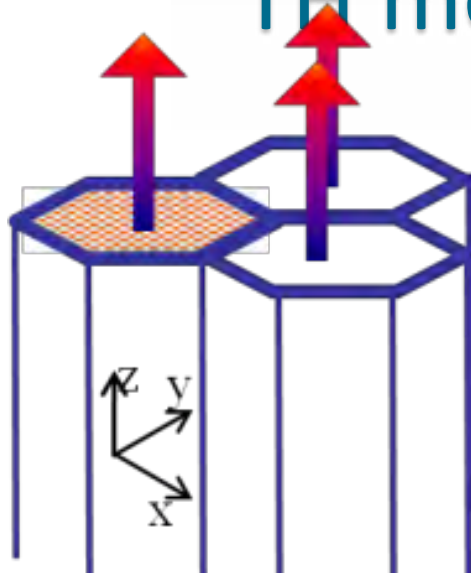
The FRENETIC code: NE module

- Transient **point kinetic** analysis [R. Bonifetto et al., *Fusion Sci. Technol.*, 2012]
- **3D neutron diffusion** model with delayed neutron emissions solved by coarse-mesh nodal method in space and direct integration in time [D. Caron et al., *presented at ICENES*, 2013]
- **Adjoint** and **quasi-static** solvers for multigroup nodal neutron diffusion equations [D. Caron et al., *Ann. Nuc. Energy*, 2015]
- Decay heat model



The FRENETIC code:

TH module



IN EACH HA:

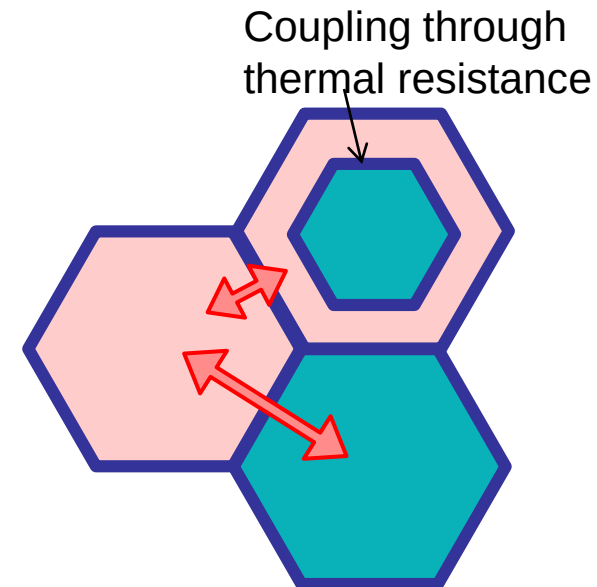
Coolant: 1D axial model (mass / momentum / energy eqs.) along each closed assembly (z), for 1+ regions in each HA

- **Single HA (1D) validation** against experimental data from CIRCE facility @ ENEA Brasimone (**Pb-Bi eutectic**) [R. Zanino et al., Transactions of the ANS, 2012]

Pins: 1D radial model, locally coupled to coolant

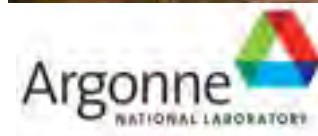
BETWEEN HAs: (weak) 2D inter-assembly thermal coupling (xy)

- Steady-state **benchmark** against RELAP5-3D© in a simplified EBR-II geometry (**Na**) [R. Zanino et al., Transactions of the ANS, 2013]
- Preliminary **validation** against EBR-II data (**Na**) [R. Zanino et al., Proceedings of ATH, 2014]



EBR-II reactor and shutdown heat removal tests transients

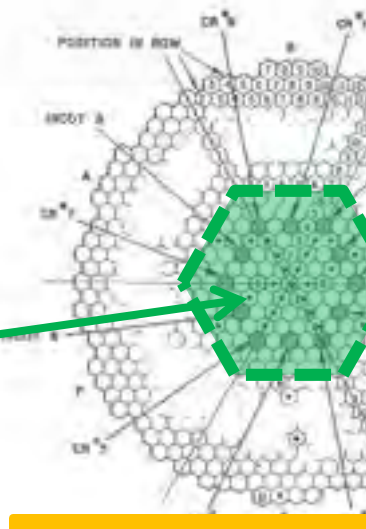
- No available database for multiple hexagonal assembly (HA) configuration cooled by Pb →
- Participation in an IAEA CRP on the shutdown heat removal tests (SHRTs) of the *sodium-cooled* Experimental Breeder Reactor-II (EBR-II, 62.5 MWth fast reactor, in operation from 1964 to 1994 at Argonne National Laboratory (ANL), USA)
- **Benefit:** provides experimental data for two transients against which participants may benchmark codes
 - SHRT-17 (protected loss of flow) to be modelled only TH
 - intended application: standalone validation of TH module
 - SHRT-45R (unprotected loss of flow) to be modelled NE+TH
 - intended application: coupled validation of FRENETIC code



EBR-II computational domain for SHRT-17 tra

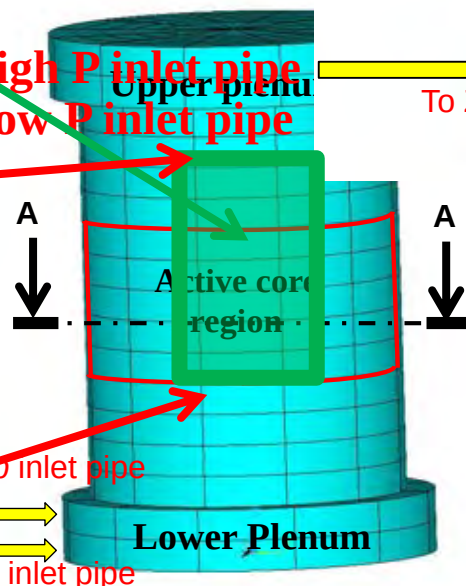
FRENETIC :

- Bundle region only (~ 0.61 m tall)
- 127 HAs (Inner-most 7 annuli)
- 120 axial nodes



High P inlet pipe
Low P inlet pipe

To Z-pipe



Limited set of available HAs
 T_{in} , $(dm/dt)_{in}$, p_{out}
measurements; missing BCs
from RELAP5-3D

RELAP5-3D full core nodalization:

- 5 radial zones x 12 azimuthal sectors
- 15 axial nodes

XX0

XX0

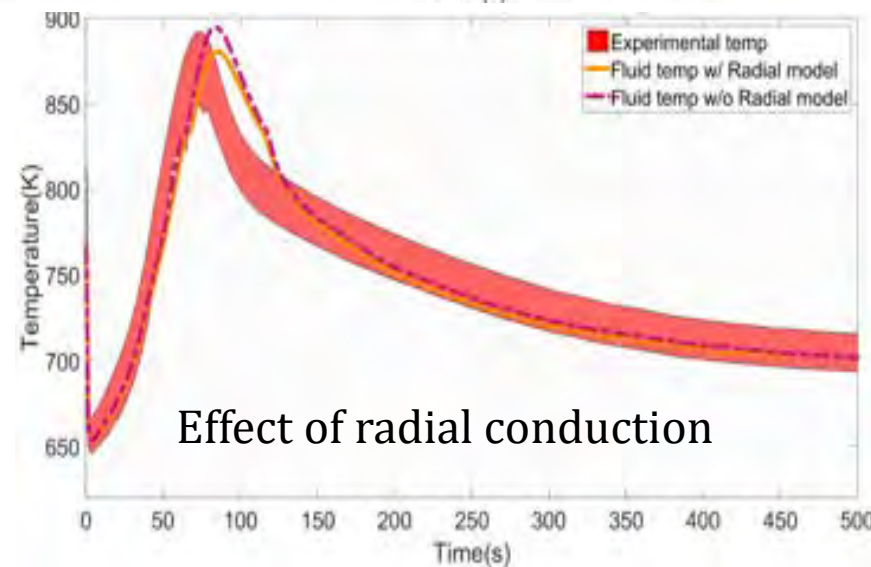
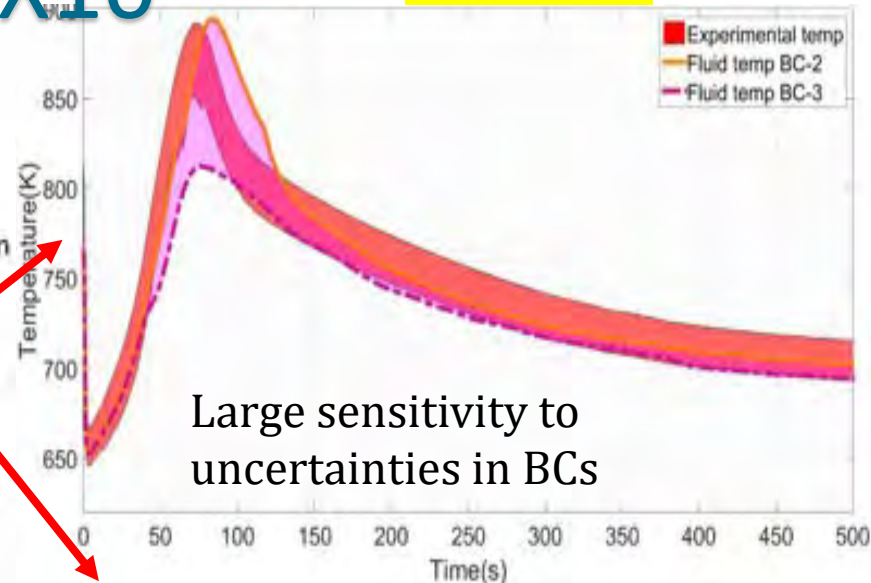
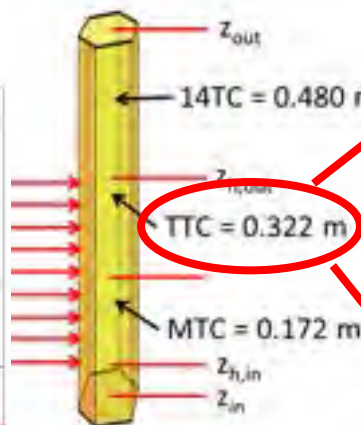
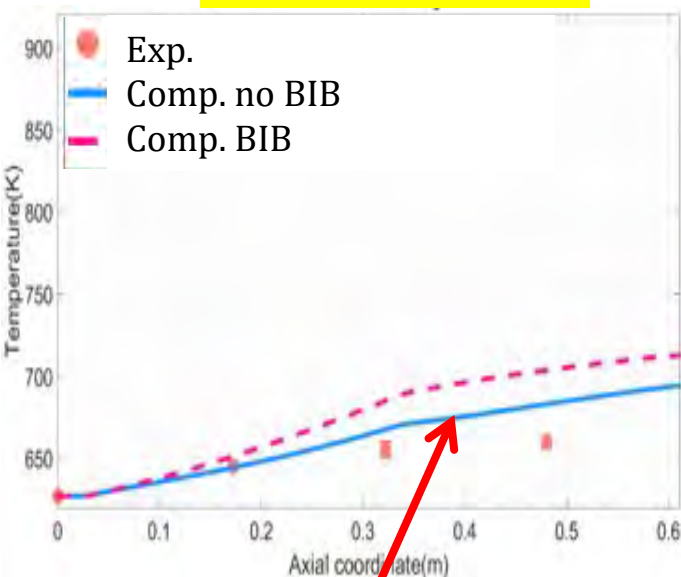
9

Simulation (SHRT-17):

XX09 and XX10

XX09

XX10 @t=0 s



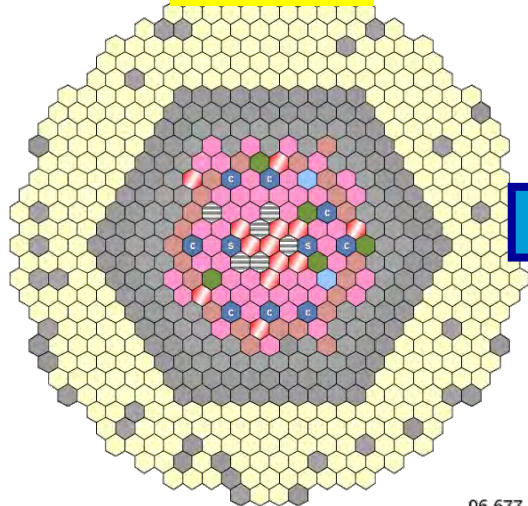
Proper description of coolant flow in thimble improves agreement wrt exp. data

NE model of EBR-II SHRT-45R transient

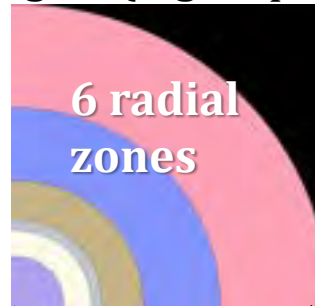
Serpent

At various ($T_{\text{fuel}}, T_{\text{coolant}}$) : homogenisation of material and
condensation of energy grid (6 groups) with JEFF3.1.1

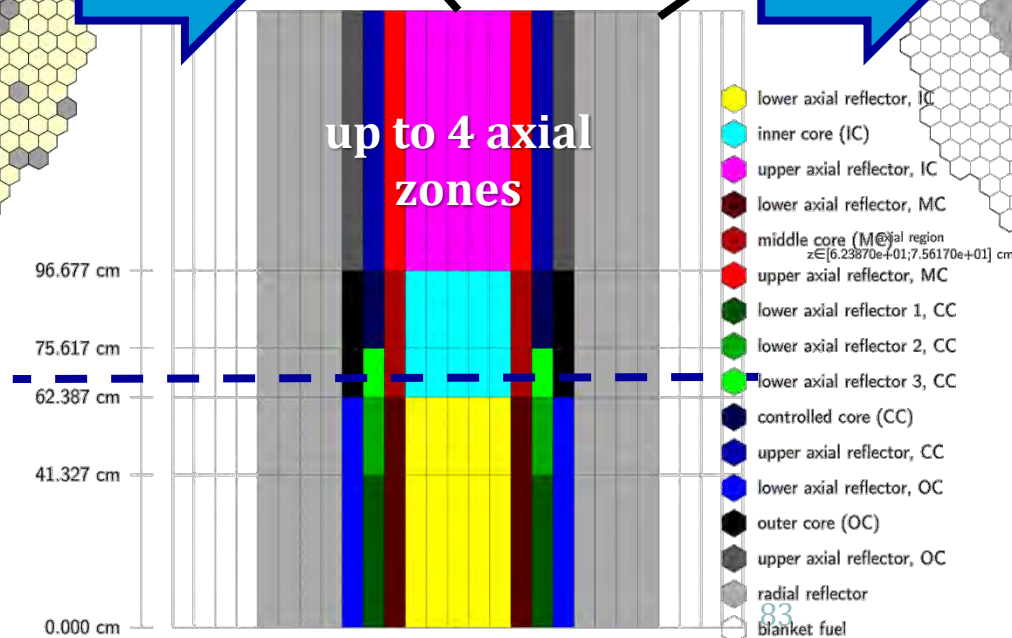
EBR-II



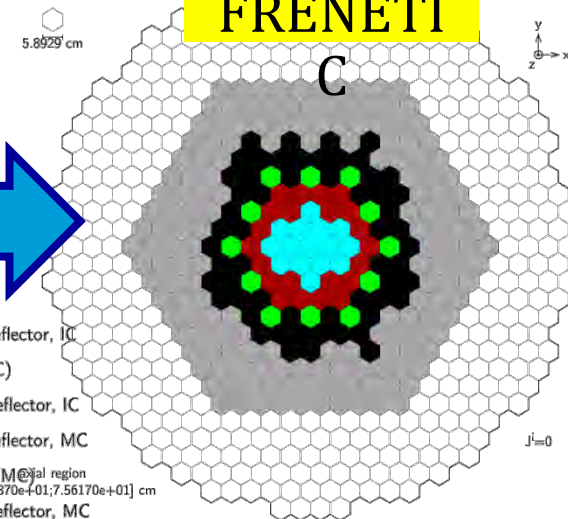
6 radial
zones



up to 4 axial
zones



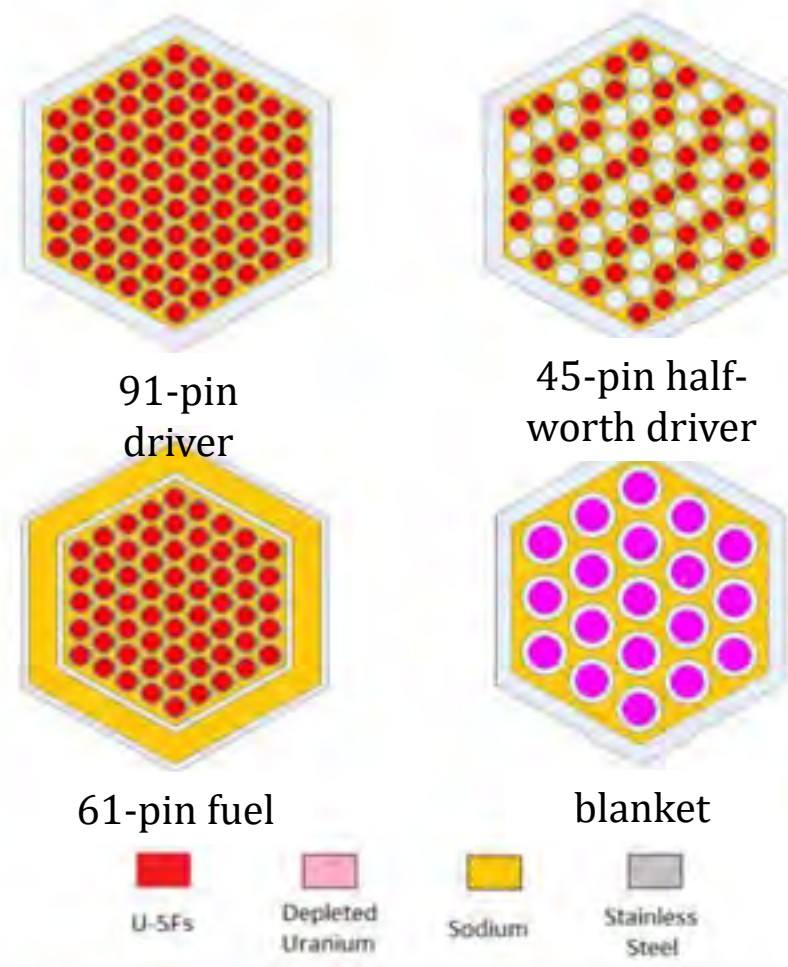
FRENETI



TH model of EBR-II SHRT-45R

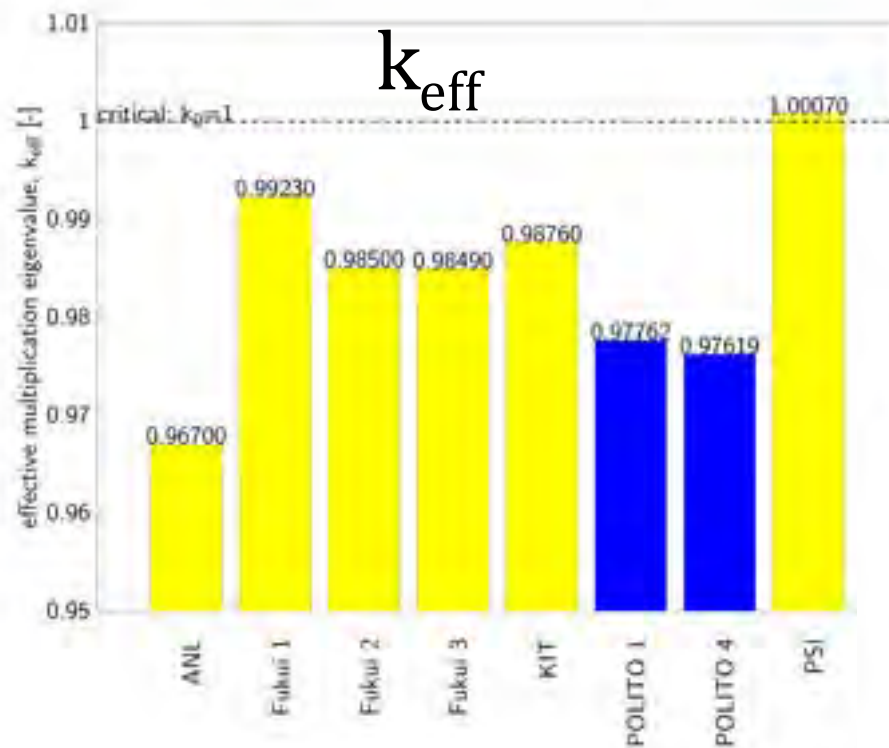
transient

- Each subassembly modelled individually, including dummy and blanket elements (total of 12 tipologies of subassemblies)
- BCs: inlet mass flow rate, inlet coolant temperature and outlet pressure (from exp. or design values)



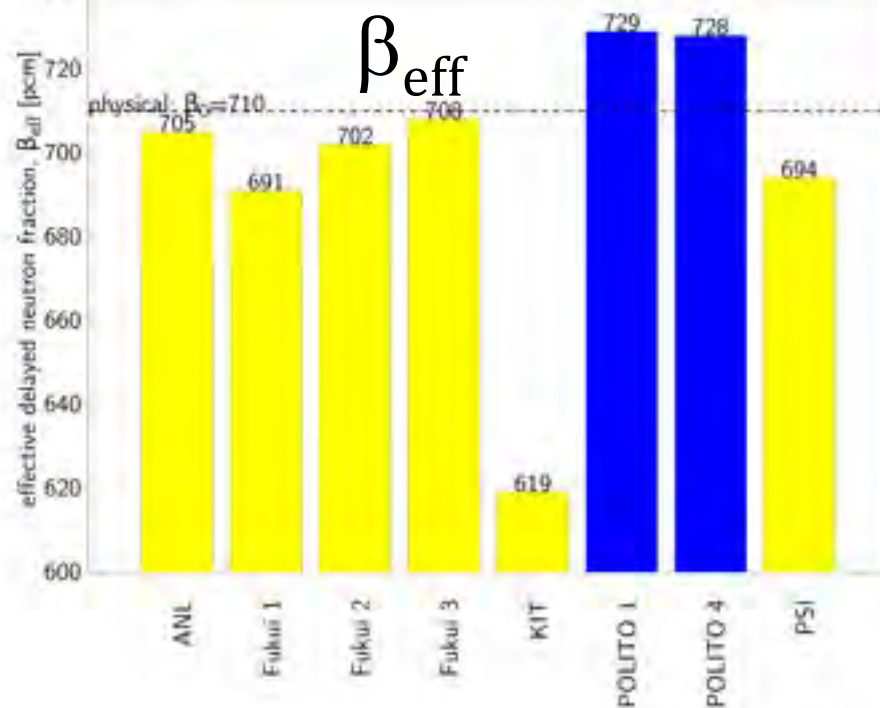
Neutronics benchmark specifications for EBR-II shutdown heat removal test SHRT-45R, Rev. 1, Argonne National Laboratory, Nuclear Engineering Division, January 2013

Benchmark against other models (integral quantities)

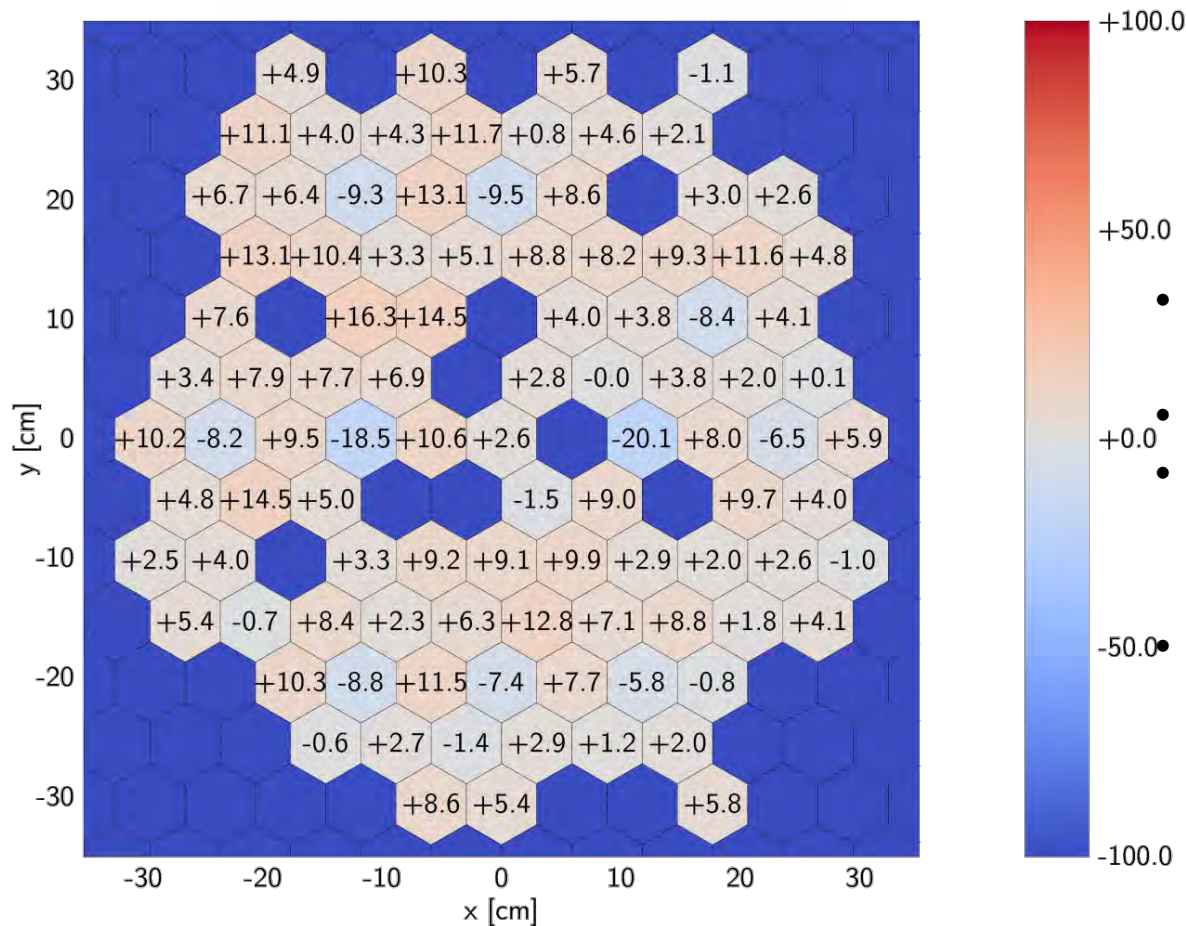


POLITO results within range
of other CRP participants

Most results within tens of
pcm



FRENETIC benchmark (SHRT-45R): initial fission power distribution



$$e_k \equiv \frac{p_k - p_{k,ref}}{p_{k,ref}} \cdot 100[\%]$$

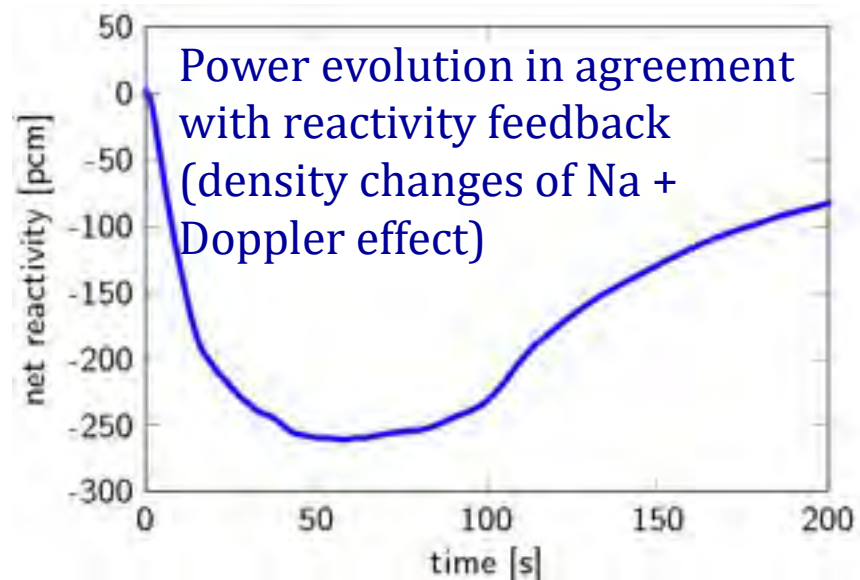
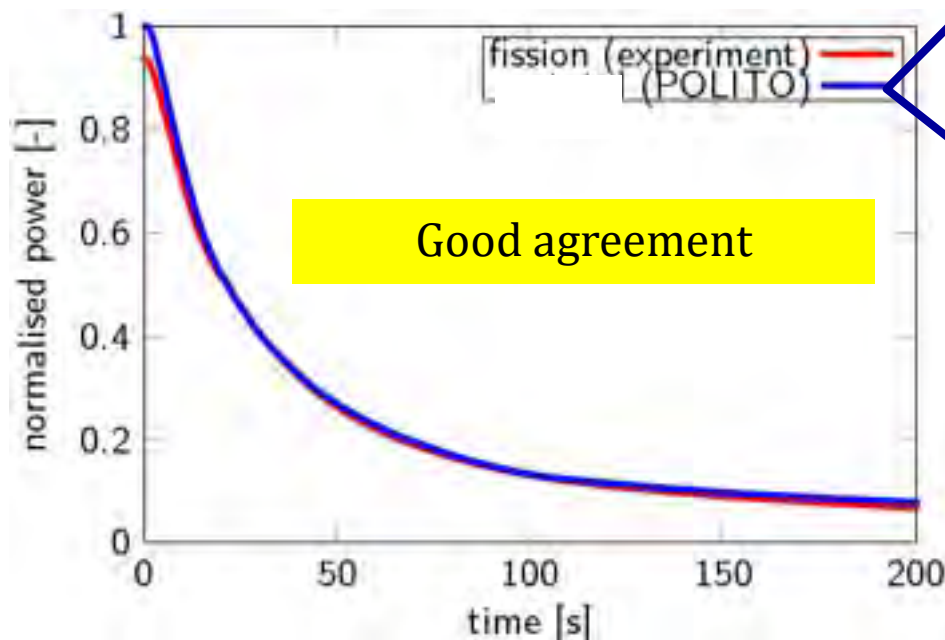
$p_k \equiv$ subassembly power

- Reference values assumed from ANL computation
- Most errors are below 10 %
- Difficult to represent heterogeneity with few materials
- Dummy and reflector elements «cold» due to lack of neutron and gamma kermas

FRENETIC validation (SHRT-45R): fission power evolution

- SHRT-45R: starting from nominal conditions, unprotected loss of flow (ULOF) accident initiated by simultaneous trip of primary and intermediate pumps

Measured fission power compared to
computed

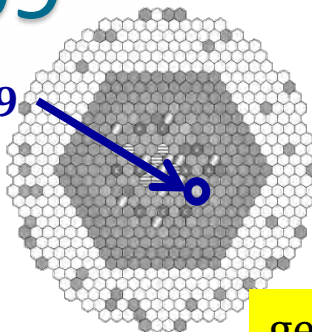


FRENETIC validation (SHRT-45R):

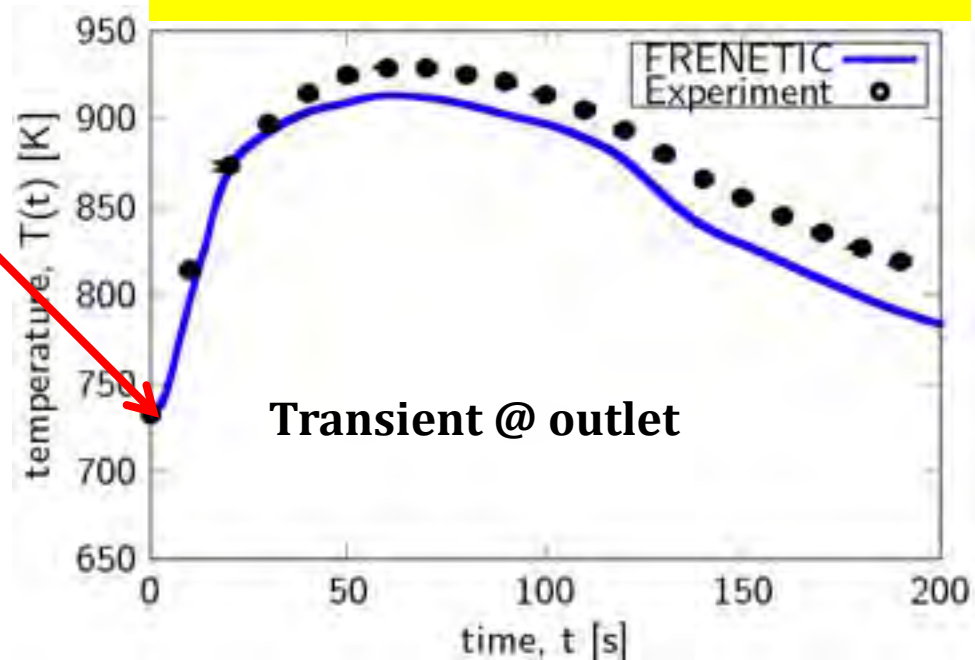
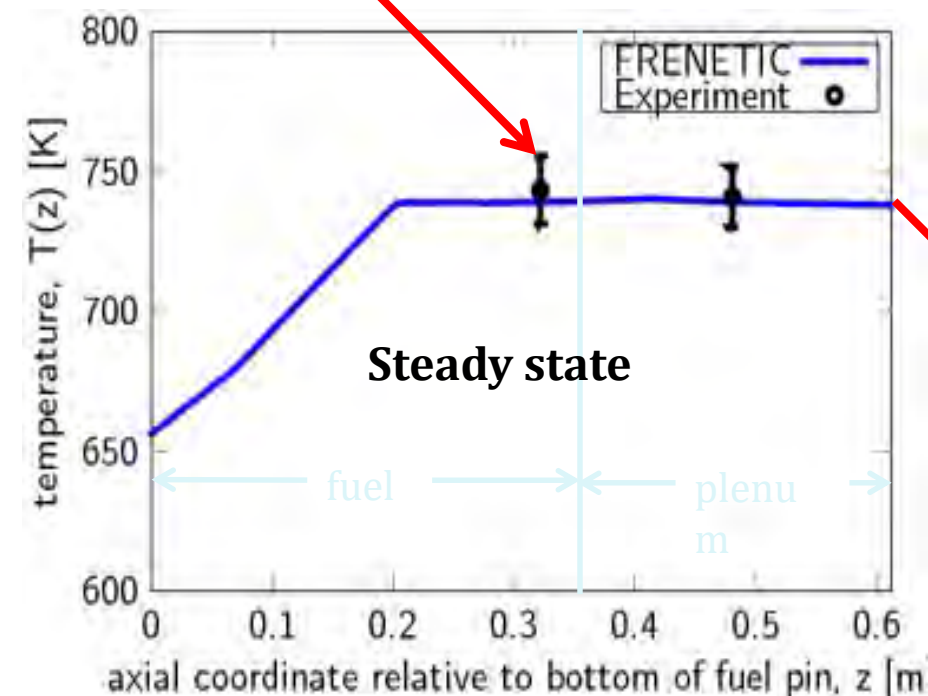
T_{coolant} in XX09

average of all thermocouples at
specified axial location +
standard deviation

XX09

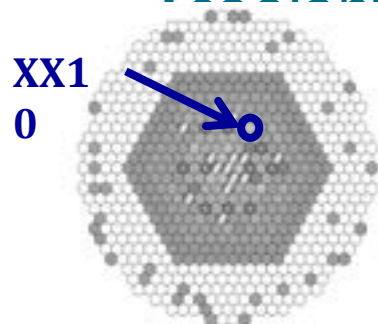


general good agreement both at
steady-state and during transient

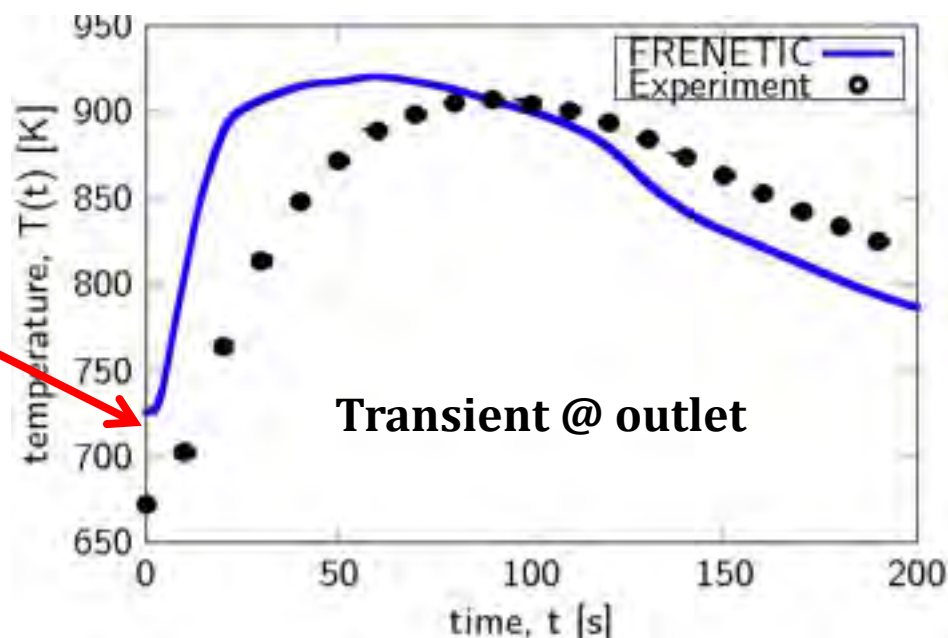
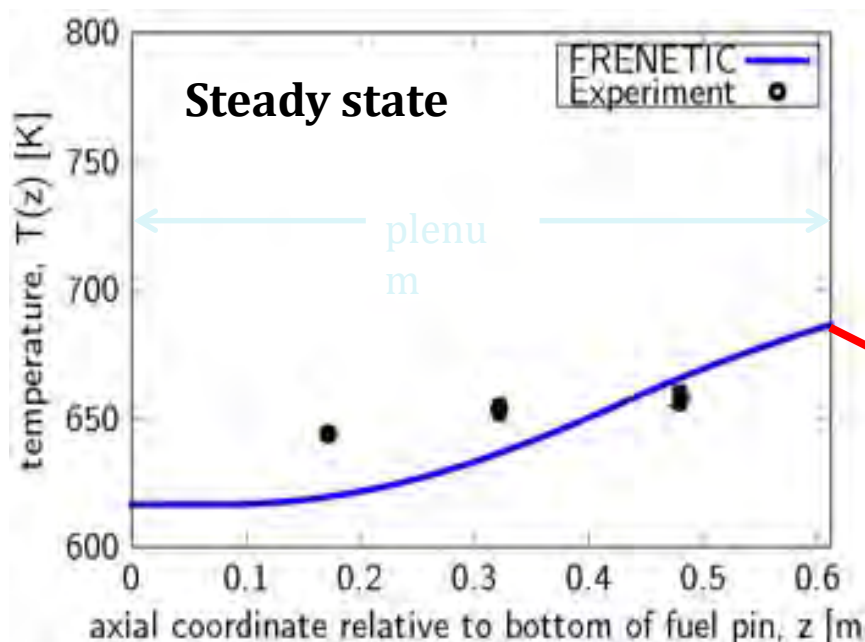


FRENETIC validation (SHRT-45R):

Temperature in XX10



XX10 heated only by the adjacent assemblies (no fissile material, no g heat deposition in the model) → XX10 is «colder» and neighbouring assemblies are «hotter» than in the reality



Conclusions and perspective

- Development of FRENETIC proceeds by improving existing models and extending overall capabilities
- The most recent FRENETIC validation activities focused on SHRT-17 (pure TH) and SHRT-45R (NE+TH) transients of EBR-II
 - steady-state and transient analysis in generally good agreement with experimental measurements
- Perspective
 - development and implementation of additional physics models (gammas, ...)
 - analysis of ALFRED transients



SAPIENZA
UNIVERSITÀ DI ROMA



Workshop Tematico PAR2014 - LP2 – LFR GEN IV
ENEA - Brasimone, 19-20 novembre 2015

System codes application to HLM nuclear systems

Fabio Giannetti, Vincenzo Narcisi, Gianfranco Caruso

Sapienza, Università di Roma

Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica

DIAEE – Area Nucleare

TH system codes

- Thermal-hydraulic system codes have demonstrated the capability to adequately predict a large variety of off-normal and accidental transients, as has been shown by exhaustive code verification and assessment programs as conducted in the last decades.
- Originally based on different assumptions and equation formulations, the T-H system computer codes generally used, e.g. RELAP5, TRAC, TRACE, ATHLET, CATHARE, are today being developed to have rather similar bases and capabilities.



TH system codes (2)

- They are now based on governing equations representing the transient, non-homogeneous, non-equilibrium, two-phase flow including heat transfer processes from solid heat structures like the fuel rods, piping and RPV wall structures, as well as internal support structure components.
- Due to the numerical approximations and the empirical nature of the models included in the T-H system codes, extensive activities (partially experimental, through IETs and SETs) related to validation of the code models have been pursued over the years.
- Nevertheless, one should not forget that good agreement with experimental integral test facilities is not always free of specific code tuning and compensating errors.



TH system codes application for HLM nuclear systems

- At present, a fairly well-based experience has been established as concerns the codes' capability to simulate the T-H conditions prevailing during various time windows in specified transient scenarios.

But.....

- All TH system codes were developed and validated for LWRs
- Minor modifications were carried out starting from water versions to analyze other fluids, mainly through:
 - *Implementation of thermo-physical two-phase properties;*
 - *Implementation of some specific heat transfer and friction factors correlations.*



TH system codes application for HLM nuclear systems

- No TH system code is presently validated for HLM, but is required a long V & V process, based on experimental data.
- This activity is needed for demonstrating the reliability of a code in the perspective of a use during the licensing.
- Four of the six Generation-IV systems have a fast neutron spectrum and two of them use liquid metal (sodium and lead) as a coolant. The increased requirements to advanced safety make it necessary to provide as accurate as possible numerical simulation of the processes of heat transfer, fluid flow, etc. in the core and in the whole reactor system.



RELAP5 versions used in HLM TH analysis

RELAP5 mod 3.3 *

Based on original NRC version developed by INL and modified by ANN, ENEA and UniPI.

Developed thermo-physical proprieties for lead, LBE and sodium

Implemented HTC correlations for liquid metal

RELAP5-3D

Developed by INL with DOE sponsored improvements:

(new fluids, *multidimensional* components, multidimensional NK, etc.)



HTC evaluation differences

- Two different correlations for rod-bundle convective heat transfer in liquid metals are used.
- In RELAP5 mod3.3 (LM version) HTC evaluation is based on the Ushakov's correlation (1977):

$$\text{Nu} = 7.55 \frac{P}{D} - 20 \left(\frac{P}{D} \right)^{-13} + \frac{3.67}{90 \left(\frac{P}{D} \right)^2} \text{Pe}^{\left(0.56 + 0.19 \frac{P}{D} \right)}$$

Validity range: $1 < \text{Pe} < 4000$, $1.2 \leq P/D \leq 2.0$

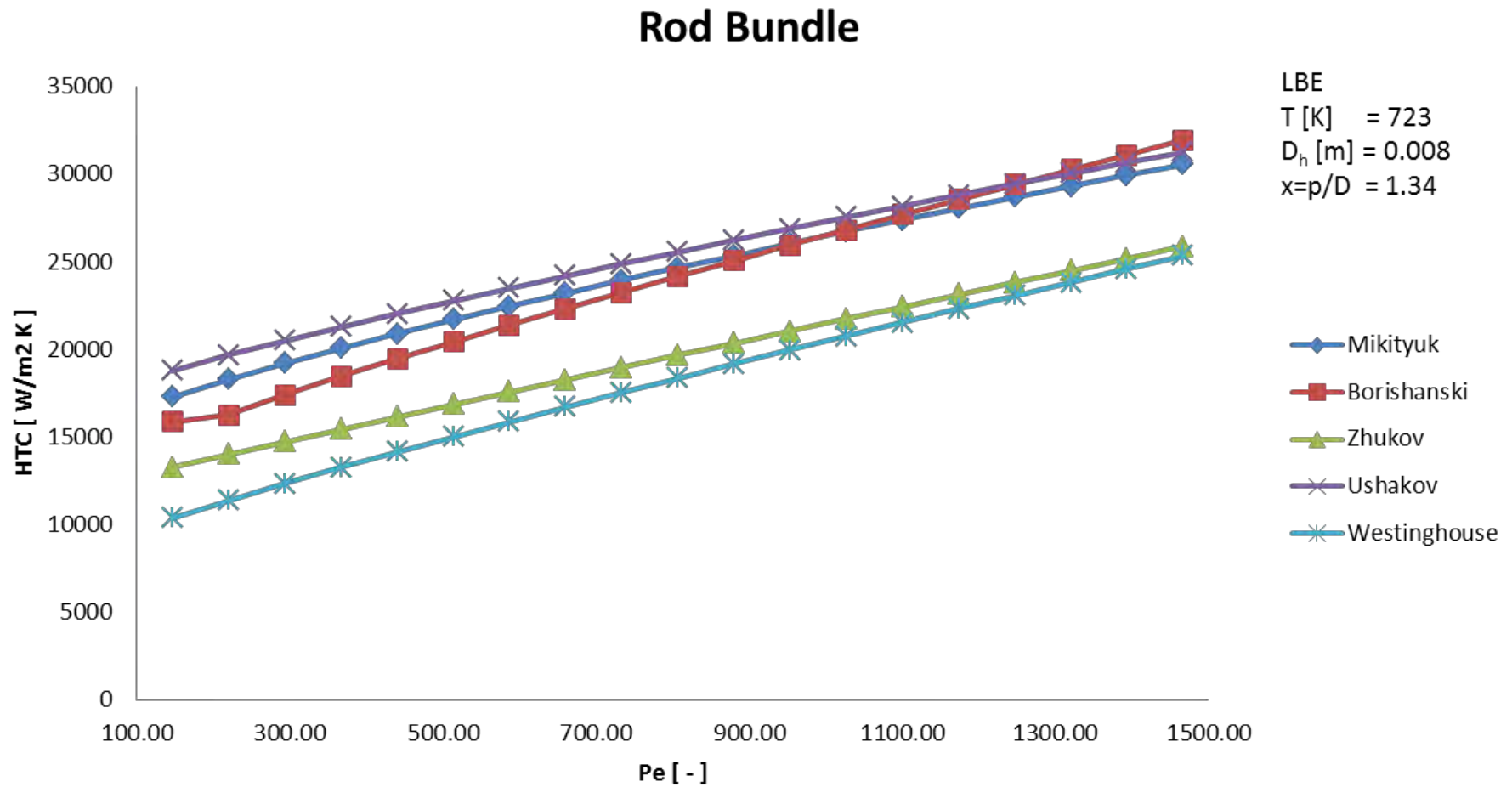
- In RELAP5-3D the westinghouse correlation (Todreas and Kazimi, 1990) is used:

$$\text{Nu} = 4.0 + 0.33(P/D)^{3.8} (\text{Pe}/100)^{0.86} + 0.16(P/D)^{5.0}$$

$$1.1 \leq P/D \leq 1.4 \text{ and } 10 \leq \text{Pe} \leq 5000$$



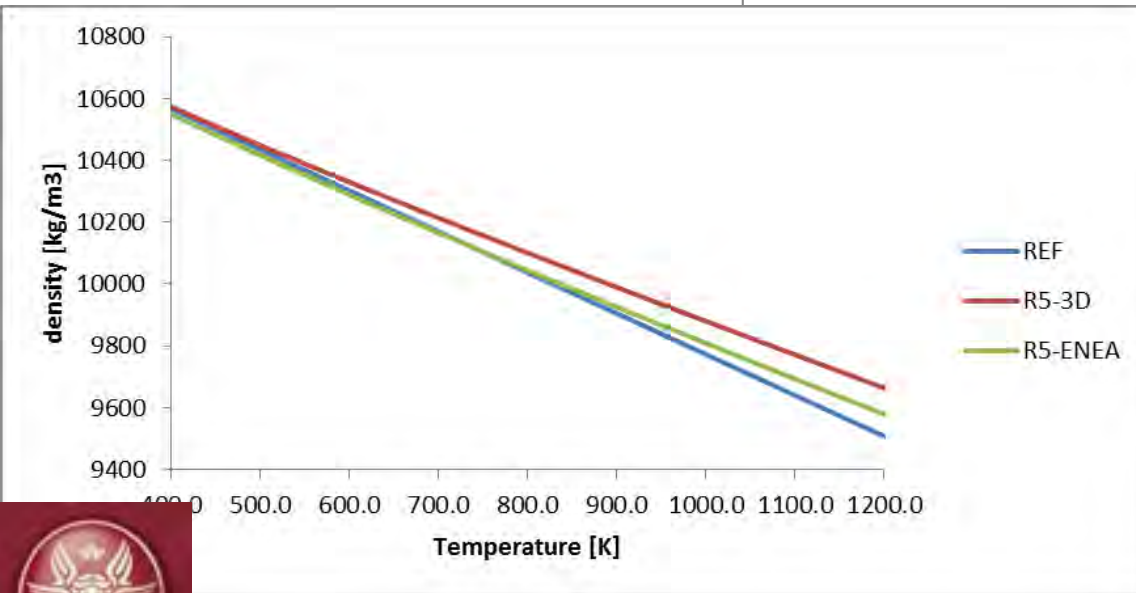
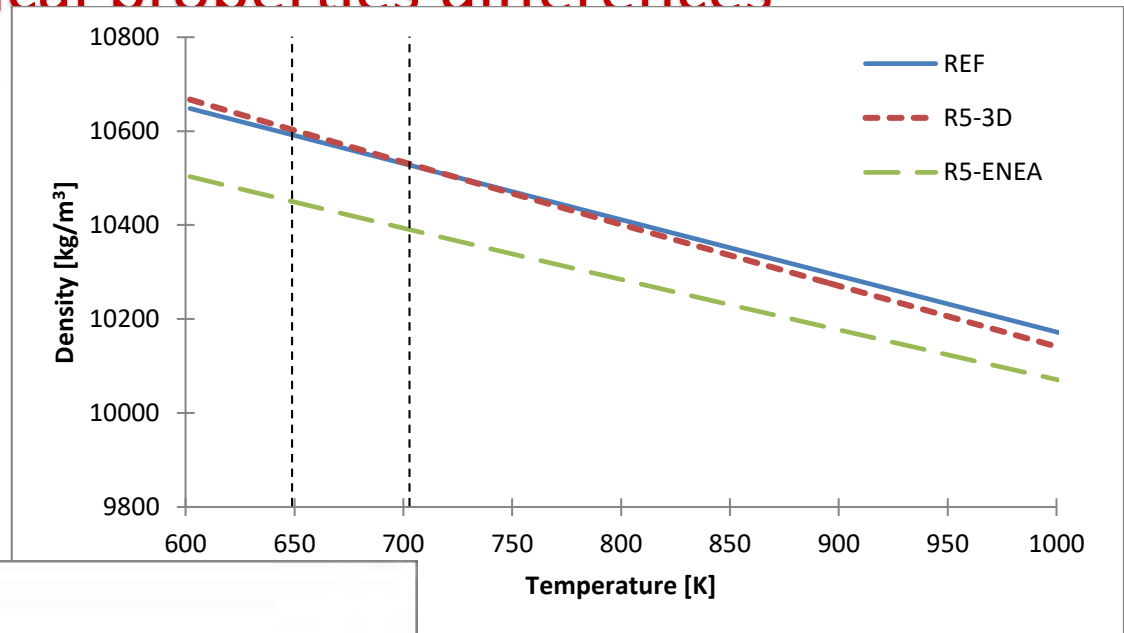
Heat transfer coefficient correlations for HLM



Thermo-physical properties differences

REF is NEA 2007

- LEAD DENSITY



3D vs reference Errore. L'origine riferimento non è stata trovata

- LBE DENSITY



Thermo-physical properties differences (2)

$$\alpha = -\frac{1}{\bar{\rho}} \frac{\partial \rho}{\partial T} \left[K^{-1} \right]$$

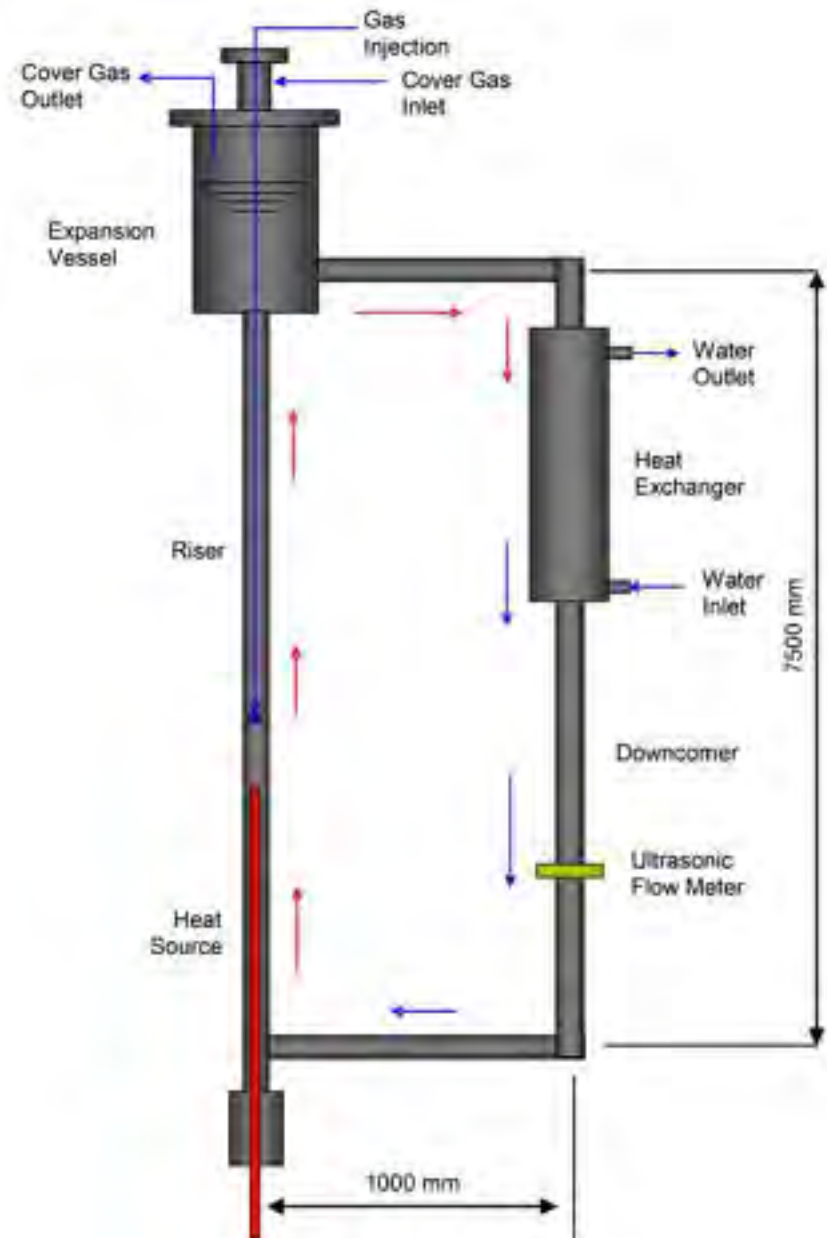
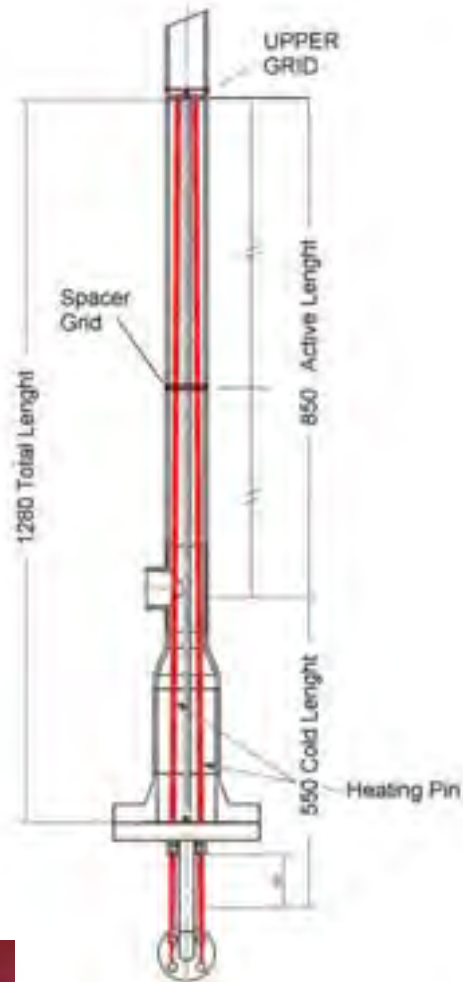
	REF	R5-3D	R5-ENEA
LEAD	1.161 E-04	1.266 E-04	1.048 E-04
LBE	1.324E-04	1.130E-04	1.206E-04

- The expansion coefficient ratio between RELAP5-3D and RELAP5 mod3.3 for lead is 1.22 and for LBE is 0.94
- A difference induced by using R5-3D respect to R5 in the natural circulation mass flow rate for a temperature range 400-480°C is about +10% for lead and -5% for LBE



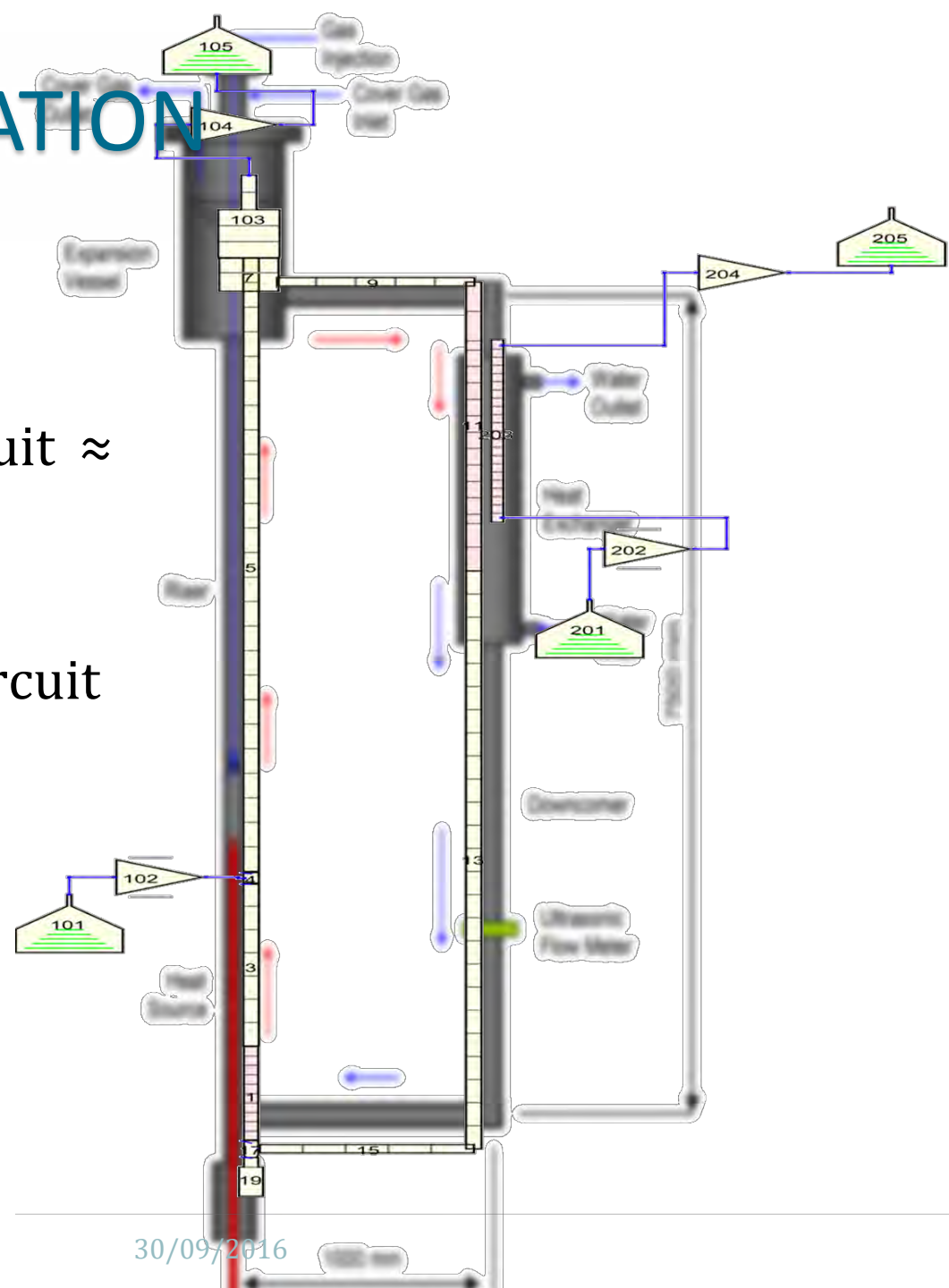
NACIE facili

*N*atural *C*irculation *E*xperiment



NACIE NODALIZATION

- Axial cell length LBE circuit ≈ 20 cm
- Axial cell length water circuit ≈ 5 cm



NACIE Relap Model details: Test 201

BOUNDARY CONDITIONS IMPOSED

- IN water mass flow rate and temperature
- Argon mass flow rate
- FPS thermal power

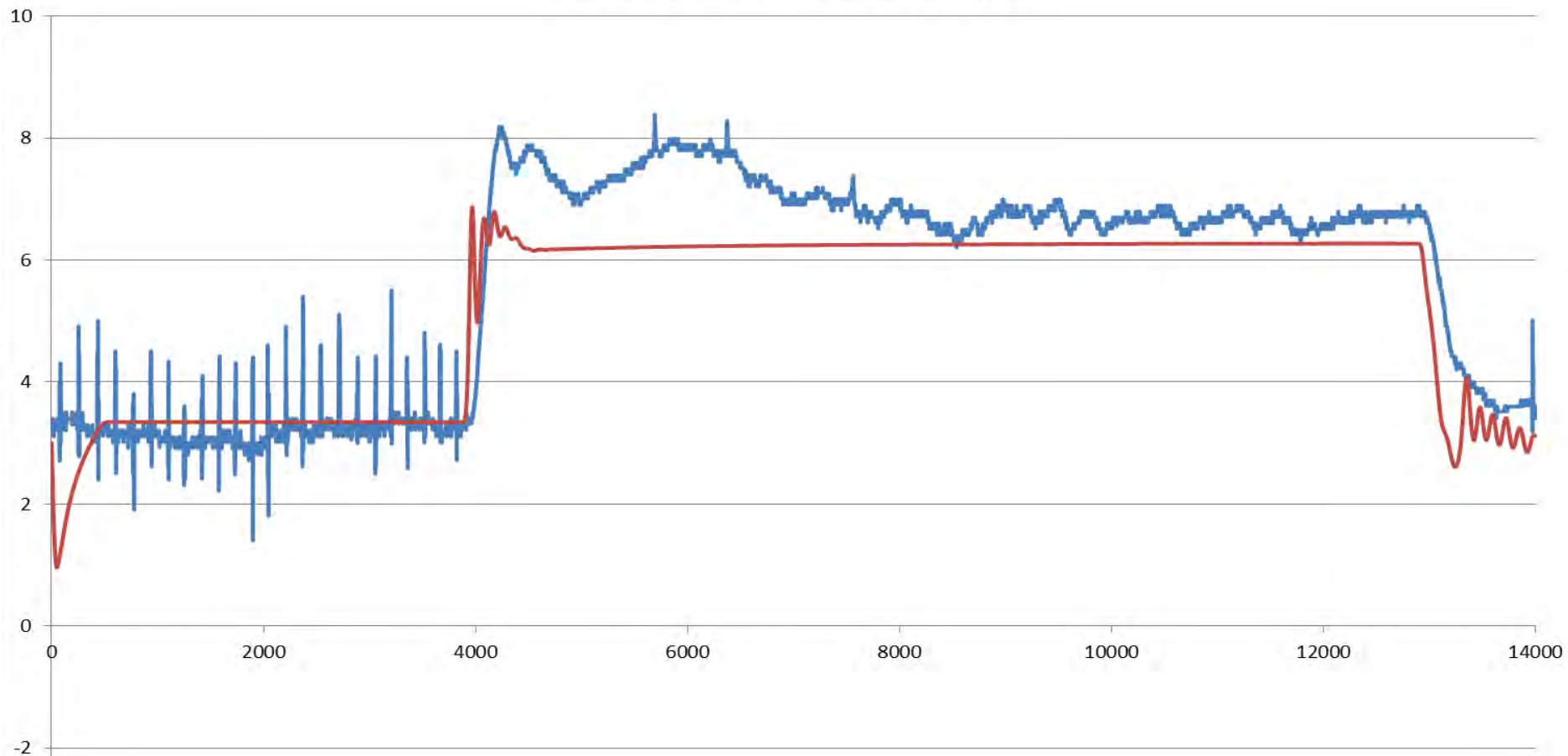
HYPOTHESIS

- $K_{\text{powder}} = 1.35 \text{ W/(mK)}$



Preliminary results

MP101 LBE Flowmeter [kg/s]



CIRCE-HERO



In the framework of SESAME project, the ENEA CIRCE pool facility has been modified to host the HERO test section.

The aims are:

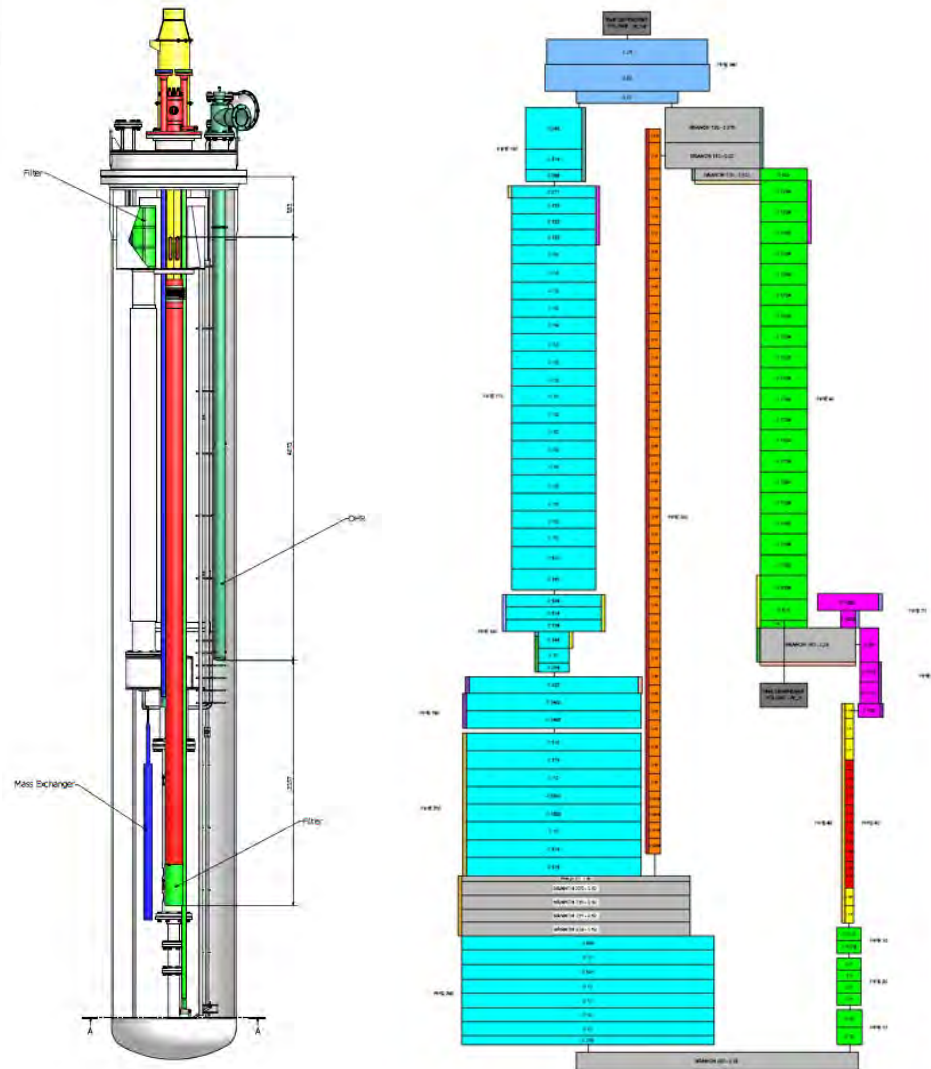
- To experimentally investigate flow behavior in all flow regimes;
- To provide experimental data for the validation and benchmarking of numerical codes on liquid metal pools.



Sapienza, University of Rome

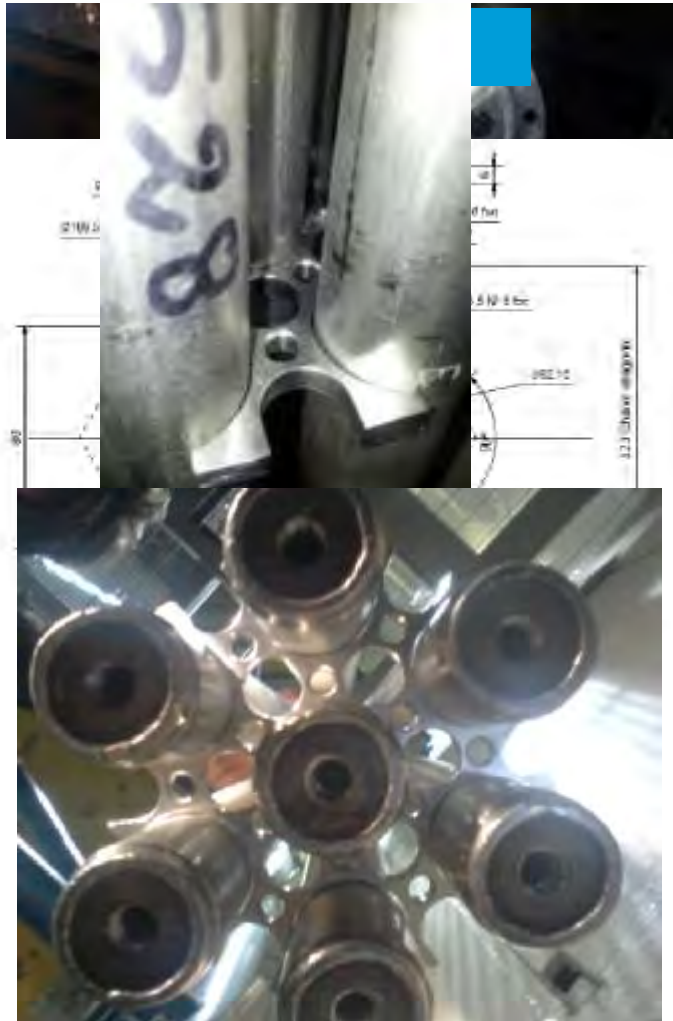
UNIRM1 will perform, during the next PAR, RELAP5-3D® calculation for the simulation of CIRCE-HERO test section to validate the code in specific tests (isothermal test?)

This year the geometry of the test section has been studied and a detailed nodalization has been prepared and preliminarily tested with RELAP5.

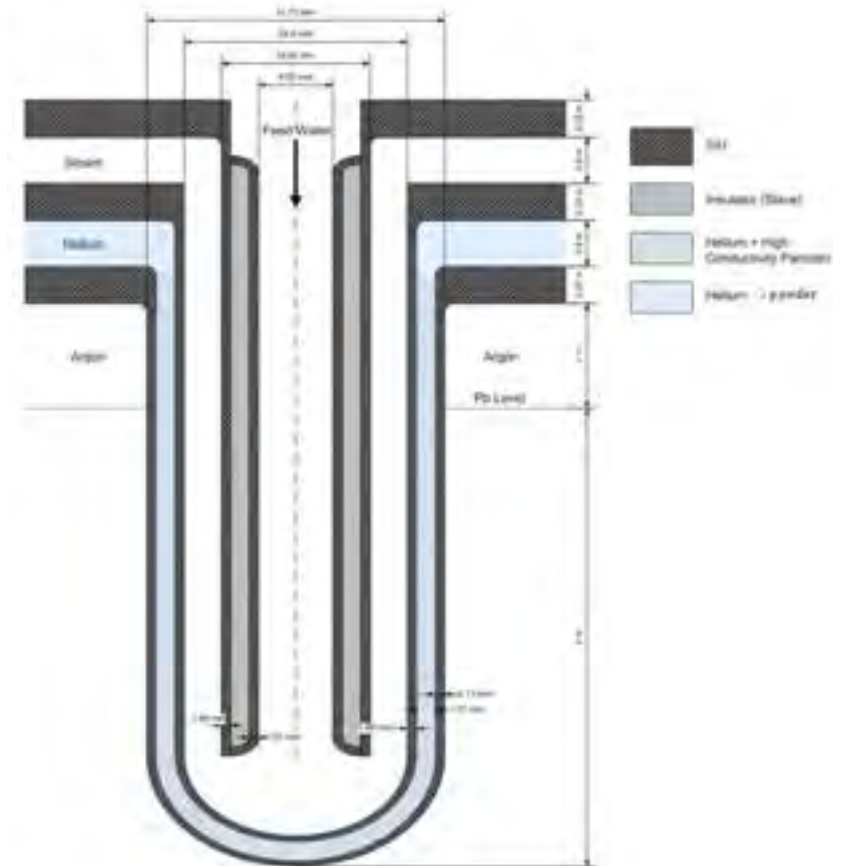


HERO SGBT

Primary side

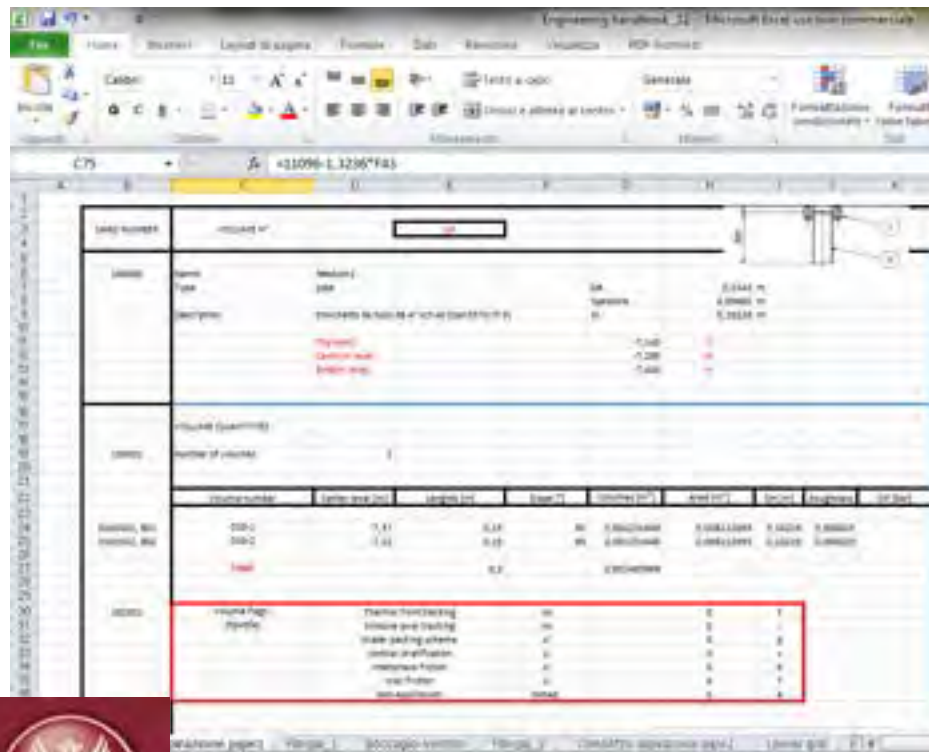


Secondary side

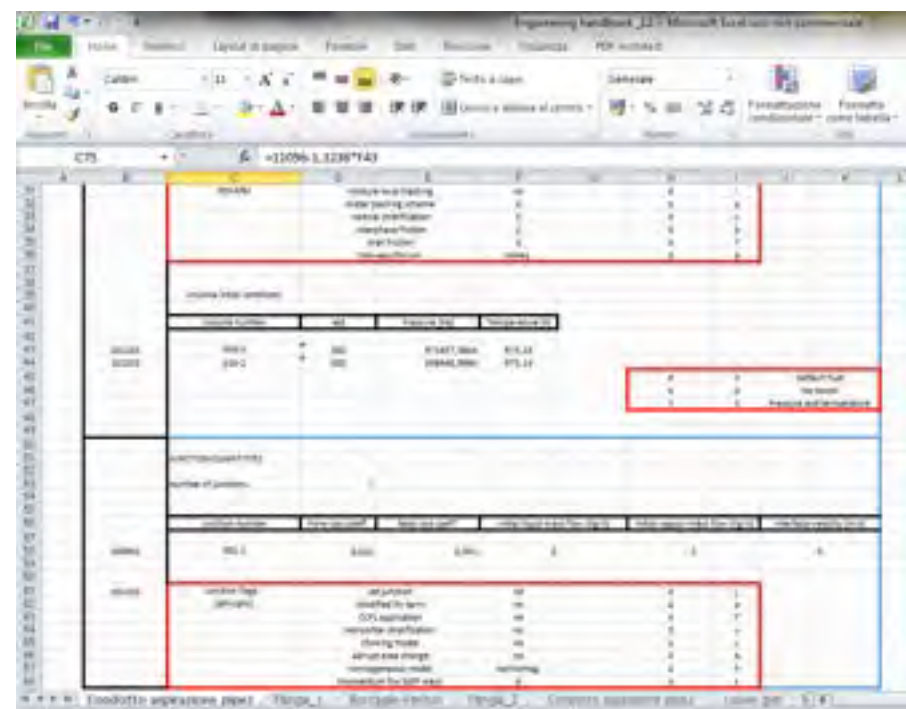


Data collection

All CIRCE-HERO main geometric data have been calculated and collected in an “Engineering Handbook” to guarantee a repeatability of the calculation with other TH codes in order to organize a benchmark



General	Geometric	Material
Name	Volume	Material
Type	Surface	Grade
Description	Area	Class
Volume	Perimeter	Code
Surface	Length	ID
Area	Width	Date
Perimeter	Height	Time
Length	Depth	User
Width	Radius	Version
Height	Diameter	Status
Depth	Thickness	Comments
Radius	Angle	Notes
Diameter	Distance	References
Thickness	Offset	Links
Angle	Tolerance	Images
Distance	Finish	Tables
Offset	Coating	Charts
Tolerance	Paint	Forms
Finish	Color	Pages
Coating	Material	Sections
Paint	Grade	Parts
Color	Class	Items
Material	Code	List
Grade	ID	Index
Class	Date	Table of Contents
Code	Time	Index of Figures
ID	User	Index of Tables
Date	Version	Index of Equations
Time	Status	Index of Symbols
User	Comments	Index of Units
Version	Notes	Index of Abbreviations
Status	References	Index of Acronyms
Comments	Links	Index of Initials
Notes	Images	Index of Surnames
References	Tables	Index of Names
Links	Charts	Index of Addresses
Images	Forms	Index of Phone Numbers
Tables	Pages	Index of Email Addresses
Charts	Sections	Index of Websites
Forms	Parts	Index of Social Media
Pages	Items	Index of Other Information
Sections	List	
Parts	Index	
Items	Table of Contents	
List	Index of Figures	
Index	Index of Tables	
Table of Contents	Index of Equations	
Index of Figures	Index of Symbols	
Index of Tables	Index of Units	
Index of Equations	Index of Abbreviations	
Index of Symbols	Index of Acronyms	
Index of Units	Index of Initials	
Index of Abbreviations	Index of Surnames	
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Index of Initials	Index of Addresses	
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Index of Addresses	Index of Websites	
Index of Phone Numbers	Index of Social Media	
Index of Email Addresses	Index of Other Information	
Index of Websites		
Index of Social Media		
Index of Other Information		



General	Geometric	Material
Name	Volume	Material
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Area	Width	Date
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Length	Depth	User
Width	Radius	Version
Height	Diameter	Status
Depth	Thickness	Comments
Radius	Angle	Notes
Diameter	Distance	References
Thickness	Offset	Links
Angle	Tolerance	Images
Distance	Finish	Tables
Offset	Coating	Charts
Tolerance	Paint	Forms
Finish	Color	Pages
Coating	Material	Sections
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Date	Version	Index of Equations
Time	Status	Index of Symbols
User	Comments	Index of Units
Version	Notes	Index of Abbreviations
Status	References	Index of Acronyms
Comments	Links	Index of Initials
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Charts	Sections	Index of Websites
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Table of Contents	Index of Equations	
Index of Figures	Index of Symbols	
Index of Tables	Index of Units	
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Index of Names	Index of Email Addresses	
Index of Addresses	Index of Websites	
Index of Phone Numbers	Index of Social Media	
Index of Email Addresses	Index of Other Information	
Index of Websites		
Index of Social Media		
Index of Other Information		



FIRST NODALIZATION

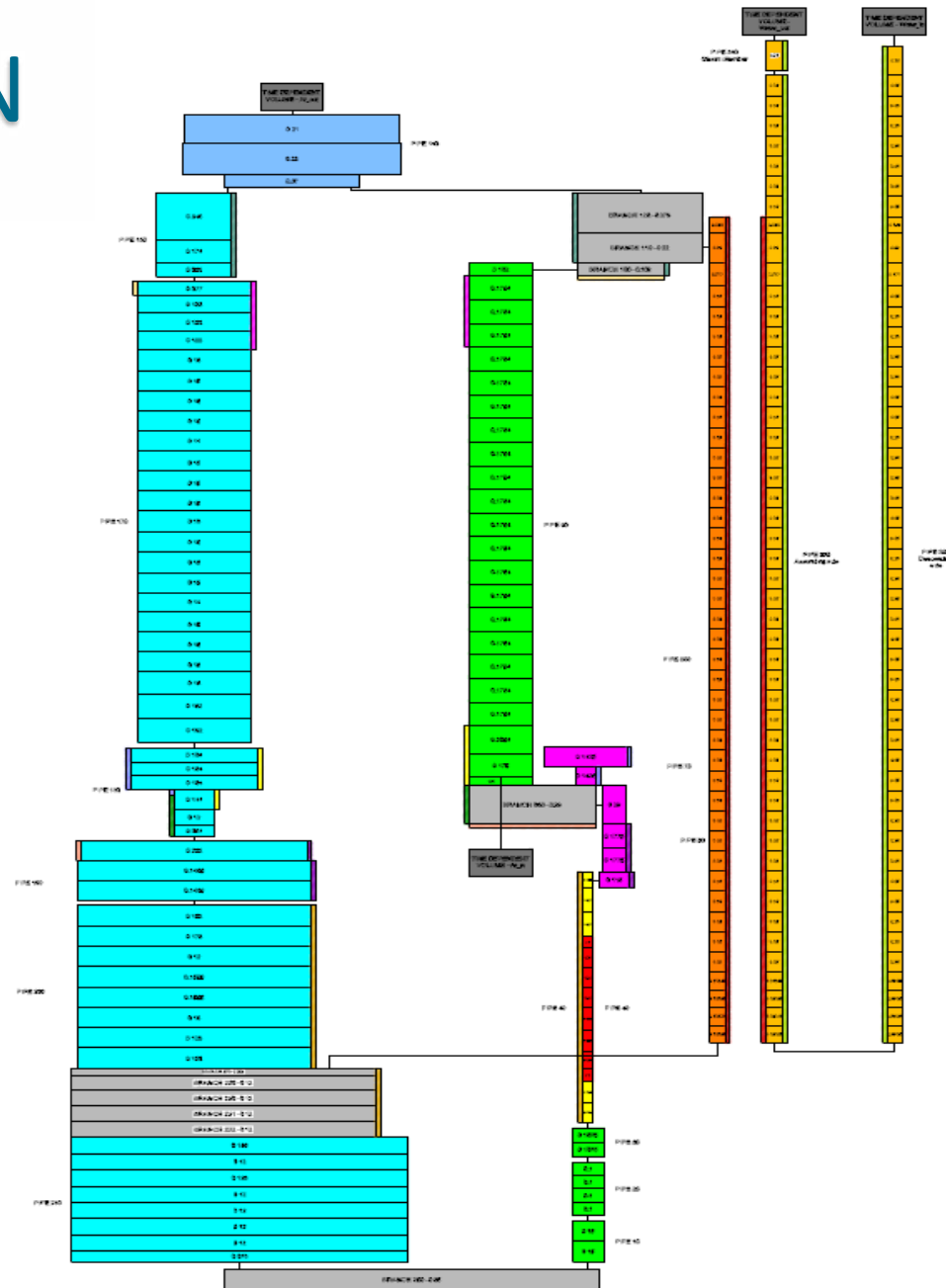
A mono-dimensional input was initially developed.

Each component is divided in several volume in order to have axial volume basic length of **150 mm**.

The primary loop is divided into **155** volumes and **156** junctions.

HERO secondary side is composed by **98** volumes and **99** junctions.

In order to study heat transfer, we have defined **12** heat structures with **155** axial mesh.



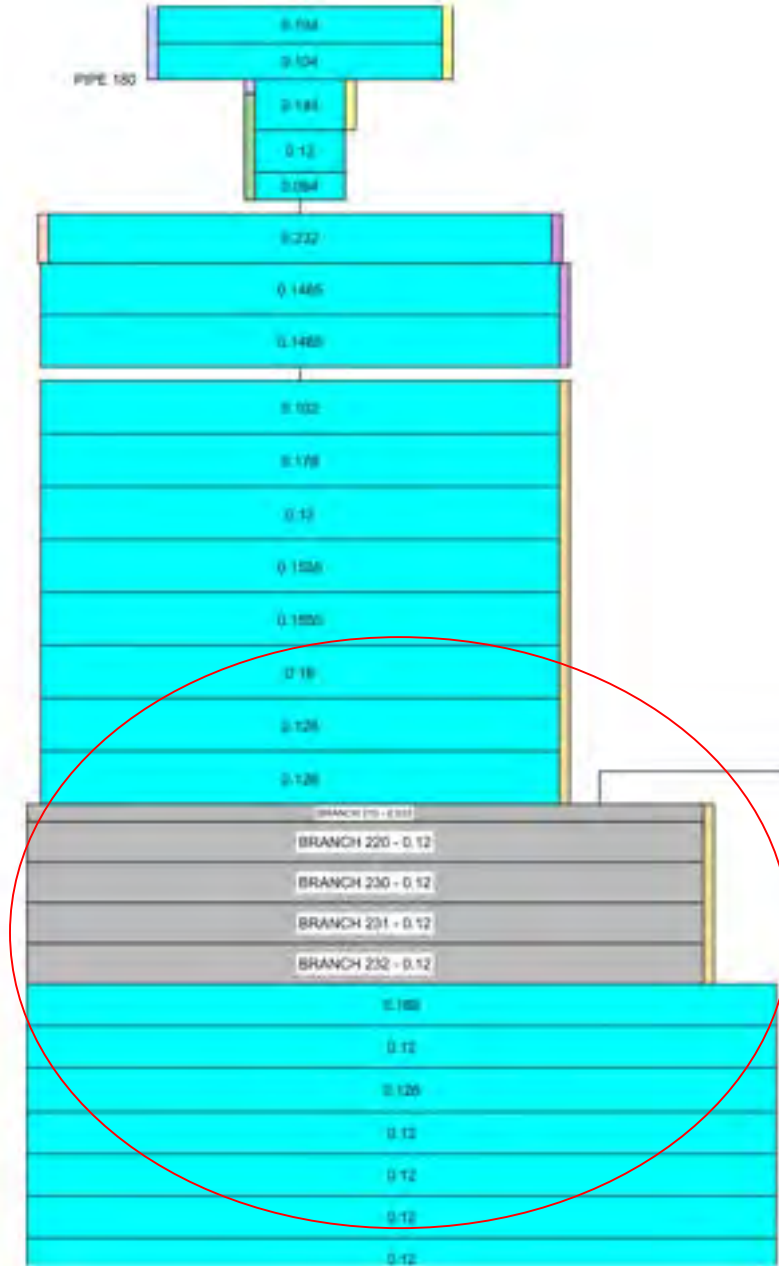
Boundary conditions

- Argon inlet mass flow rate, pressure and temperature
- HERO secondary side inlet mass flow rate, pressure and temperature
- FPS power
- DHR power



3D POOL VOLUM

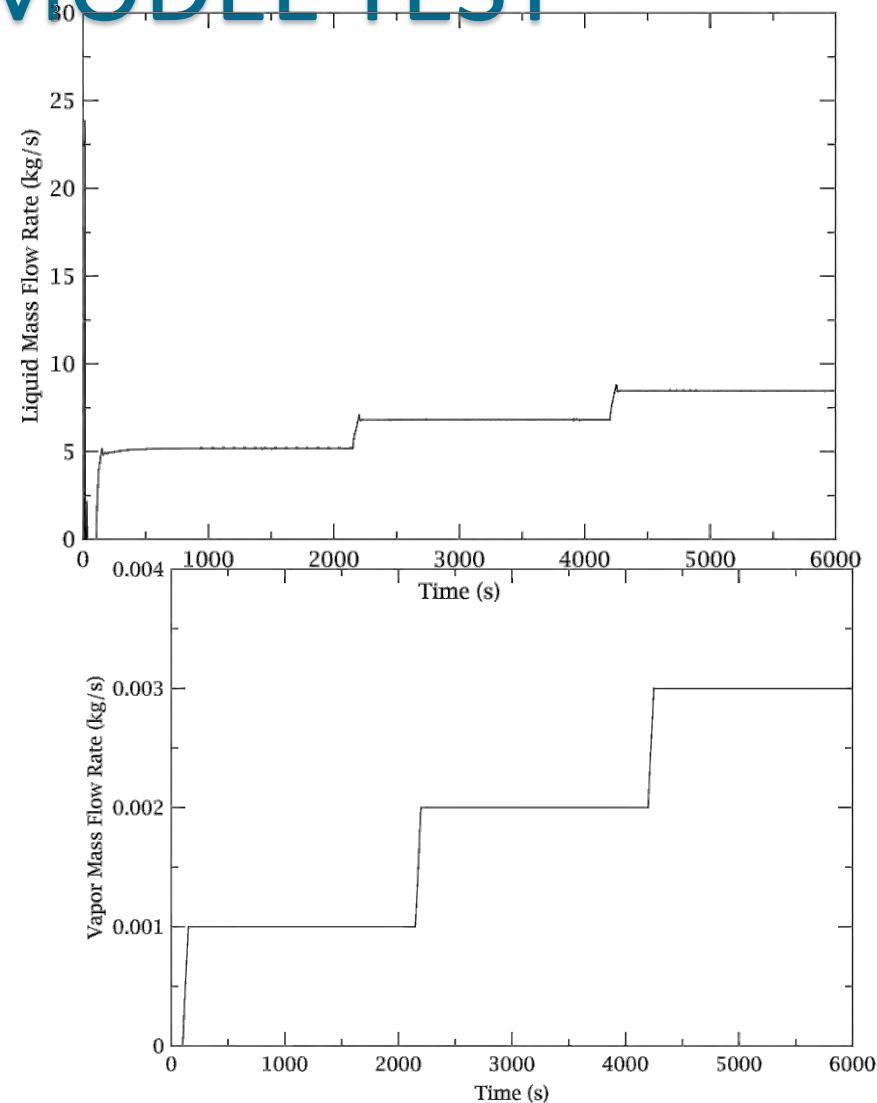
- The pool will be nodalized with same 3D volumes for the analysis of the pool mixing.
- In particular, for the HERO outlet zone:
 - 8 azimuthal zone
 - 6 radial zone
 - 10 axial levels



PRELIMINARY MODEL TEST

The first test carried out:

- isothermal with the gas lift circulation
- Acceptable stability of the model obtained using 0.0005 s as time step, but 1E-4 has been chosen to avoid spurious crash.
- Verification of the pressure drop in progress



Future works

- Verification of the CIRCE thermal dissipations
- Qualification of total pressure drops with experimental data (isothermal test)
- Comparison with R5-ENEA analysis
- Implementation of a new thermophysical properties for Pb and LBE in R5-3D with a state-of-the-art data



Thank you!



WORKSHOP TEMATICO
LFR-GEN IV

STATO ATTUALE DELLA TECNOLOGIA E PROSPETTIVE DI SVILUPPO
ADP ENEA-MSE (PAR2014-LP2)

Centro Ricerche ENEA Brasimone, 19-20 Novembre, 2015

Verifica e validazione preliminare sull'accoppiamento del
codice di calcolo RELAP5-3D e il codice di
fluidodinamica computazionale ANSYS CFX

Attività svolta per conto di GRNSPG – UNIPI – CIRTEN

Fabio Moretti
GRNSPG – Università di Pisa
NINE – Nuclear and Industrial Engineering srl
f.moretti@nineeng.com

Contenuti

- Contesto e Obbiettivi Generali
- Programma di Lavoro Pluriennale
- Caratteristiche del Tool di Accoppiamento
- Validazione dell'Accoppiamento
- Sintesi dei Risultati
- Conclusioni e Prospettive

Contesto e Obiettivi Generali

- Sviluppo e messa a punto (*) di uno strumento che permetta l'utilizzo **accoppiato** del codice di calcolo termoidraulico di sistema **RELAP** e del codice CFD **ANSYS CFX**.
 - Potenziamento delle capacità disponibili per l'analisi termoidraulica di sistemi **GEN IV**, mediante un approccio «ibrido» teso a combinare le capacità dei codici individuali, ovvero ad ovviare a parte delle rispettive limitazioni
 - Con particolare riferimento a situazioni in cui processi e **fenomeni locali e tridimensionali** (p.es. scambio termico turbolento a livello di componente) hanno un impatto importante sul comportamento dell'intero sistema (p.es. circolazione naturale)
 - Analoghi contributi «coupling-related» da parte di diversi partecipanti in ambito LP2, nell'ottica di un'ulteriore estensione delle capacità di analisi, e di un maggiore approfondimento delle problematiche connesse con l'accoppiamento tra codici

(*) mediante attività di *Verification & Validation*

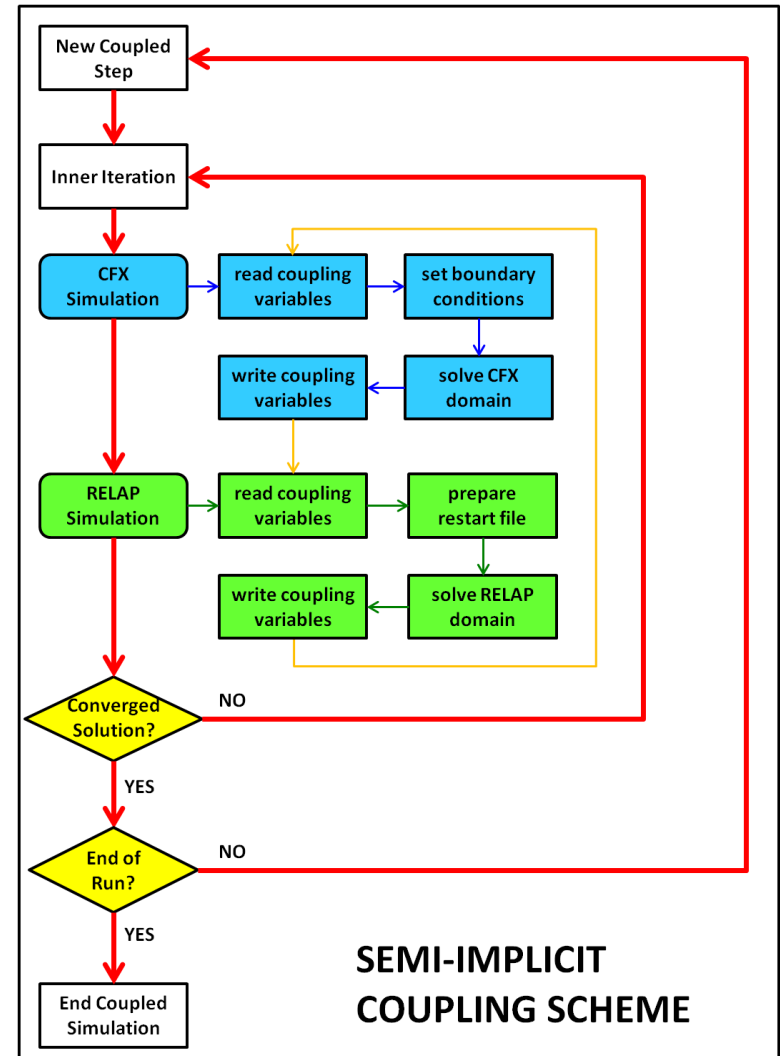
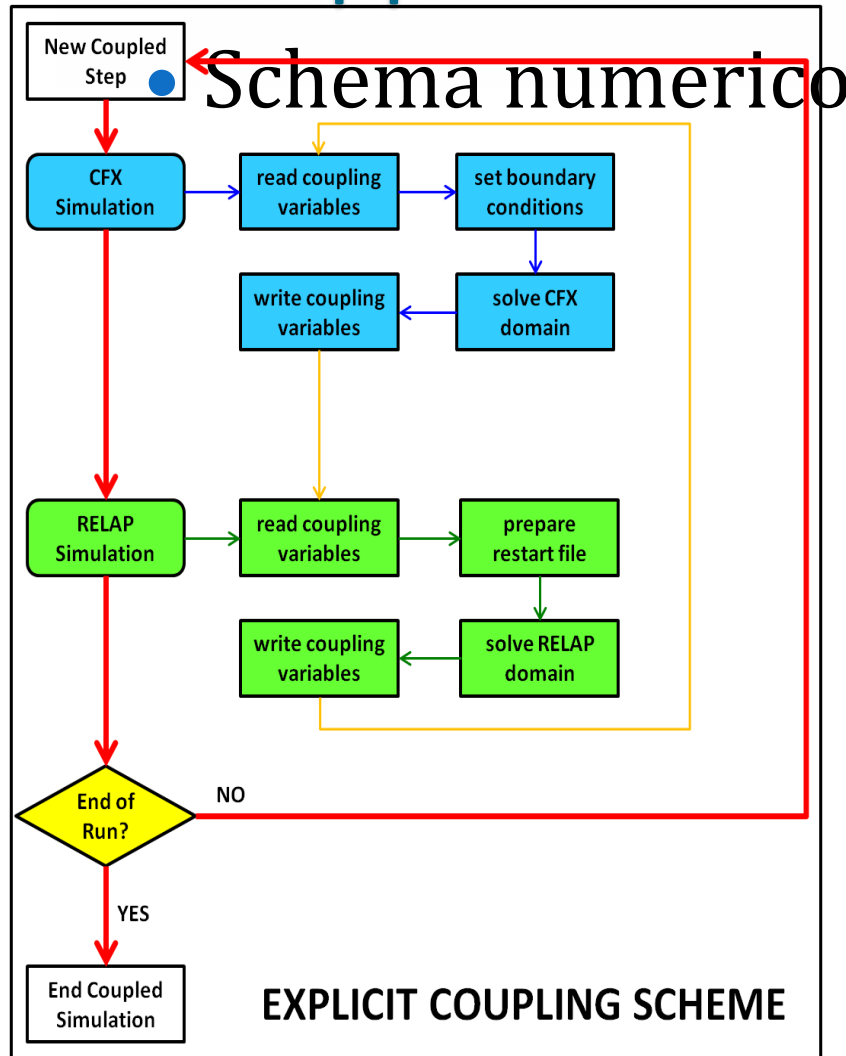
Programma di Lavoro Pluriennale

- PAR 2011
 - ✓ Analisi dello stato dell'arte
 - ✓ Predisposizione di una prima interfaccia di accoppiamento
- PAR 2012
 - ✓ Perfezionamento e ampliamento del tool precedentemente sviluppato (anche mediante sviluppo di un'interfaccia grafica)
 - ✓ Parziale attività di V&V – Concentrata su «**Verification**»
- PAR 2013
 - ✓ Ulteriore potenziamento e perfezionamento del tool di accoppiamento
 - ✓ Prosecuzione dell'attività di V&V – Questa volta con particolare riferimento alla **validazione** a fronte di dati sperimentali
- PAR 2014
 - ✓ **Estensione della base di validazione**
 - Mediante simulazioni di esperimenti NACIE, sia accoppiate che standalone
 - ✓ **Parallelizzazione (e altri miglioramenti)**

Caratteristiche del Tool di Accoppiamento

- Non-overlapping (1D-SYS / 3D-CFD):
 - I due domini di calcolo sono distinti, con regioni non sovrapposte
- Partitioned:
 - Due codici distinti si scambiano le variabili di accoppiamento «esternamente»
 - Impossibilità di risoluzione di una singola matrice di calcolo
- Sub-cycling:
 - I codici possono eseguire sotto-iterazioni / time-steps in maniera indipendente fino a raggiungere il punto di sincronizzazione per l'accoppiamento
- Sequential Coupling:
 - I due codici lavorano in modo sequenziale alternativo
 - Maggiori tempi di calcolo
 - Maggior stabilità
- Explicit & Implicit
- Underrelaxation
- ...

Caratteristiche del Tool di Accoppiamento



Caratteristiche del Tool di Accoppiamento

- Interfacce di accoppiamento
 - Due principali tipologie di interfaccia (default):
 - In-Flow: Flusso entrante nel dominio di calcolo

Type	CFX		RELAP	
	COMPONENTS	VARIABLES	VARIABLES	COMPONENTS
In-Flow	Inlet/Opening (GET)	Possible 1D -> 3D profiles ● (Default: Uniform Profile)	Temperature (Enthalpy) Velocity (Mass Flow Rate)	PIPE/BR SNGJ
	Inlet/Opening (SEND)	Pressure ●		TDV
Out-Flow	Outlet/Opening (GET)	●	Pressure	PIPE/BR
	Outlet/Opening (SEND)	Temperature (Enthalpy) Velocity (Mass Flow Rate)		TDV TDJ

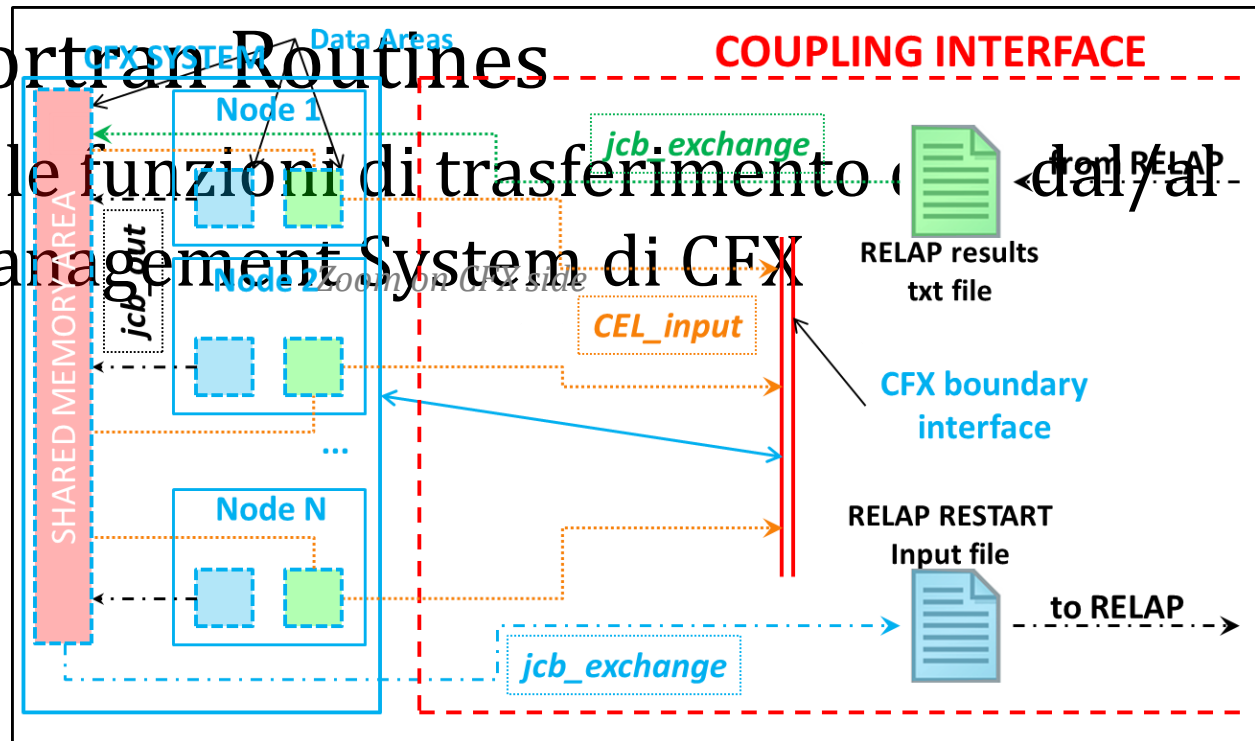
Implementazione del Tool di

Accoppiamento

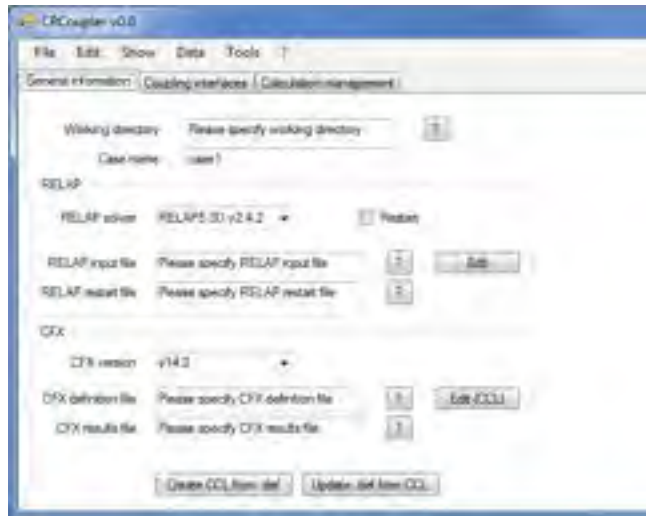
- Coupling Master
 - Routine PERL che coordina l'esecuzione dei due codici e gestisce i file necessari per il trasferimento dati

- CFX User Fortran Routines

- Gestiscono le funzioni di trasferimento di dati al Memory Management System di CFX



- Interfaccia grafica



Interface name	Serial code	CFX boundary	RELAP boundary	RELAP boundary label	Exchanged variable	Control variable	Control variable name	Initial value	Velocity profile
Inlet	RELAP	inlet	134010000	cool	Temperature	na	na	1	Fully developed
202	RELAP	inlet	100000000	anglun	Velocity	na	na	1	Uniform
303	CFX	inlet	138010000	coolpval	Pressure	20590010	press1	1	na
304	CFX	outlet	030010000	coolpval	Temperature	20590020	temp1	1	na
305	CFX	outlet	202000000	anglun	Velocity	20590030	vel1	1	na
306	RELAP	outlet	254010000	cool	Pressure	na	na	1	na

CFX Coupler v0.0.0

File Edit Show Data Tools ?

General information | Coupling interfaces | Calculation management

Coupling scheme: Explicit

Under-relaxation factor:

Write coupling input file

Update CFX definition file

Run coupled calculation

Stop coupled calculation

Test standalone CFX run

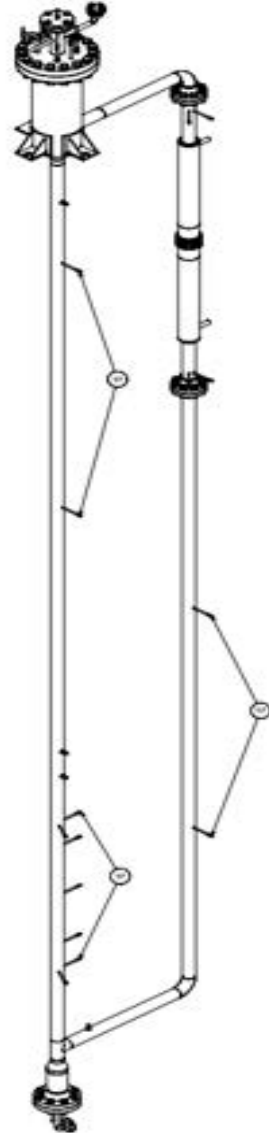
Test standalone RELAP run

File shown: temporary &file_001.out

Component	Iteration	Time	Status
CFX	1	0.00	Running
RELAP	1	0.00	Running
CFX	2	0.00	Running
RELAP	2	0.00	Running
CFX	3	0.00	Running
RELAP	3	0.00	Running
CFX	4	0.00	Running
RELAP	4	0.00	Running
CFX	5	0.00	Running
RELAP	5	0.00	Running
CFX	6	0.00	Running
RELAP	6	0.00	Running
CFX	7	0.00	Running
RELAP	7	0.00	Running
CFX	8	0.00	Running
RELAP	8	0.00	Running
CFX	9	0.00	Running
RELAP	9	0.00	Running
CFX	10	0.00	Running
RELAP	10	0.00	Running
CFX	11	0.00	Running
RELAP	11	0.00	Running
CFX	12	0.00	Running
RELAP	12	0.00	Running
CFX	13	0.00	Running
RELAP	13	0.00	Running
CFX	14	0.00	Running
RELAP	14	0.00	Running
CFX	15	0.00	Running
RELAP	15	0.00	Running
CFX	16	0.00	Running
RELAP	16	0.00	Running
CFX	17	0.00	Running
RELAP	17	0.00	Running
CFX	18	0.00	Running
RELAP	18	0.00	Running
CFX	19	0.00	Running
RELAP	19	0.00	Running
CFX	20	0.00	Running
RELAP	20	0.00	Running
CFX	21	0.00	Running
RELAP	21	0.00	Running
CFX	22	0.00	Running
RELAP	22	0.00	Running
CFX	23	0.00	Running
RELAP	23	0.00	Running
CFX	24	0.00	Running
RELAP	24	0.00	Running
CFX	25	0.00	Running
RELAP	25	0.00	Running
CFX	26	0.00	Running
RELAP	26	0.00	Running
CFX	27	0.00	Running
RELAP	27	0.00	Running
CFX	28	0.00	Running
RELAP	28	0.00	Running
CFX	29	0.00	Running
RELAP	29	0.00	Running
CFX	30	0.00	Running
RELAP	30	0.00	Running
CFX	31	0.00	Running
RELAP	31	0.00	Running
CFX	32	0.00	Running
RELAP	32	0.00	Running
CFX	33	0.00	Running
RELAP	33	0.00	Running
CFX	34	0.00	Running
RELAP	34	0.00	Running
CFX	35	0.00	Running
RELAP	35	0.00	Running
CFX	36	0.00	Running
RELAP	36	0.00	Running
CFX	37	0.00	Running
RELAP	37	0.00	Running
CFX	38	0.00	Running
RELAP	38	0.00	Running
CFX	39	0.00	Running
RELAP	39	0.00	Running
CFX	40	0.00	Running
RELAP	40	0.00	Running
CFX	41	0.00	Running
RELAP	41	0.00	Running
CFX	42	0.00	Running
RELAP	42	0.00	Running
CFX	43	0.00	Running
RELAP	43	0.00	Running
CFX	44	0.00	Running
RELAP	44	0.00	Running
CFX	45	0.00	Running
RELAP	45	0.00	Running
CFX	46	0.00	Running
RELAP	46	0.00	Running

Validazione dell'Accoppiamento

- Verificare il corretto funzionamento del tool di accoppiamento mediante verifica di consistenza tra
 - risultati simulazione RELAP5-3D standalone, e
 - risultati simulazione accoppiata RELAP5-3D / CFX
- Le simulazioni si riferiscono a esperimenti di circolazione naturale e assistita di LBE (NaClE)
 - Obiettivo: validare l'applicazione dell'accoppiamento in ambito



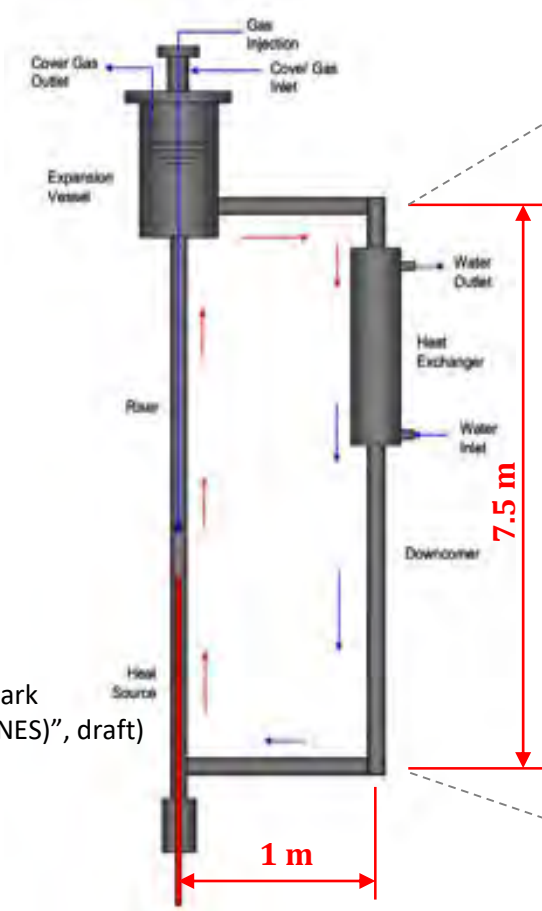
Validazione dell'Accoppiamento

Test NACIE (2012) selezionati

ID	T_{av} [°C]	Power %	Power [kW]	Ramp t [min]	Heat Sink	Glift [NI/min]	Transition NC to GLC	Transition GLC to NC
201	200-250	50	9.5	5	YES	0	NO	NO
203	200-250	50	9.5	5	YES	5	NO	YES
204	200-250	50	9.5	5	YES	2,4,5,6,8, 10,6,5,4,2	YES	NO
206	200-250	0	0	-	NO	2,4,5,6,8, 10,6,5,4,3	NO	NO
301	300-350	100	21.5	5	YES	0	NO	NO
303	300-350	100	21.5	5	YES	5	NO	YES
304	300-350	100	21.5	5	YES	2,4,5,6,8, 10,6,5,4,2	YES	NO
305	300-350	50	9.5	5	YES	0	NO	NO
306	300-350	0	0	-	NO	2,4,5,6,8, 10,6,5,4,2	NO	NO
406	350-360	25	3.5	5	NO	2,4,5,6,8, 10,6,5,4,2	NO	NO

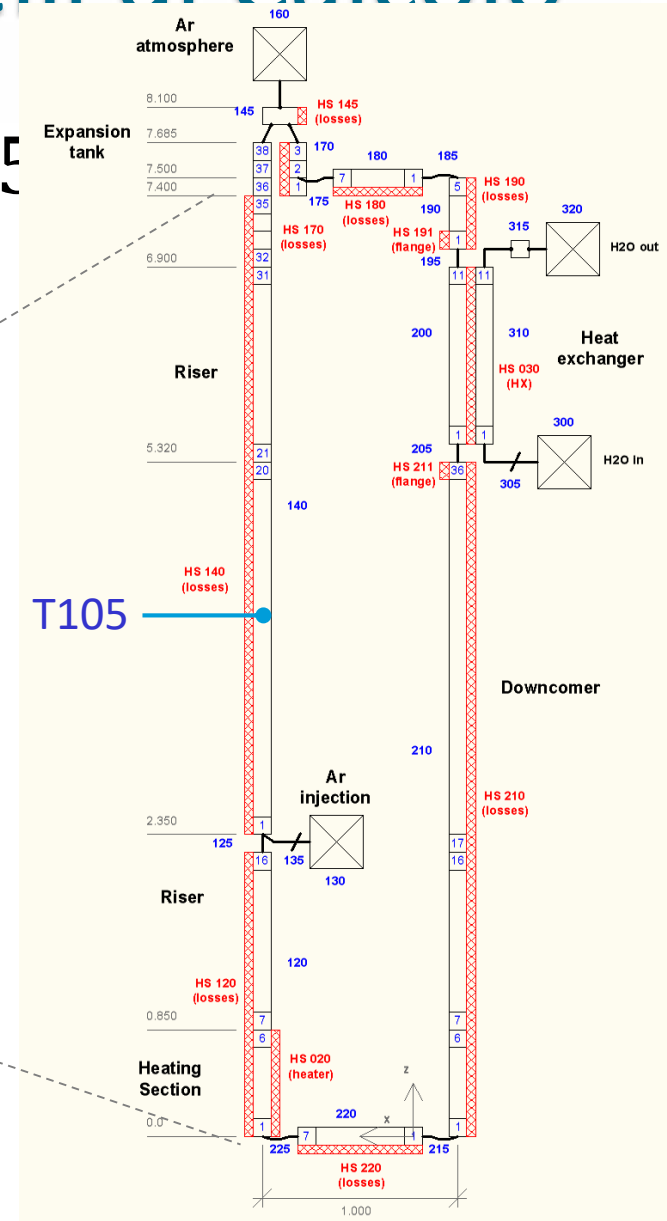
Validazione – Modelli di Calcolo

- Nodalizzazione RELAP5



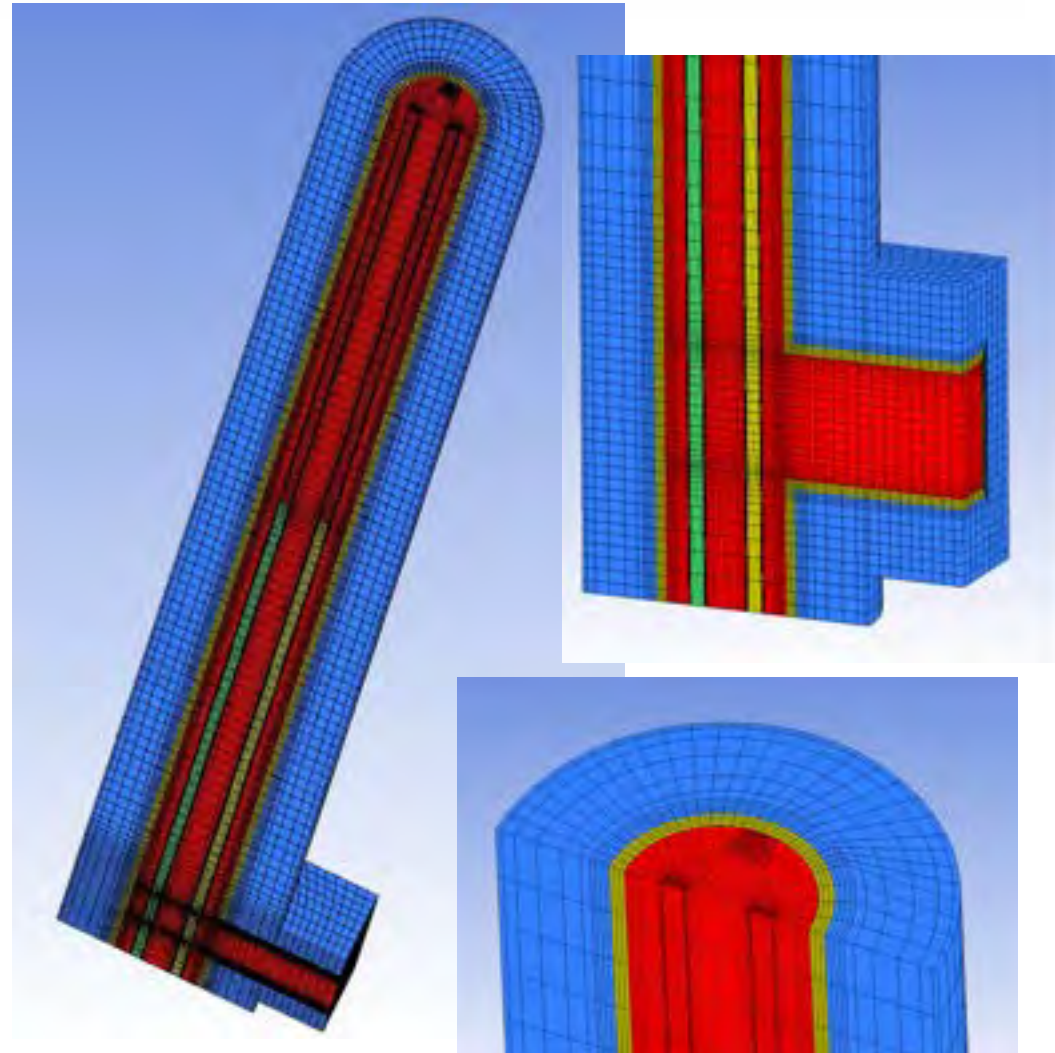
Schema della test facility NACIE

(Ref. P. Meloni, M. Polidori, "NACIE Benchmark Specifications and Experimental Data (LACANES)", draft)

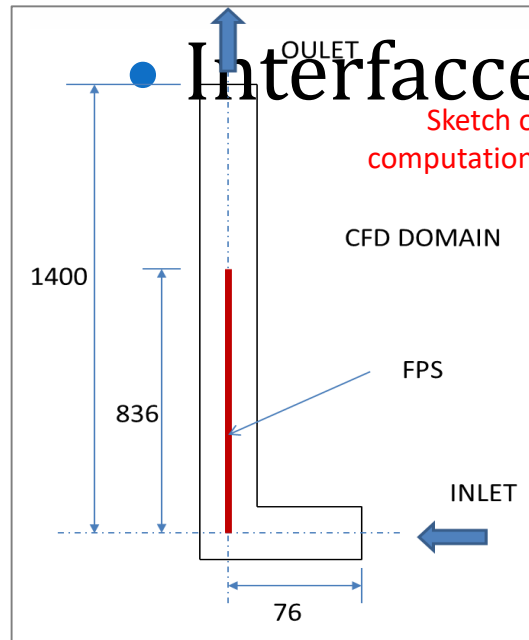


Validazione – Modelli di Calcolo

- Mesh ANSYS CFX
 - Dominio di calcolo dimezzato (simmetria)
 - Include LBE, FPS, tubo inox, coibentazione
 - Esteso per ca. 1m a valle del FPS
 - Geometria inlet semplificata per migliorare la qualità della griglia e quindi la performance numerica
 - Mesh esaedrica, buona qualità, 142000 nodi (di cui 68000 per LBE)

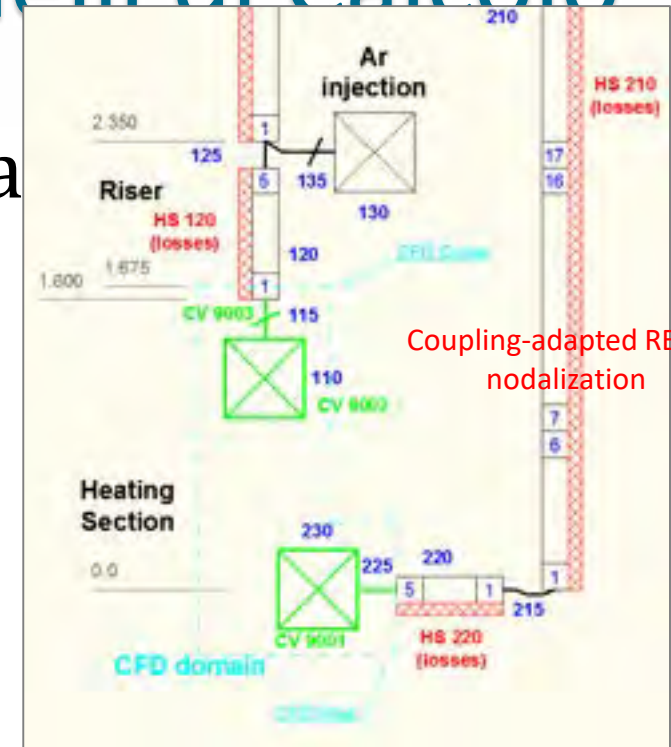


Validazione – Modelli di Calcolo



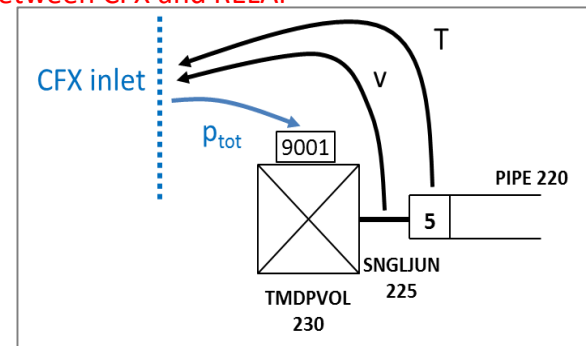
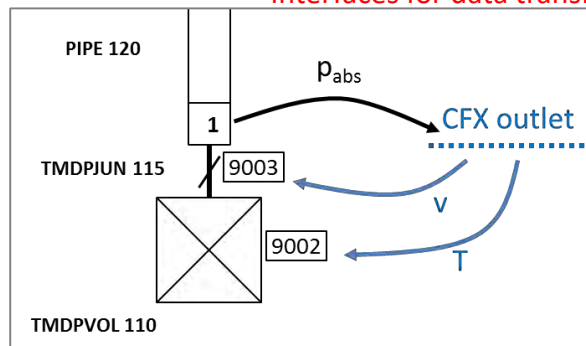
• Interfacce di accoppia

Sketch of CFD
computational domain



Coupling-adapted RELAP
nodalization

Interfaces for data transfer between CFX and RELAP



Validazione – Modelli di Calcolo

□ Interfacce di accoppiamento

Variables exchanged from RELAP to CFX

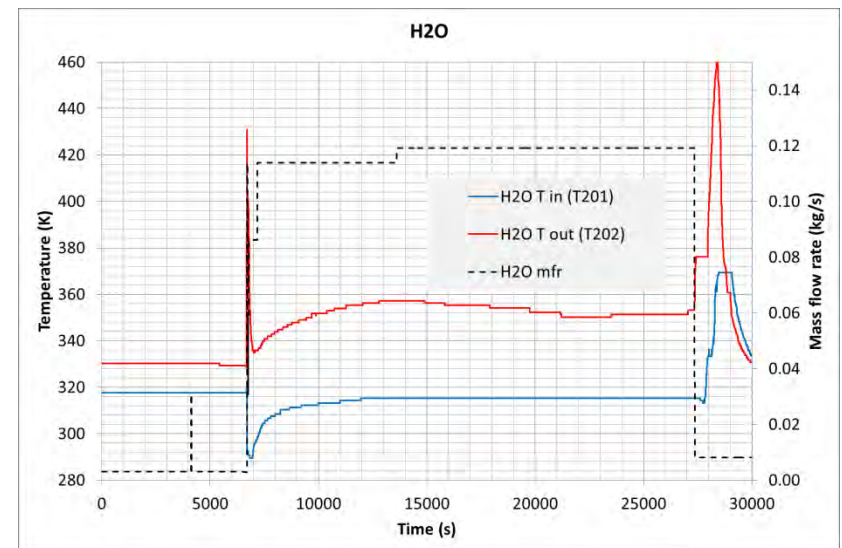
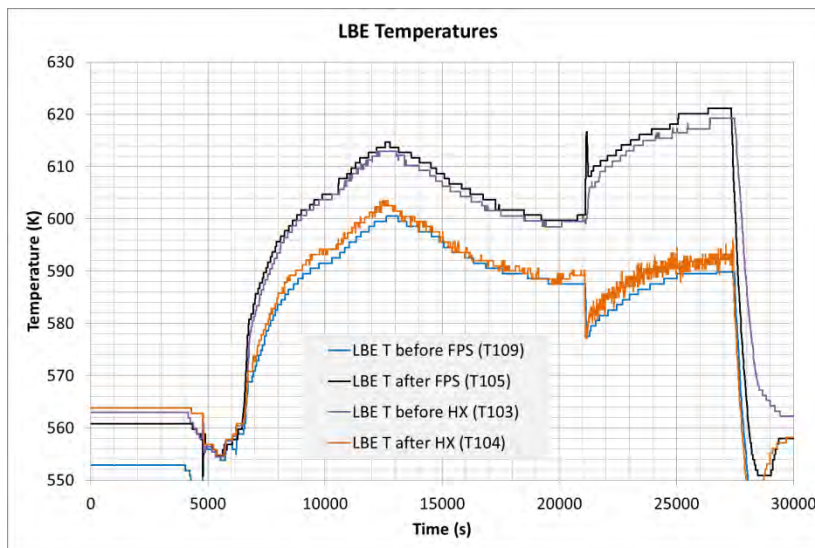
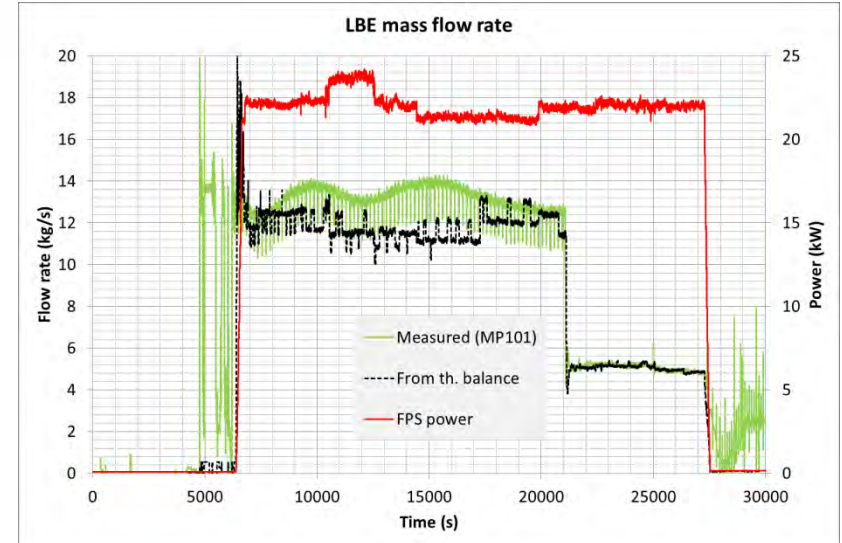
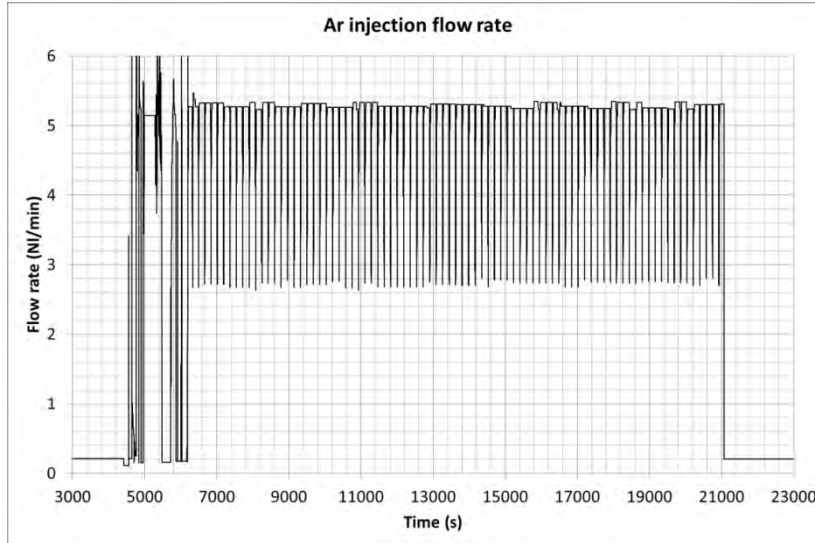
Var #	Variable	From	To
001	T	22005	inlet
002	V	22500	inlet
006	p	12001	outlet

Variables exchanged from CFX to RELAP

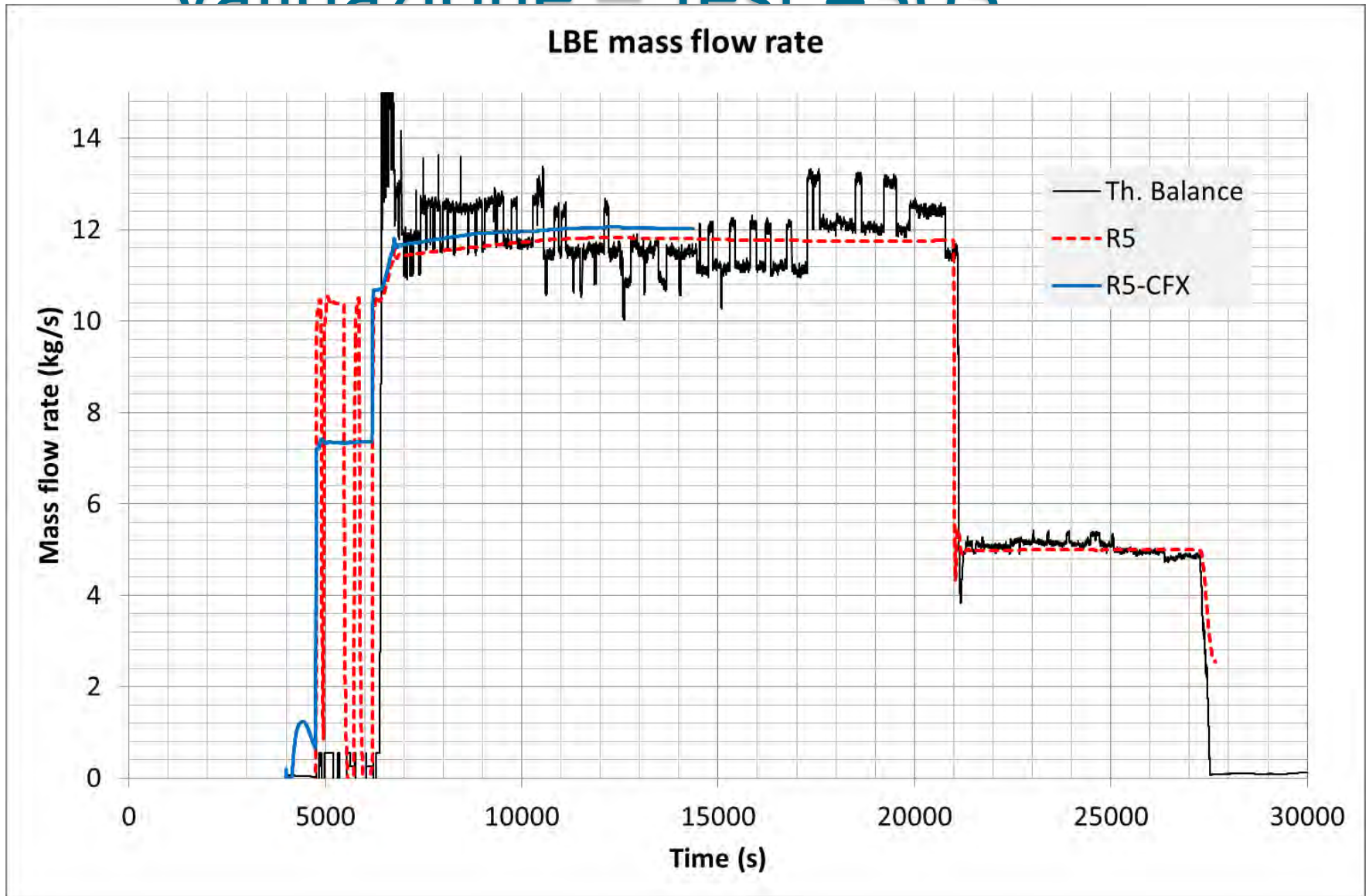
Var #	Variable	From	To	Control var.
003	p (tot)	inlet	23001	9001
004	T	outlet	11001	9002
005	v	outlet	11500	9003

Validazione – Test #303

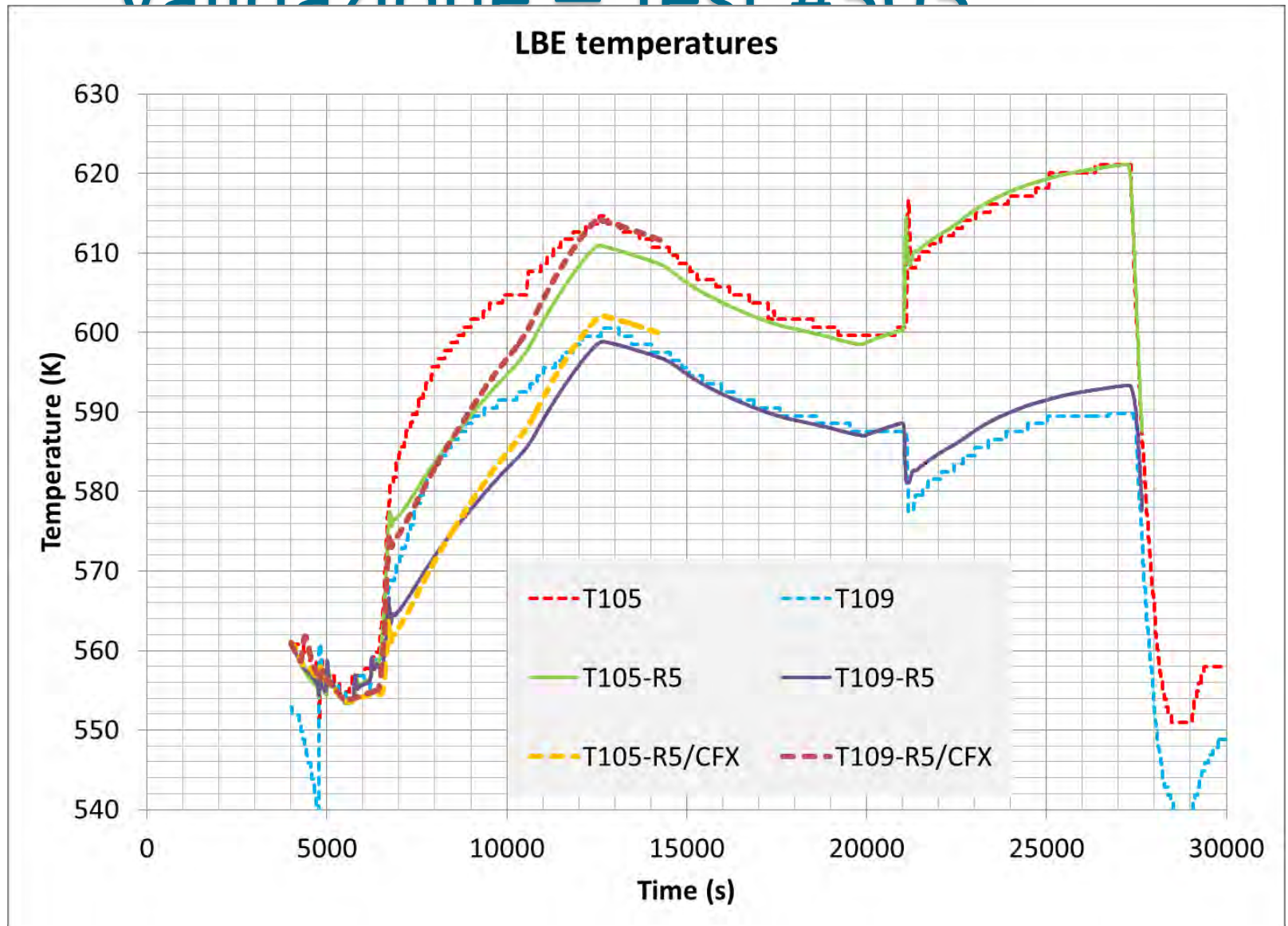
300-350 °C; 21.5 kW; with HX; NC + gas lift



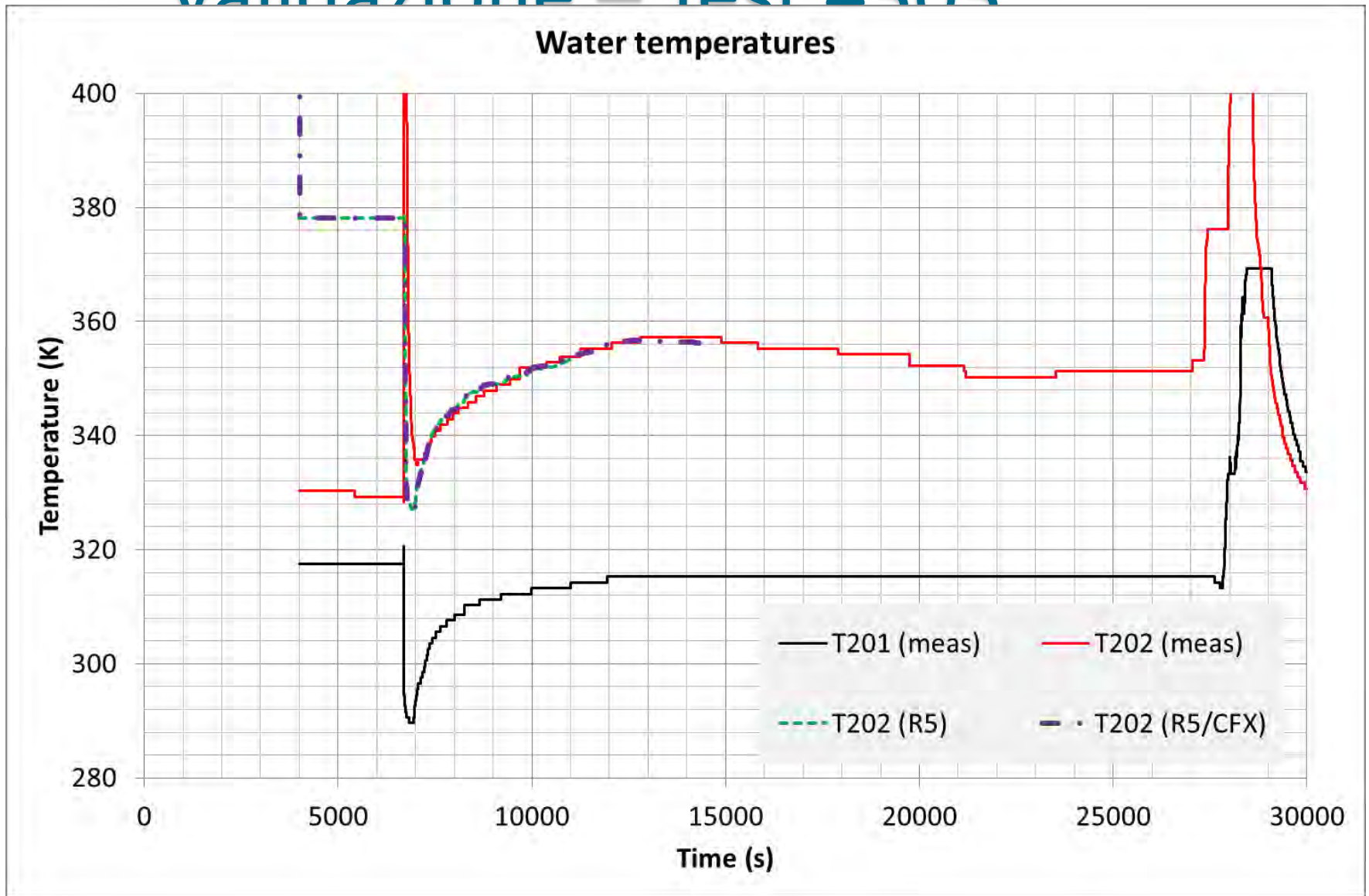
Validazione – Test #303



Validazione – Test #303

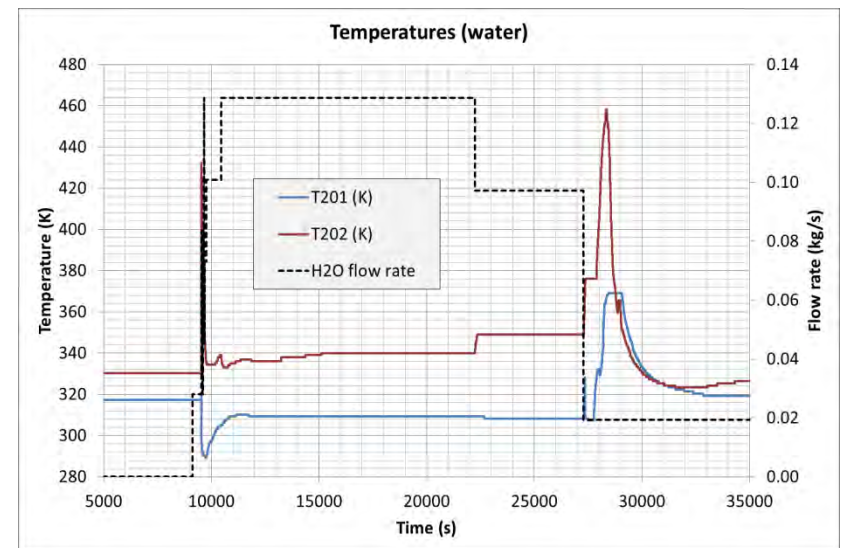
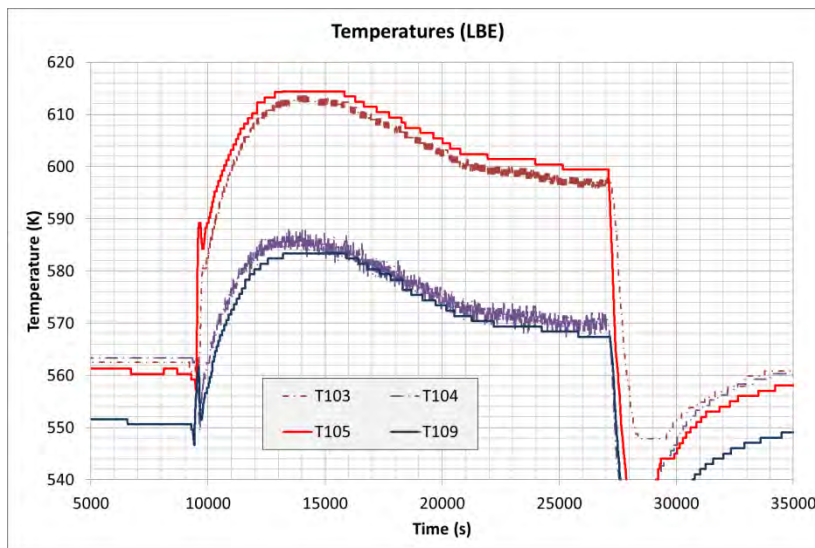
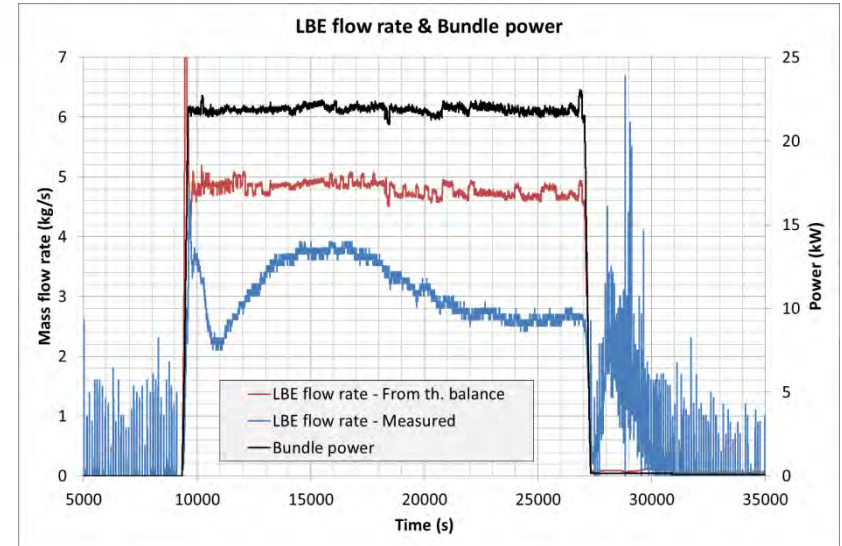
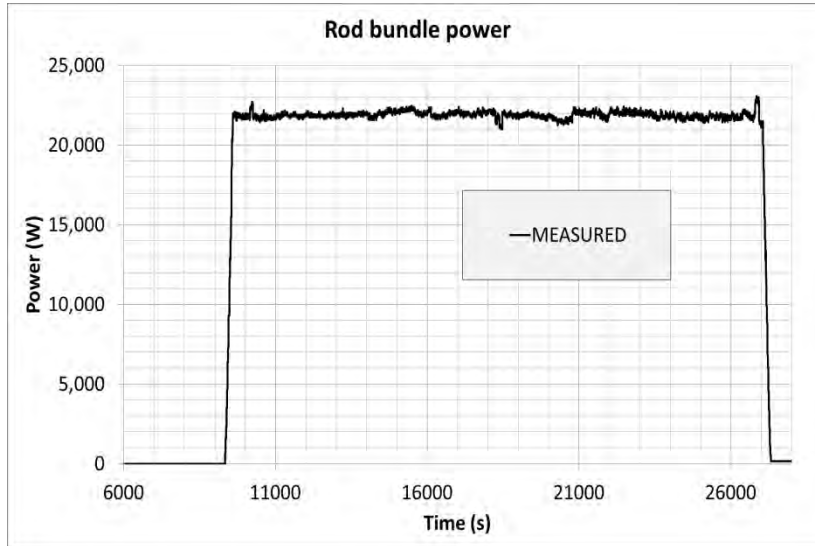


Validazione – Test #303



Validazione – Test #301

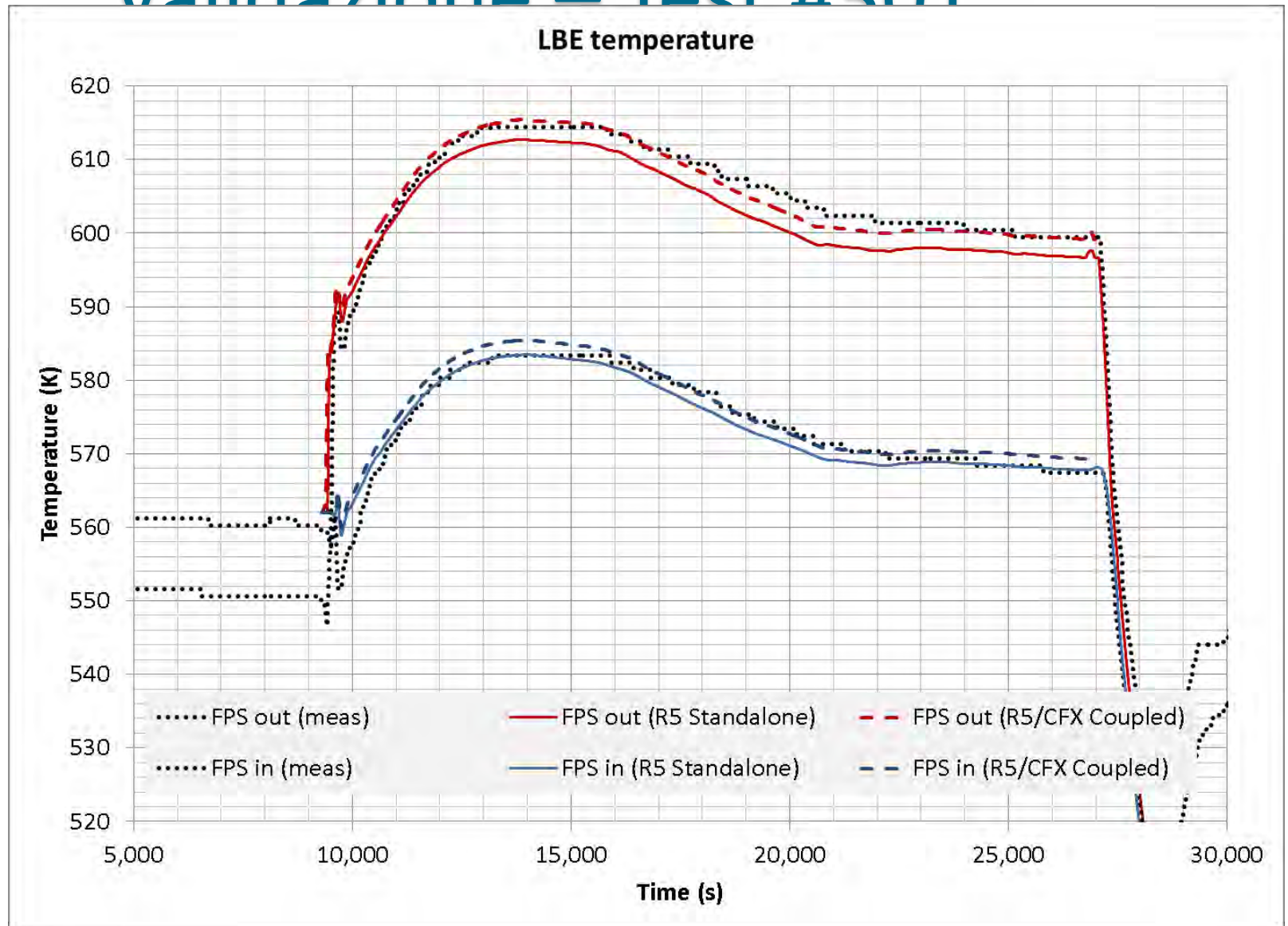
300-350 °C; 21.5 kW; with HX; NC only (no gas lift)



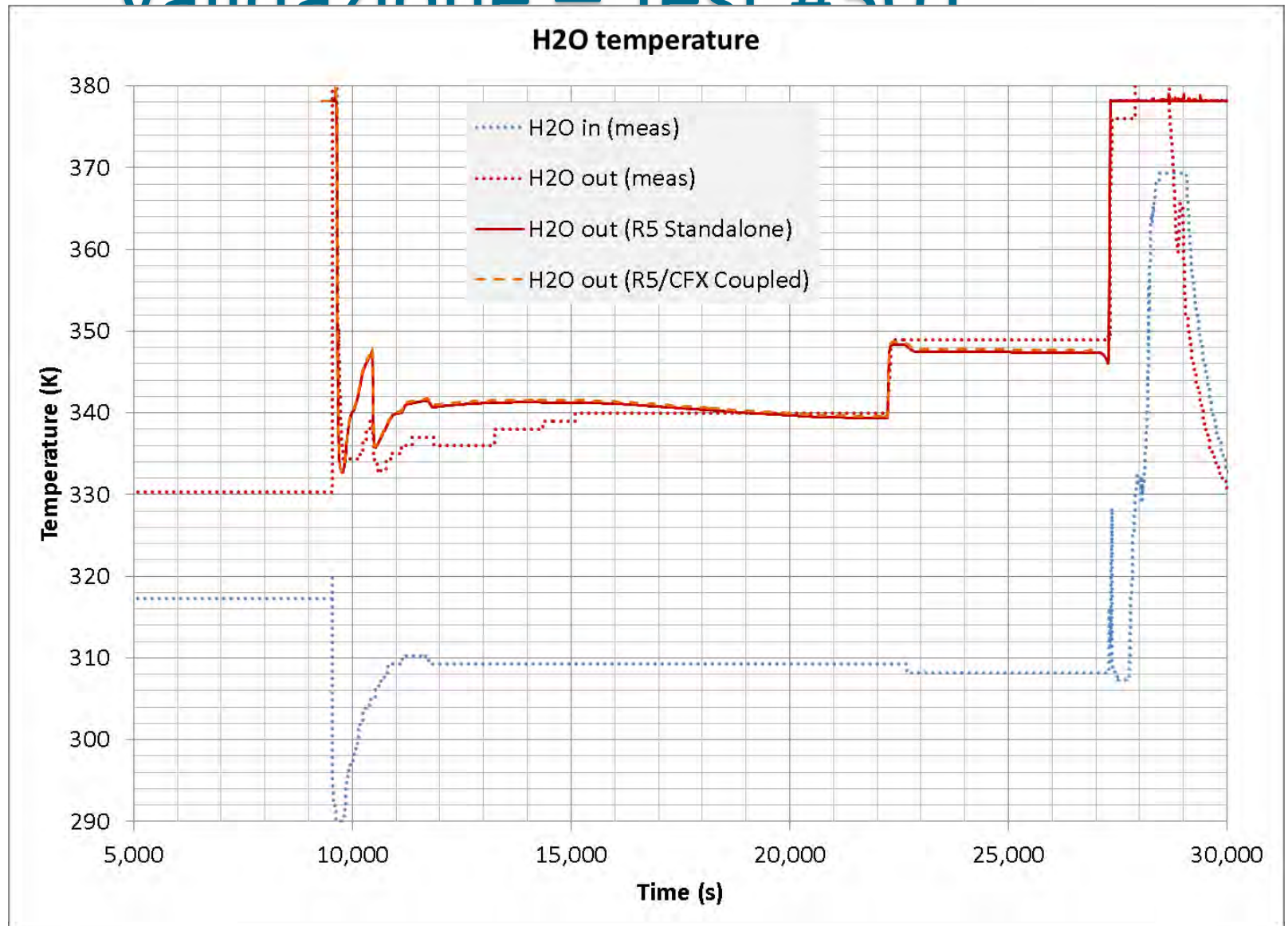
Validazione – Test #301



Validazione – Test #301

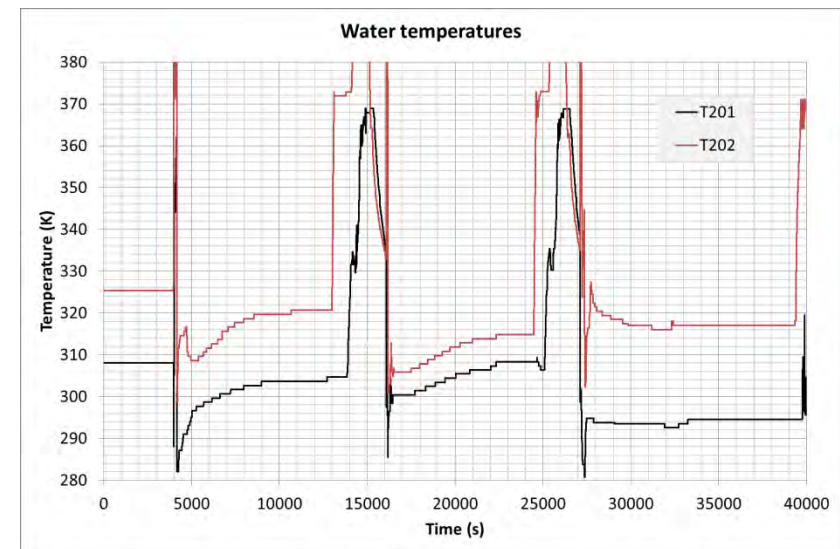
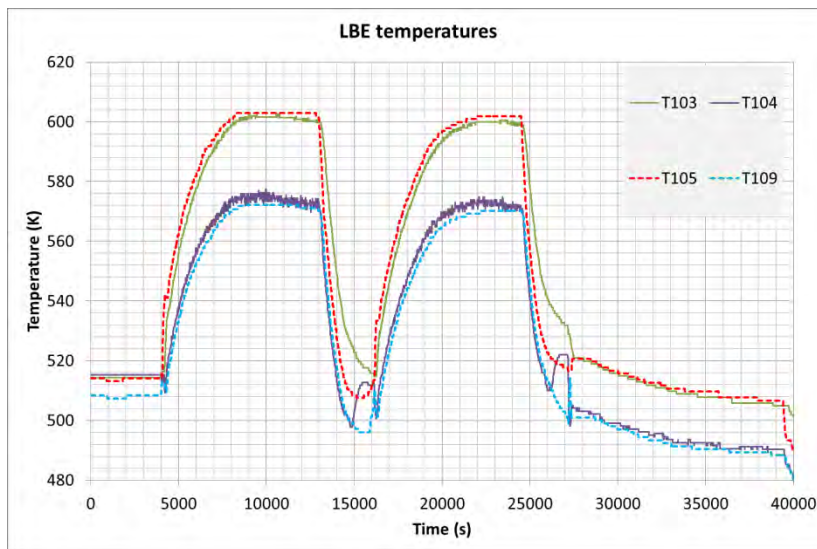
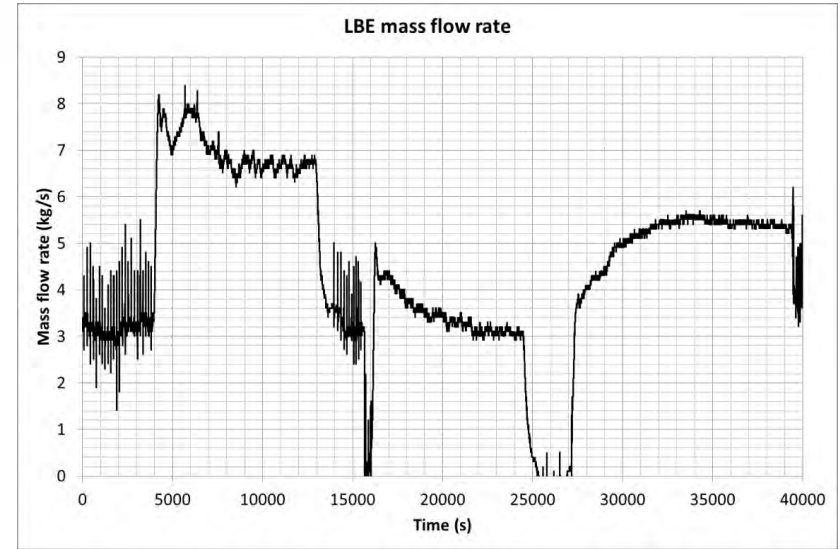
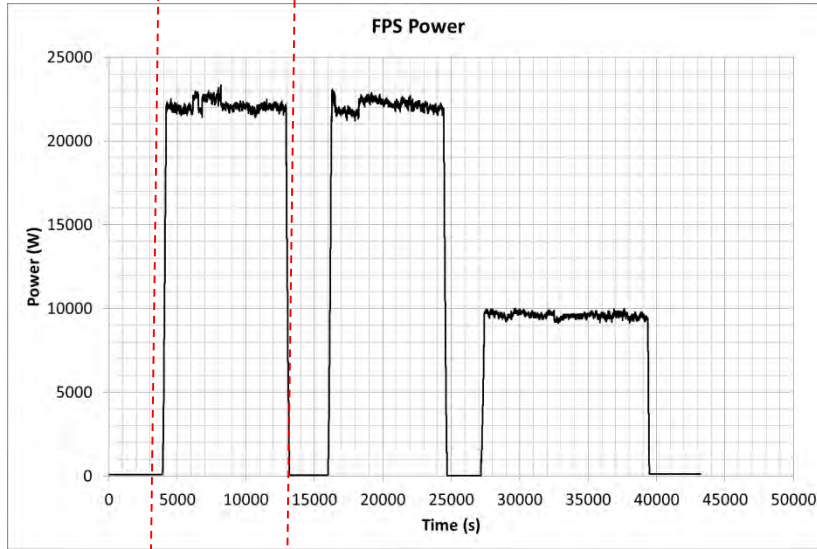


Validazione – Test #301

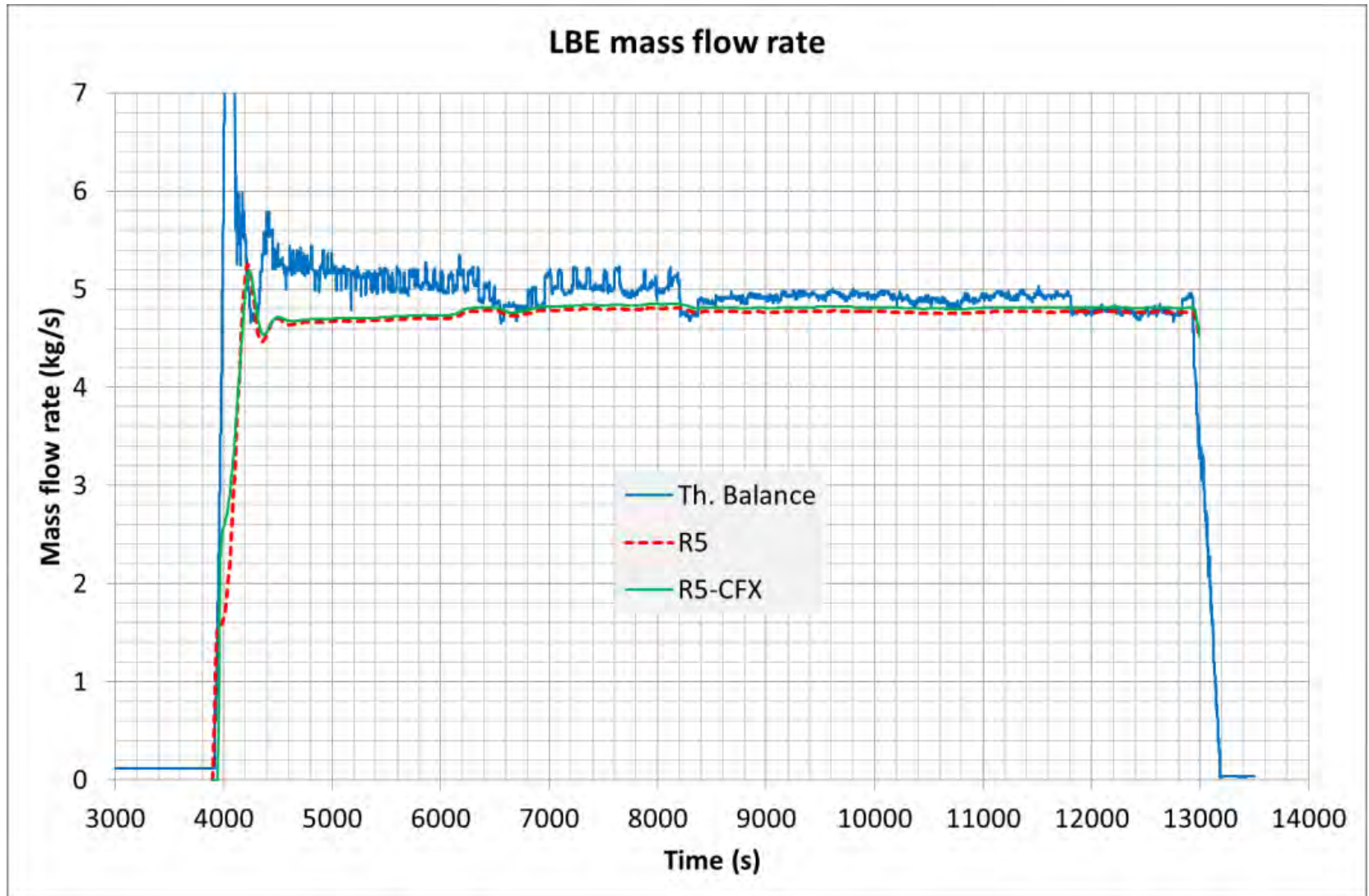


Validazione – Test #201

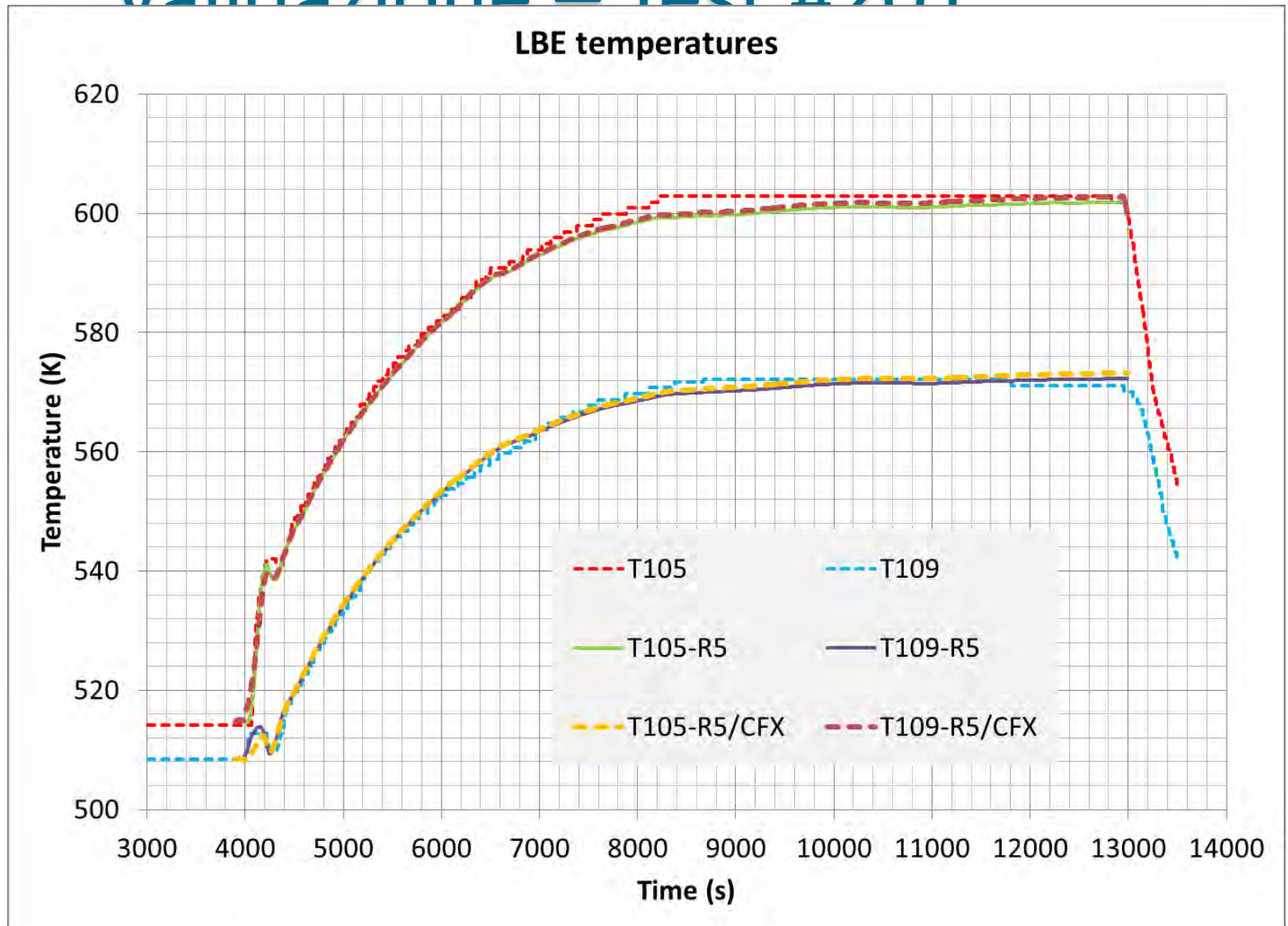
200-250 °C; 10 kW; with HX; NC only (no gas lift)



Validazione – Test #201

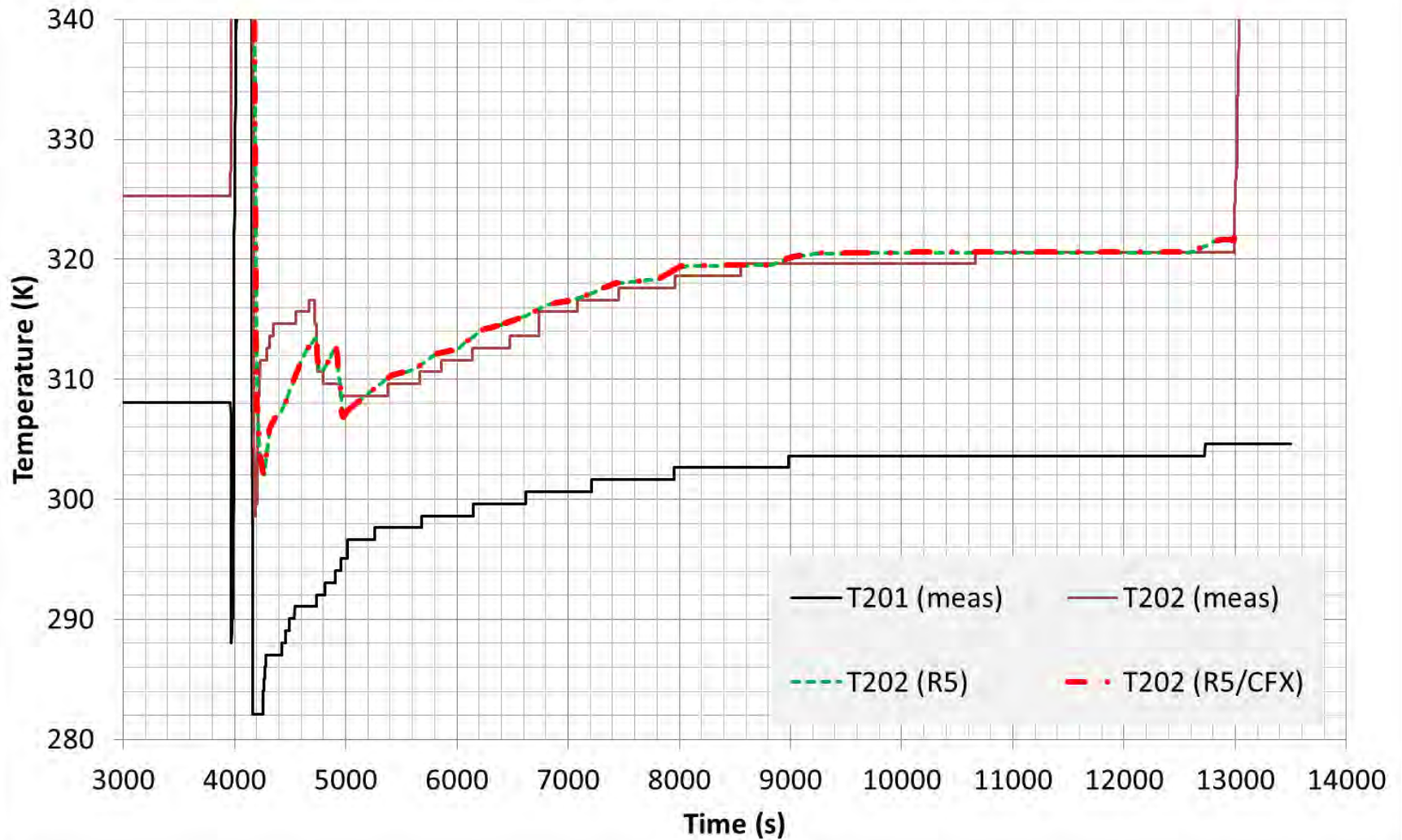


Validazione – Test #201



Validazione – Test #201

Water temperatures



Sintesi dei Risultati

- TEST #201
 - I risultati della simulazione accoppiata RELAP/CFX sono consistenti con quelli della simulazione RELAP standalone
 - **Prova della corretta implementazione e del corretto funzionamento del tool di accoppiamento**
- TEST #301
 - I risultati della simulazione accoppiata RELAP/CFX sono «abbastanza» consistenti con quelli della simulazione RELAP standalone
 - Discrepanza nelle temperature di LBE dovuta a piccole differenze nelle proprietà del materiale isolante adottate nelle due simulazioni
 - Interessante indicazione del ruolo dello **user effect** nelle simulazioni accoppiate (maggiore numero di *modelling issues* da tenere in debita considerazione)
- TEST #303
 - Piccole discrepanze su portata e temperature di LBE, dovute ad alcune inconsistenze tra i *setup* delle due simulazioni (da ripetere)
 - Proprietà materiali; condizioni iniziali e al contorno; ecc.

Conclusioni e Prospettive

- Il tool di accoppiamento è stato ulteriormente migliorato
 - **Parallelizzazione** della parte CFD
 - Ottimizzazione della gestione dei file di output
- L'attività di V&V svolta ha dimostrato la corretta implementazione del tool e la sua applicabilità all'analisi termoidraulica di circuiti a circolazione naturale e assistita di metalli liquidi
 - Risultati «coupled» **consistenti** con risultati «standalone», salvo discrepanze indotte da inconsistenze tra i setup delle due simulazioni
- L'analisi accoppiata mostra, in generale, una minore robustezza numerica e maggiori difficoltà di convergenza
 - Necessari aggiustamenti dei time step e dei parametri di sottorilassamento
- L'eventuale applicazione alla simulazione di esperimenti diversi, magari con strumentazione CFD-grade (o comunque più estesa e accurata), costituirà la base per una validazione più approfondita e solida, e potrà mettere in evidenza i vantaggi dell'integrazione 1D-3D
 - Possibilità di tener conto adeguatamente della natura 3D dei fenomeni termofluidodinamici e di predire più accuratamente lo scambio termico



UNIVERSITY OF PISA

Dipartimento di Ingegneria Civile e Industriale (DICI)

RELAP5/FLUENT COUPLING MODEL DEVELOPMENT FOR CIRCE FACILITY

Daniele Martelli
Nicola Forgione
Davide Rozzia
Francesco Andreoli

ADP ENEA-MSE (PAR 2014-LP2)
C.R. ENEA Brasimone 19-20 Nov. 2015

Outline

- **CIRCE Experimental facility**
- **RELAP5 model**
- **Coupling Overview**
- **Coupling tool**
- **Tool Applications (Loop type facility)**
- **Tool Applications (Pool type facility)**
- **Test Matrix**
- **Preliminary results**
- **Conclusions**

CIRCE Experimental facility

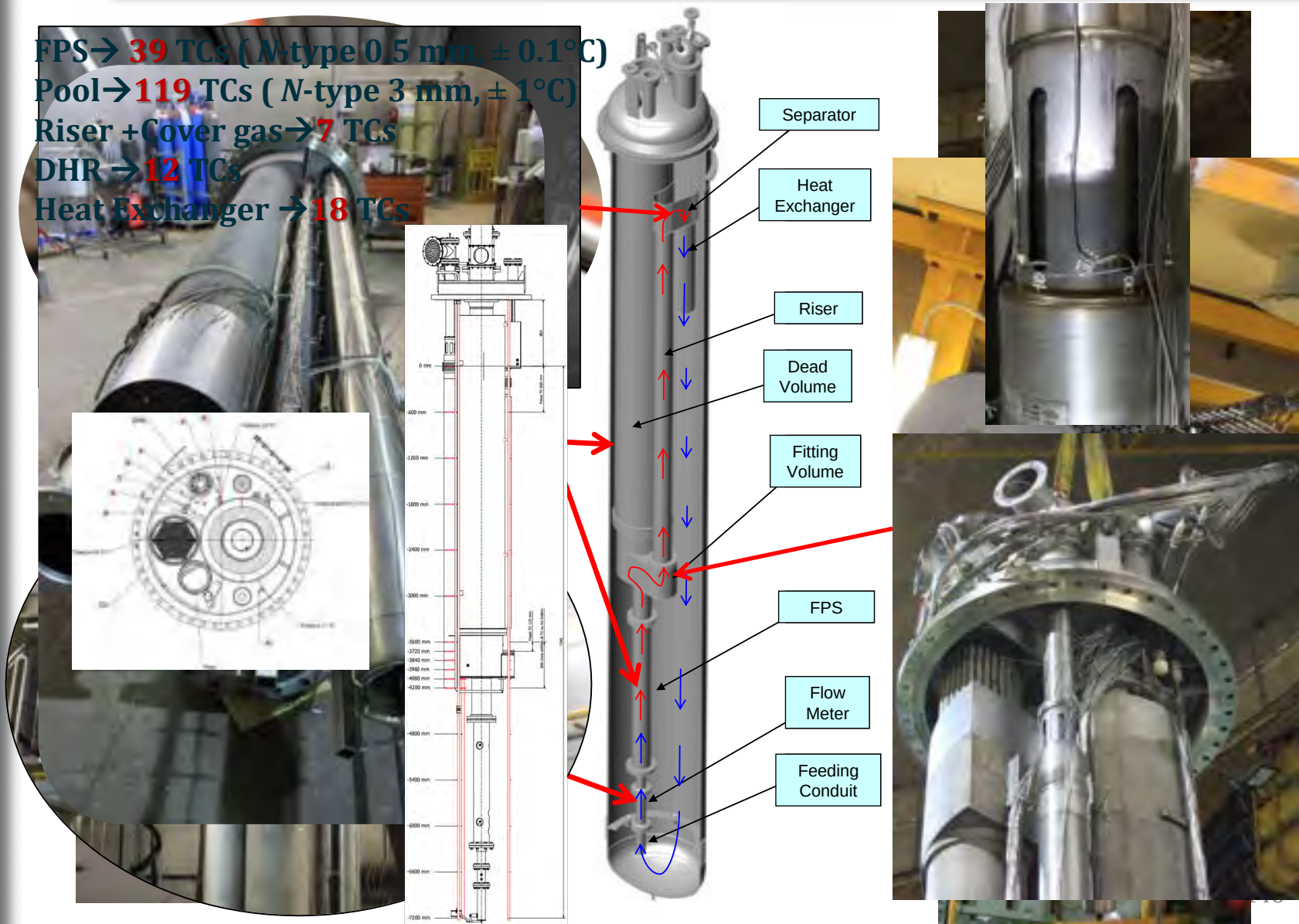
FPS → **39** TCs (*N*-type 0.5 mm, $\pm 0.1^\circ\text{C}$)

Pool → **119** TCs (*N*-type 3 mm, $\pm 1^\circ\text{C}$)

Riser + Cover gas → **7** TCs

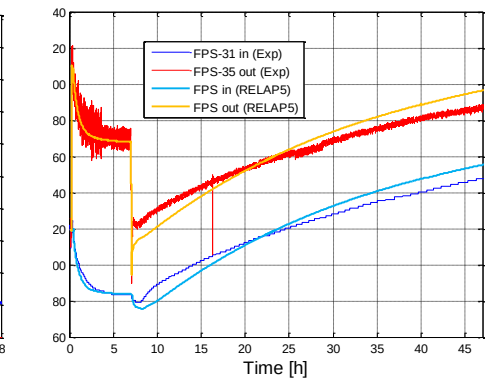
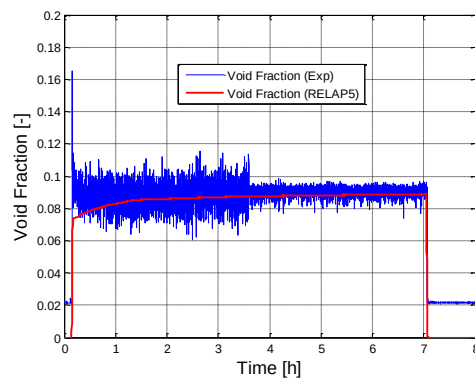
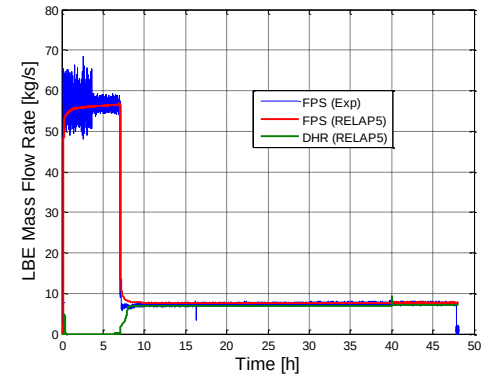
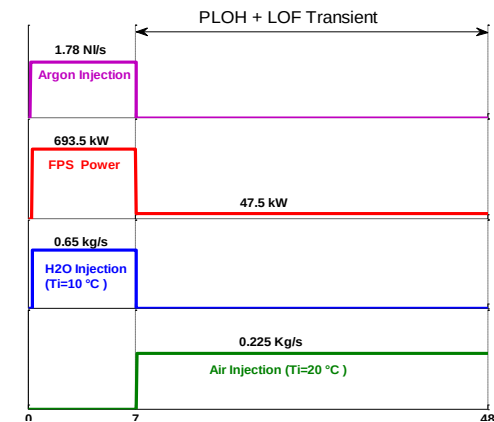
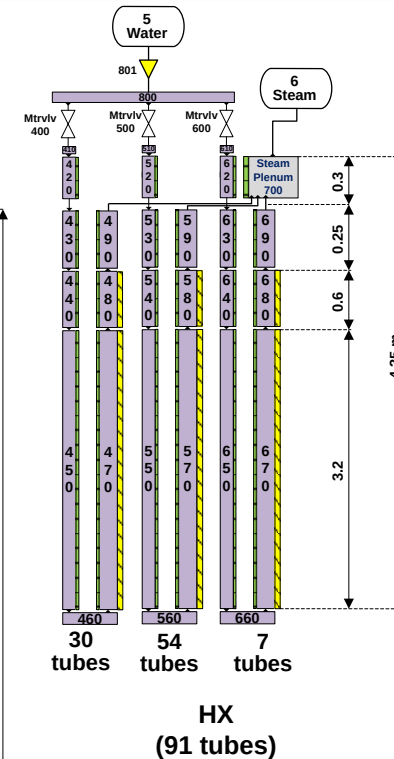
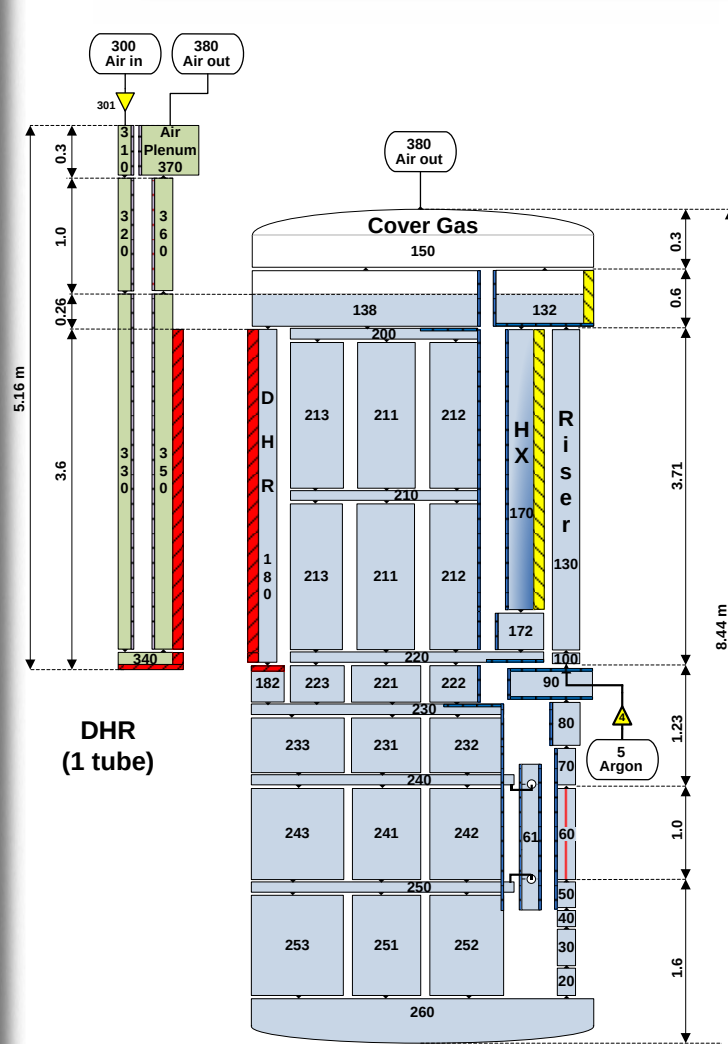
DHR → **12** TCs

Heat Exchanger → **18** TCs



RELAP5 model

Coupling overview



Coupling overview

1D System codes offer:

- Possibility to model behavior of large part of a NPP (at least the **entire system**)
- Tested physical models for **two-phase** applications and **Phase transition**

3D CFD Codes offer:

- Better techniques for modeling large “open” volume with **complex flows**
- Detailed information on 3D flows such as **Turbulence, Flow Patterns** (multidimensional phenomena in general)
- Fine phenomena can be represented: **mixing, stratification....**
(Thermal stratification phenomena **cannot be adequately investigated using only STH codes** for the importance related to the axial conduction in such phenomena)

Benefits:

- ✓ **Best of both “worlds”**
- ✓ **Mutually improved boundary conditions**
- ✓ **RELAP5/mod3.3 CFD ANSYS Fluent**

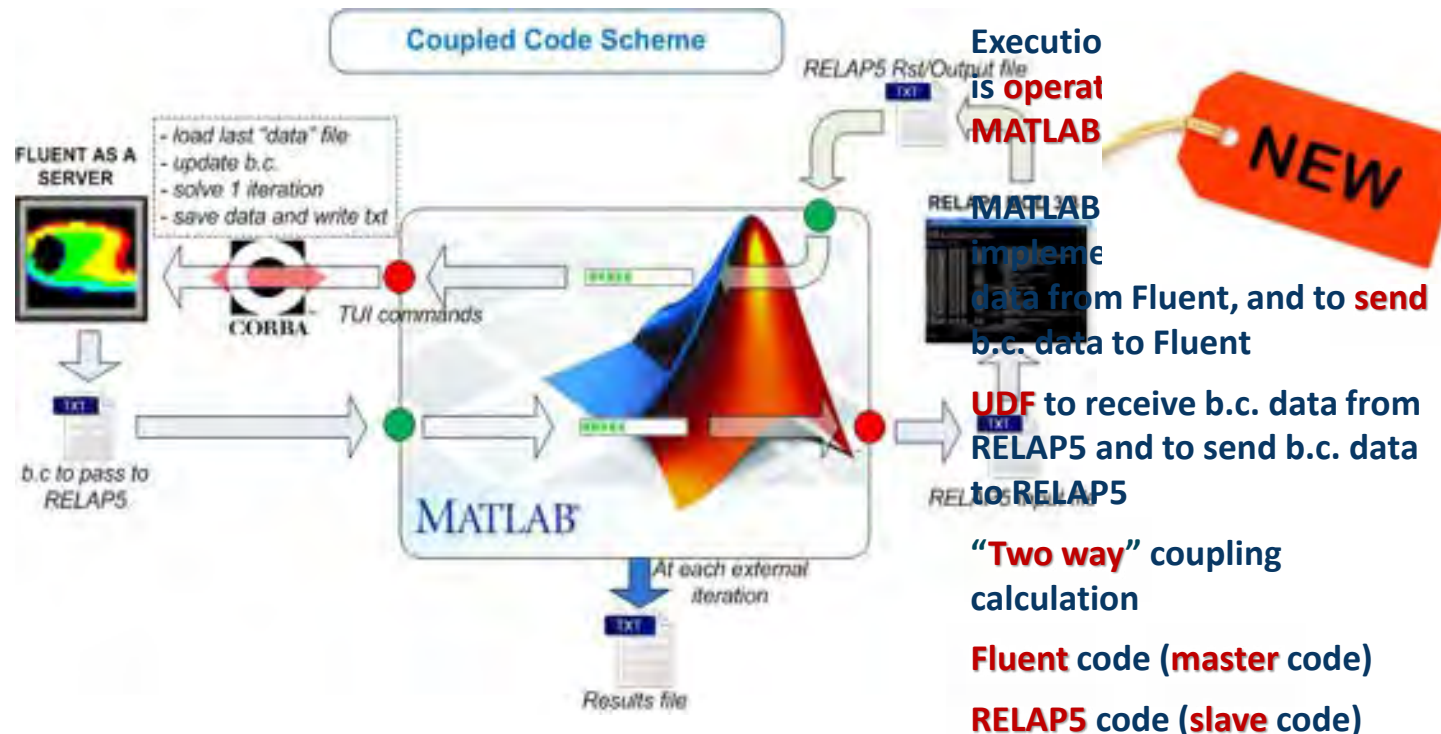
Coupling tool

“A coupled system consist of **two of more different but well defined sub-system:** each one is governed by **its own set of differential equations** but **some variables are shared** so that the sub-systems **cannot** be solved separately”

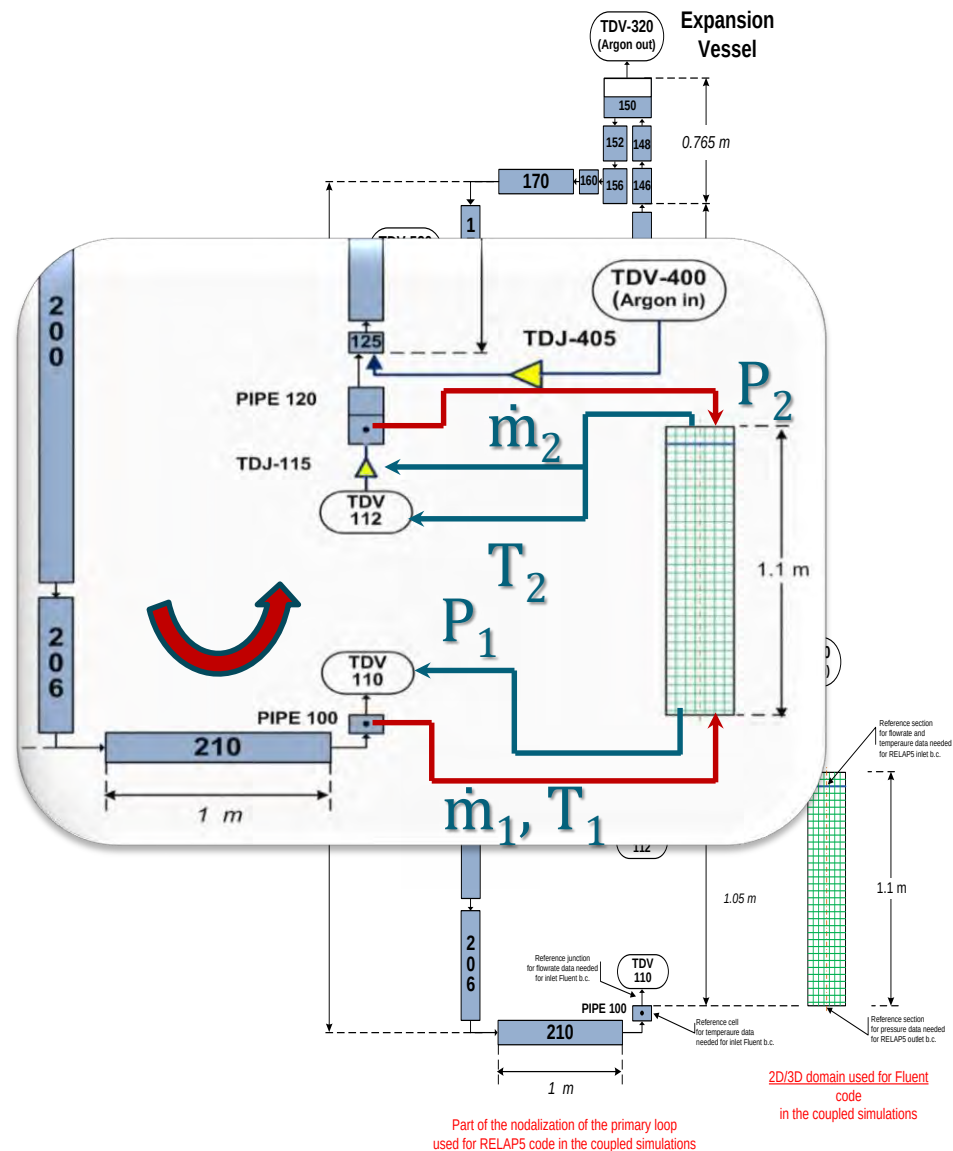
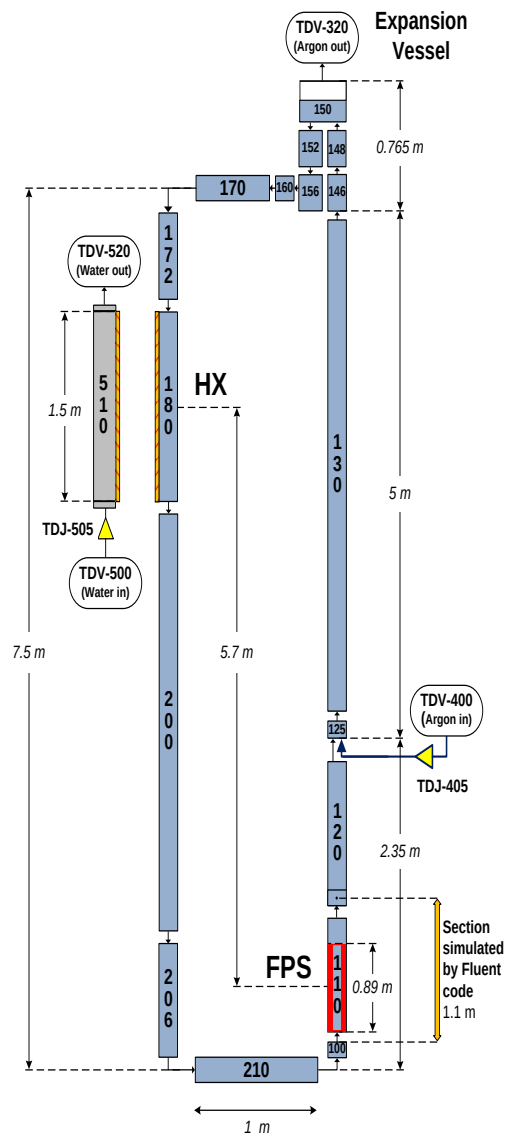
Code Integration:

Monolithic solution → Ad hoc solver to **simultaneously** solve the coupled system

Partitioned solution → **Independent** solvers are employed (coupling interface)



Tool applications (Loop facility)



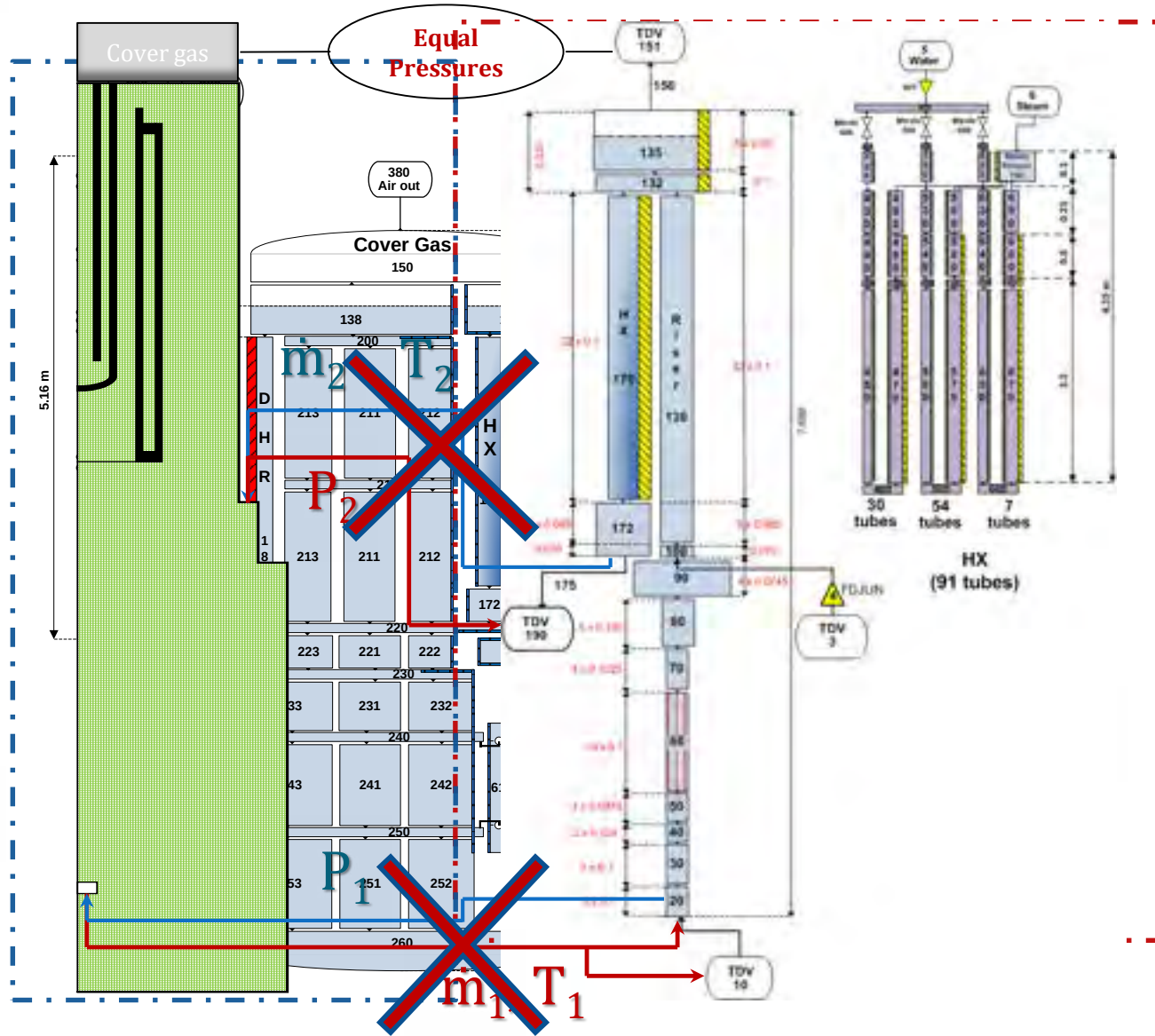
Part of the nodalization of the primary loop
used for RELAPS code in the coupled simulations

2D/3D domain used for Fluent
code
in the coupled simulations

Tool applications (Pool facility) 1 of 2

**FLUENT VOF
MODEL**
simulating the
cover gas

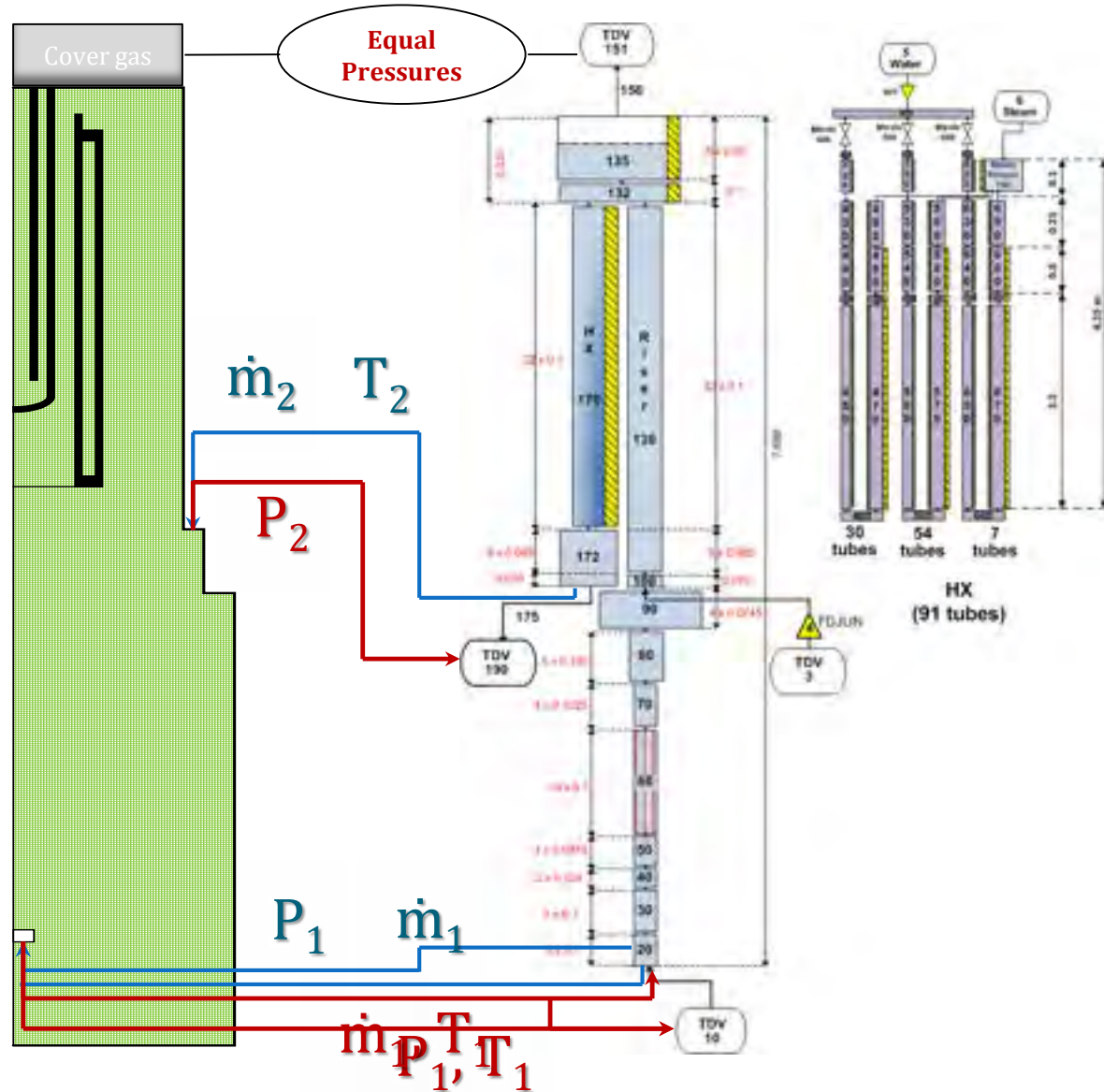
Starting from RELAP5 stand-alone.....



Tool applications (Pool facility) 2 of 2

**FLUENT VOF
MODEL**
simulating the
cover gas

Test Matrix



Pressure
outlet
changed in
Velocity
outlet

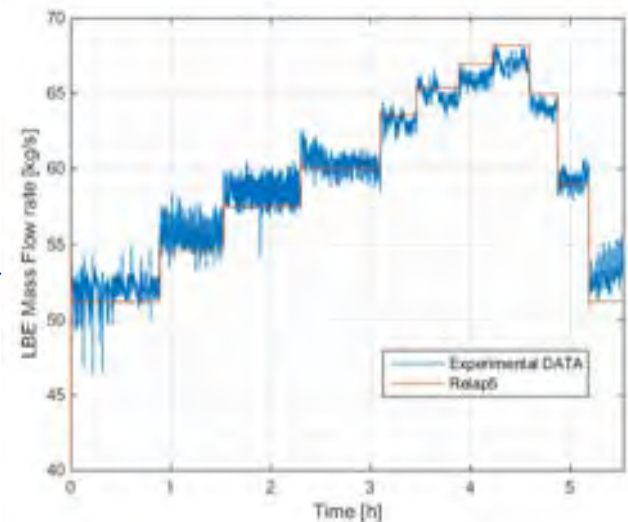
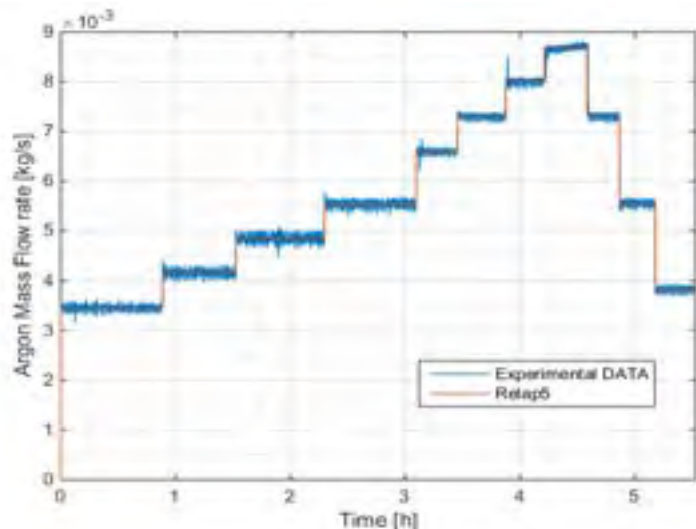
Test Matrix

Preliminary
coupled
results

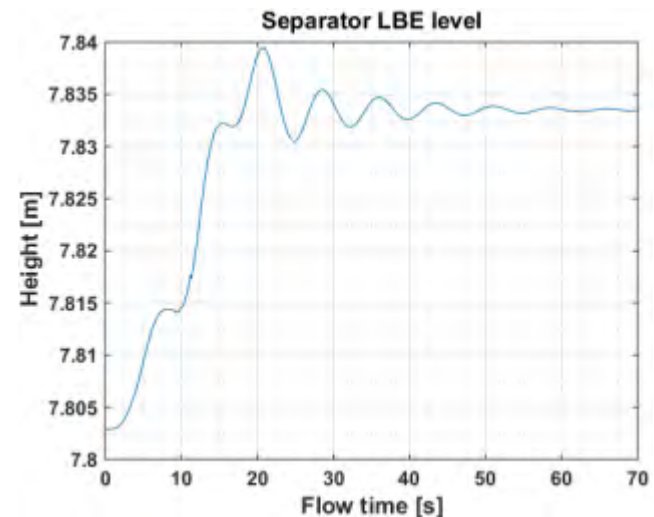
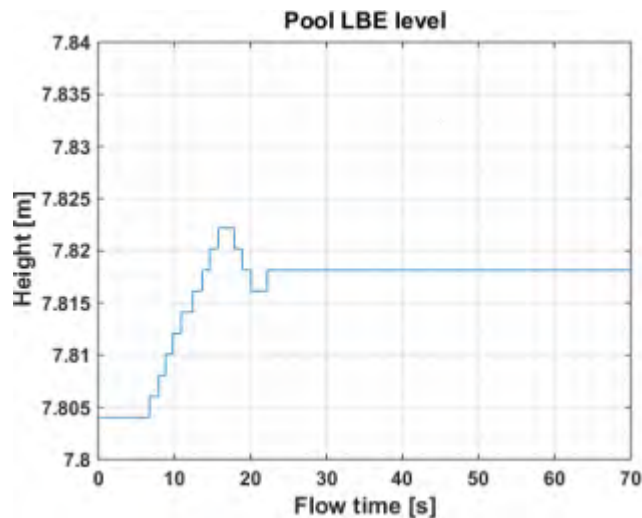
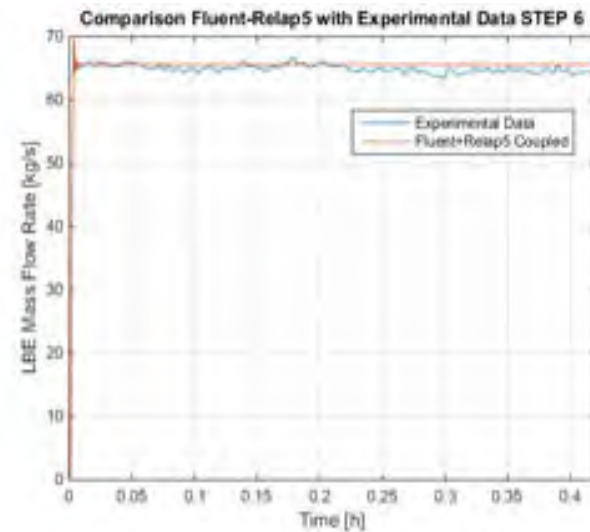
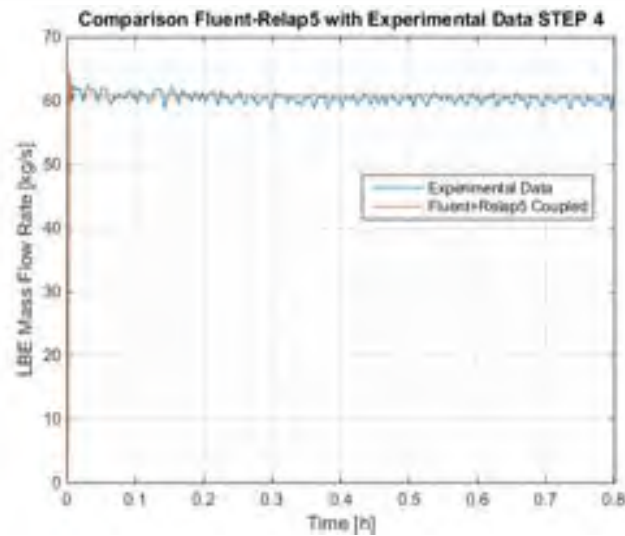
Experimental DATA: courtesy by **ENEA**

T [°C]	FPS Power %	HX Power %	Gas_lift [Nl/s]			
280	0	0	Step 1	1.9	Step 7	4.5
			Step 2	2.3	Step 8	4.9
			Step 3	2.7	Step 9	4.1
			Step 4	3.1	Step 10	3.1
			Step 5	3.7	Step 11	2.2
			Step 6	4.1	-	-

Name	Time Step	CFD Geometrical Domain	Serial/Parallel
RELAP5 Stand - alone	Max Courant limit	-	serial
Fluent + RELAP5 Coupled	0.025 s	2D	Parallel-Implicit scheme

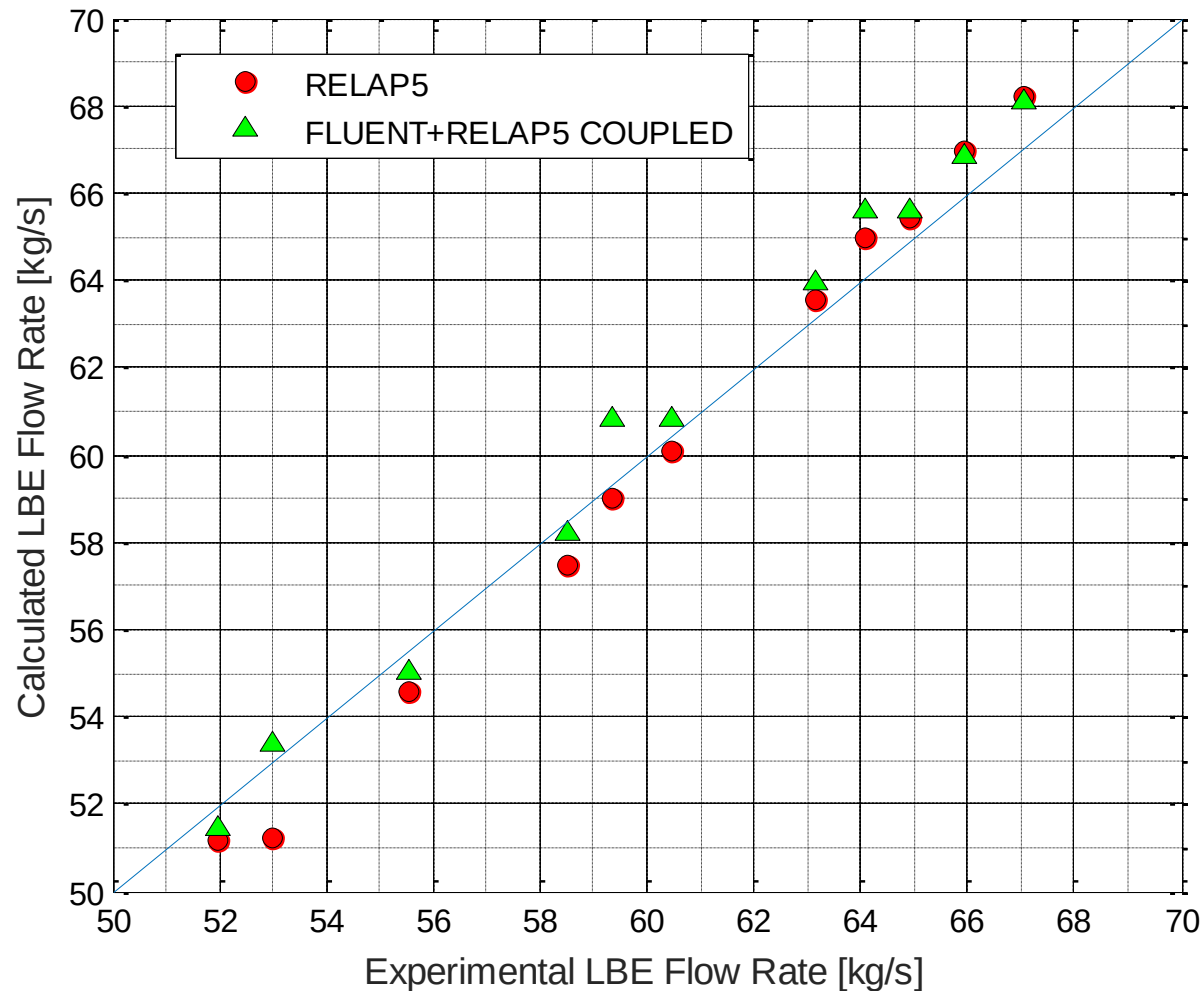


Preliminary coupled results

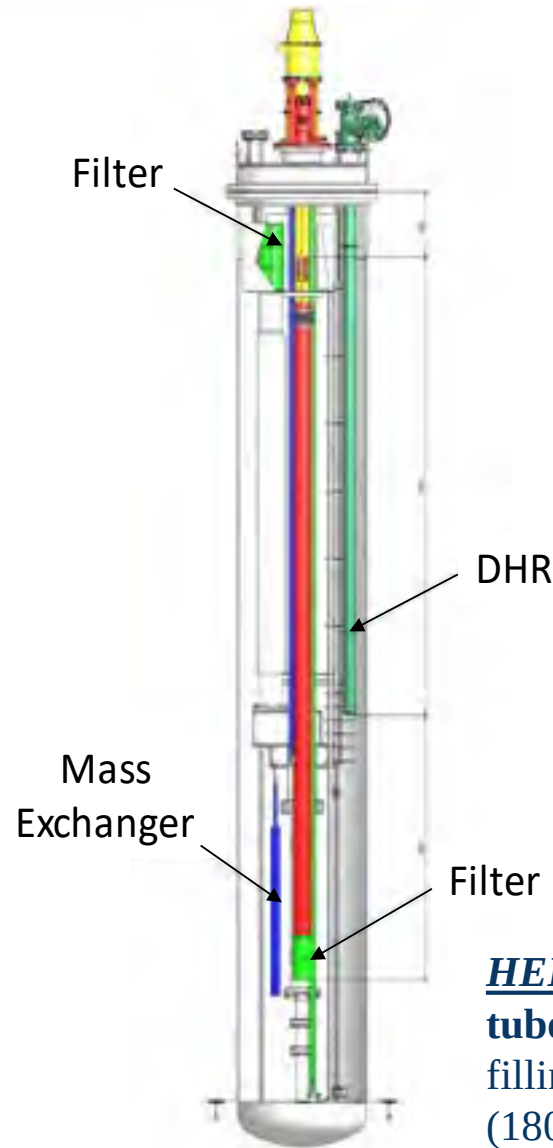


Preliminary coupled results

CIRCE-HERO



Obtained preliminary results shows **good agreement** with the available experimental data

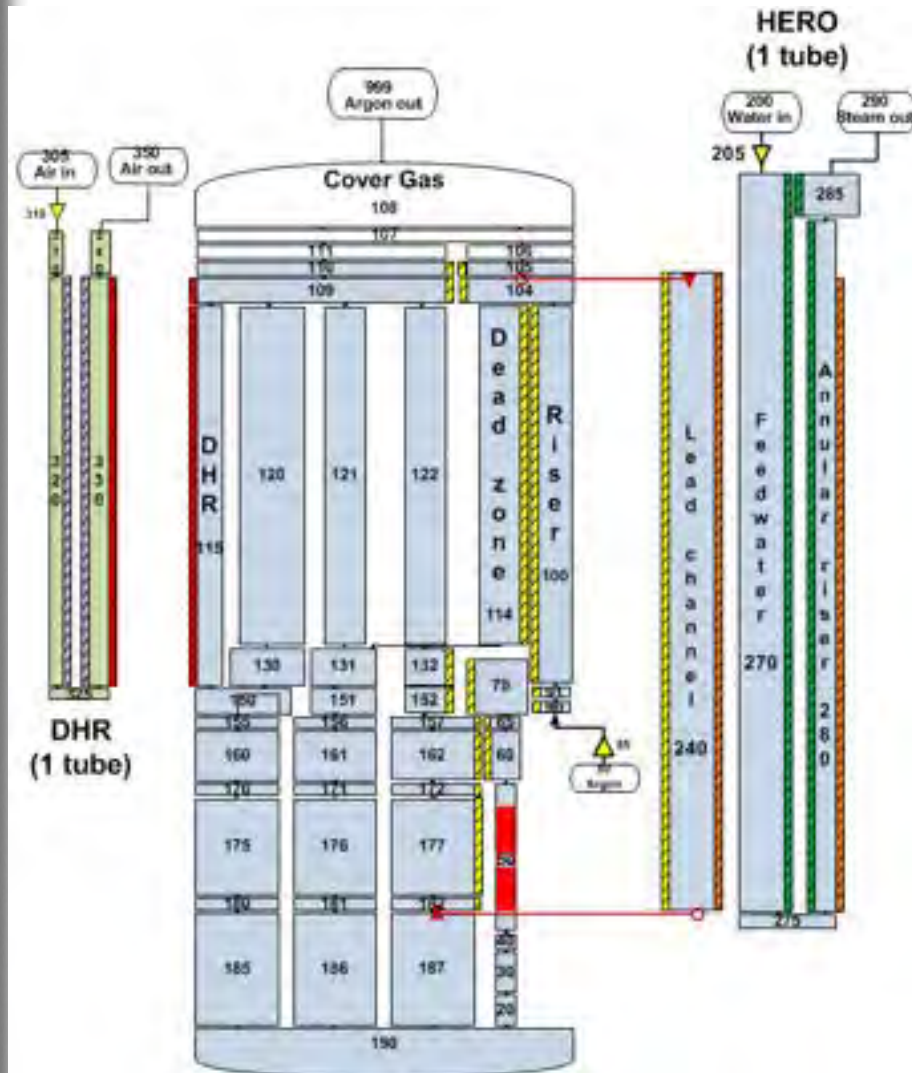


Filter

HERO-SGBT: seven double-walls bayonet tubes (with stainless steel powder filling the gap) fed by pressurized water (180 bar @ 335°C). It has a thermal duty of about **500 kW**

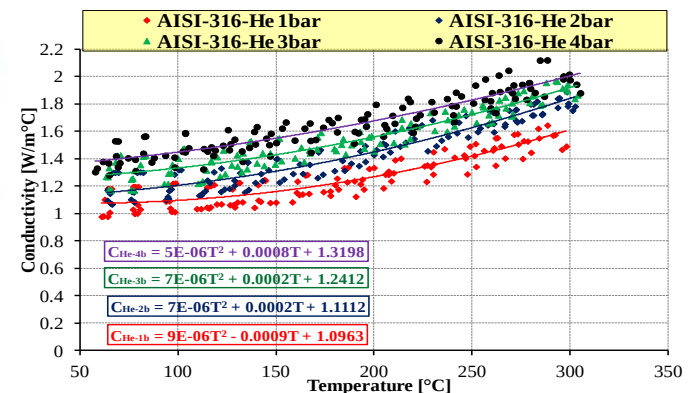
CIRCE-HERO RELAP5 model

Conclusions



The HERO SGBT includes

- The feed-water tube, the annular steam riser and the equivalent lead channel.
- The heat exchange between the annular steam riser and the Argon zone has been neglected.
- The insulating zone in the feed-water tube has been considered.
- The material adopted for the tubes is SS
- The filling powder (AISI-316) in the double wall meatus is according to the experimental findings achieved in TxP Facility.
- The heat transfer between the lead side and the annular riser is modeled according to the Mikityuk correlation.



Conclusions

- **RELAP5 model** of CIRCE pool type facility **developed** and preliminary results verified against experimental data
- **Improvements in the coupling tool** in order to simplify the interface (Fluent **UDF no more needed**) and substantial reduction of the required computational time
- The **cover gas** of the pool simulated in the FLUENT code through the **VOF** model
- **A “coupled model” of the CIRCE facility is developed** (ICE test section simulated by RELAP5 and the pool simulated by FLUENT code)
- Thermodynamic variables exchanged at the interfaces adapted for simulations applied to a pool type configuration (CIRCE) → **pressures are computed by FLUENT** while LBE **mass flow rates computed by RELAP5**
- Preliminary RELAP5/FLUENT coupled simulations of isothermal tests in forced circulation conditions are performed
- Obtained results show a **good agreement with experimental data** with differences in the LBE mass flow rate in the range $\pm 5\%$
- RELAP5 model of the CIRCE-HERO pool facility **under development**

Thank you for the attention

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Dip. Ingegneria Civile e Industriale
Largo Lucio Lazzarino, 2 56122 Pisa (Italy),
Phone: +39 050 2218060
Mobile +39 3476243491
e-mail: daniele.martelli@ing.unipi.it



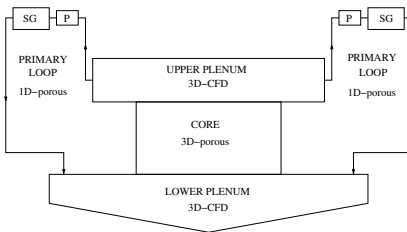
ADP ENEA-MSE (PAR 2014-LP2)
C.R. ENEA Brasimone 19-20 Nov. 2015

Integrazione del codice FEM-LCORE nella piattaforma SALOME

D. Cerroni, R. Da Vià, S. Manservigi, F. Menghini

Alma Mater Studiorum - Università di Bologna

20 Novembre 2015, Centro Ricerche ENEA Bologna



Sviluppo piattaforma SALOME per sistemi LFR

- Piattaforma SALOME per sistemi LFR

- Piattaforma Open-Source per sistemi LFR

- Piattaforma CEA per sistemi LFR

Schema calcolo neutronico multiscala

Schema calcolo termo-idraulico multiscala (DEFECTIVE METHOD)

Test 1 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Conclusioni



Sviluppo piattaforma SALOME per sistemi LFR

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Test 1 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

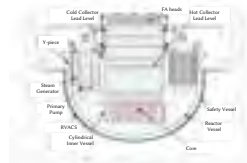
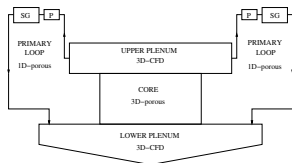
Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Conclusioni



Sviluppo piattaforma SALOME LFR

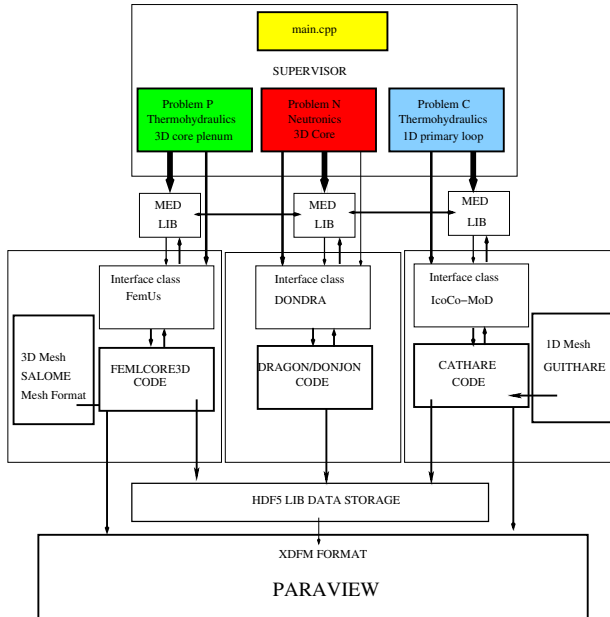
Piattaforma di calcolo ENEA-UNIBO (per I



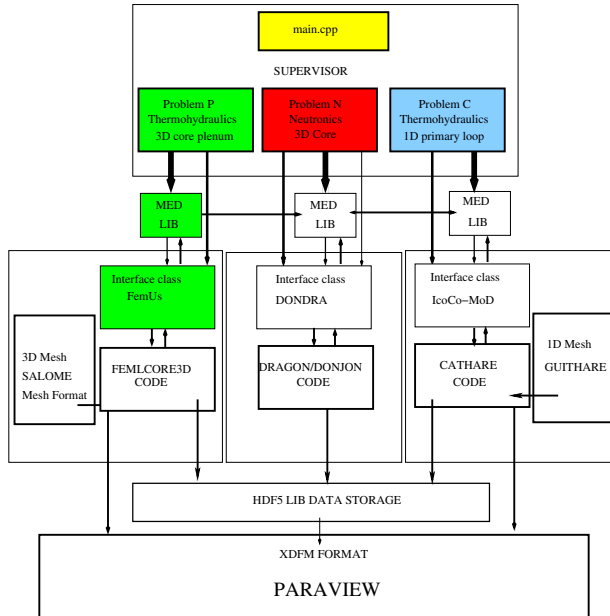
fisica	scala 1	scala 2
Termoidraulica	CFD-porous 3D	sistema 1D
open-src CEA-EDF	FEMLCORE MC/TRIOU	FEMuS CATHARE
Neutronica	trasporto	diffusione 2-5 gruppi
open-src CEA-EDF	DRAGON (assembly)	DONJON (reticolo) APOLLO
Strutturale	3D strutturale	1D travi
open-src CEA-EDF	FEMuS Code Aster	FEMuS Code Aster
Multifase	interfaccia	modello due fluidi
open-src CEA-EDF	FEMuS TRIOU NEPTUNE	FEMuS CATHARE



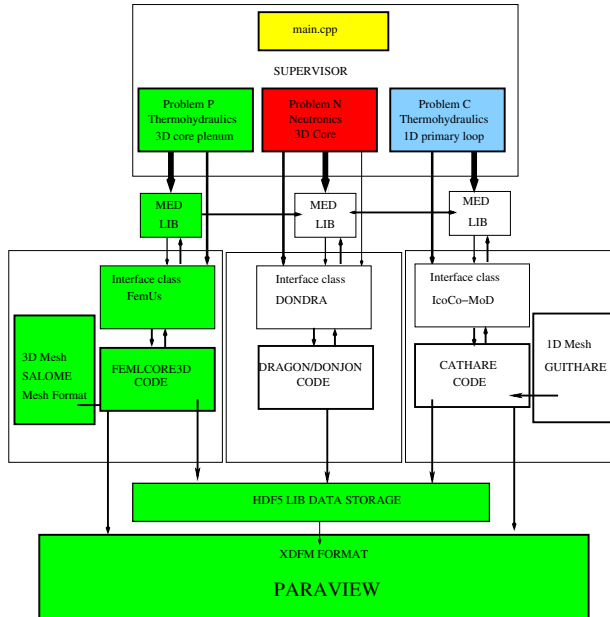
Sviluppo piattaforma SALOME LFR



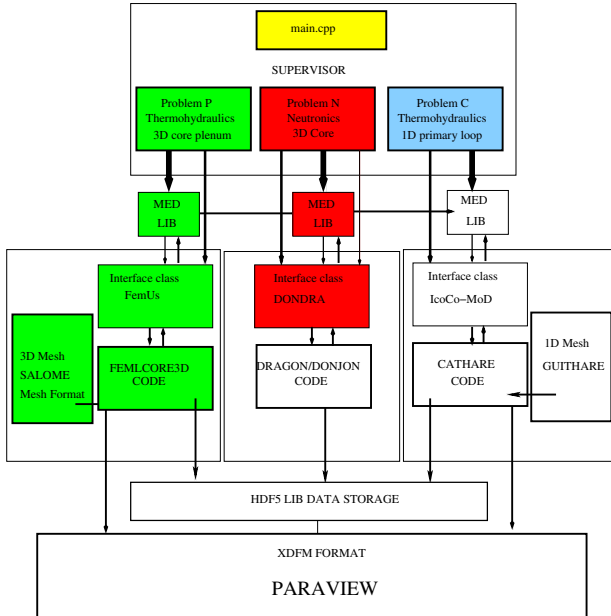
Sviluppo piattaforma SALOME LFR



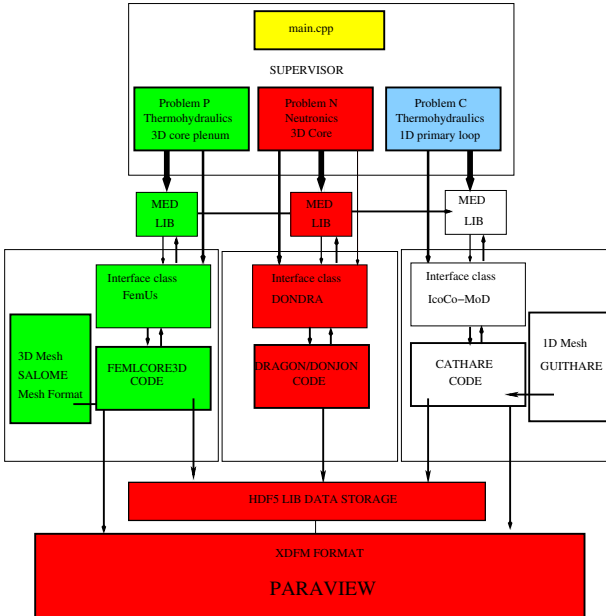
Sviluppo piattaforma SALOME LFR



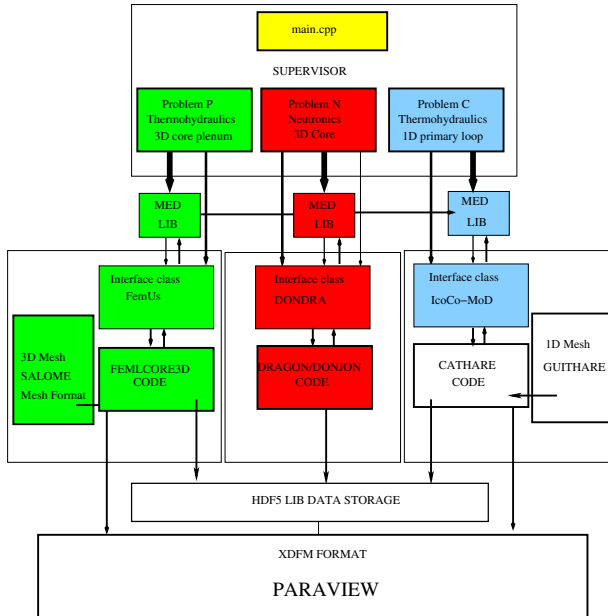
Sviluppo piattaforma SALOME LFR



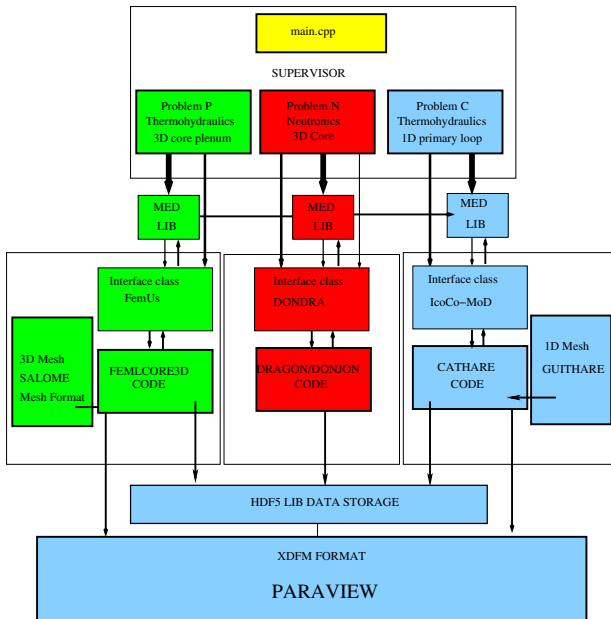
Sviluppo piattaforma SALOME LFR



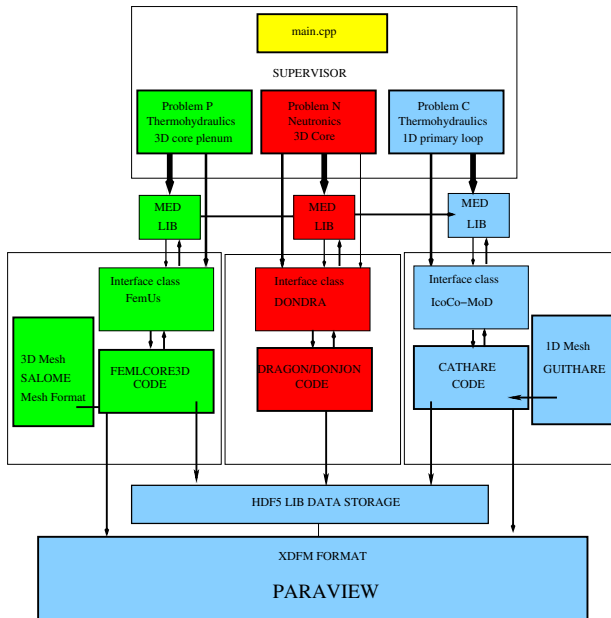
Sviluppo piattaforma SALOME LFR



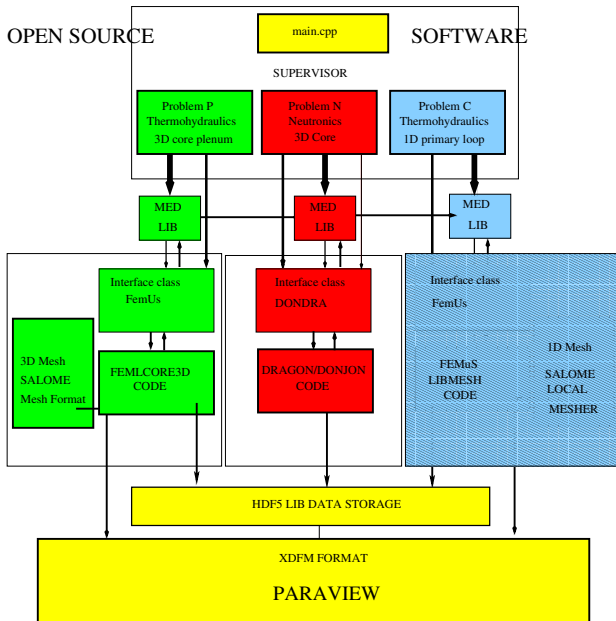
Sviluppo piattaforma SALOME LFR



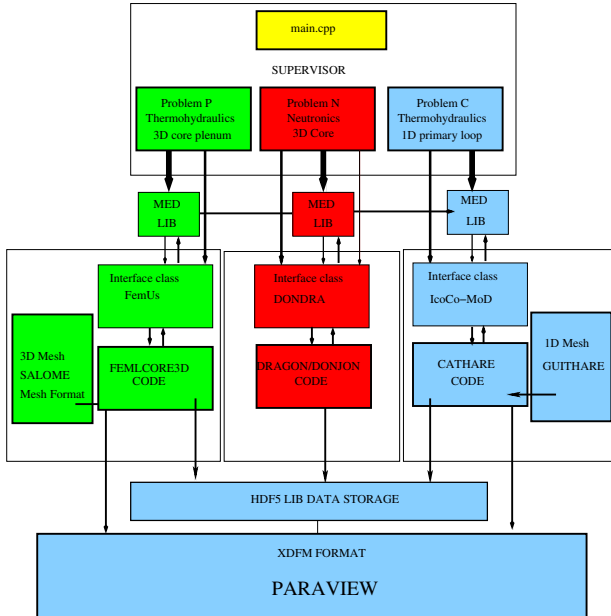
Sviluppo piattaforma Open-Source SALOME LFR



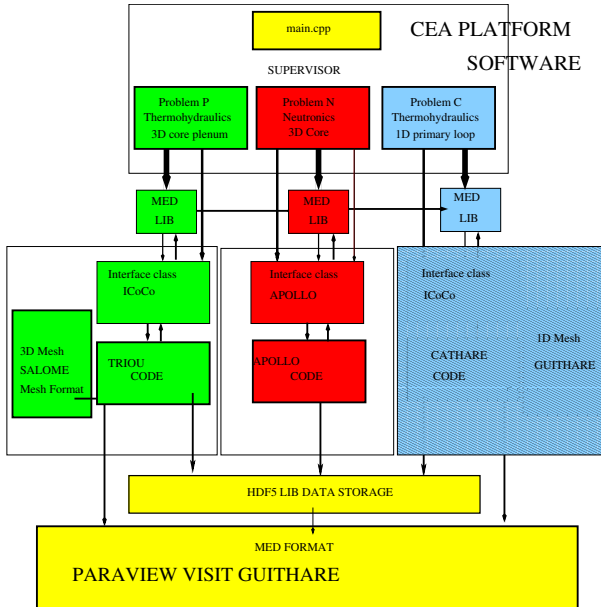
Sviluppo piattaforma Open-Source SALOME LFR



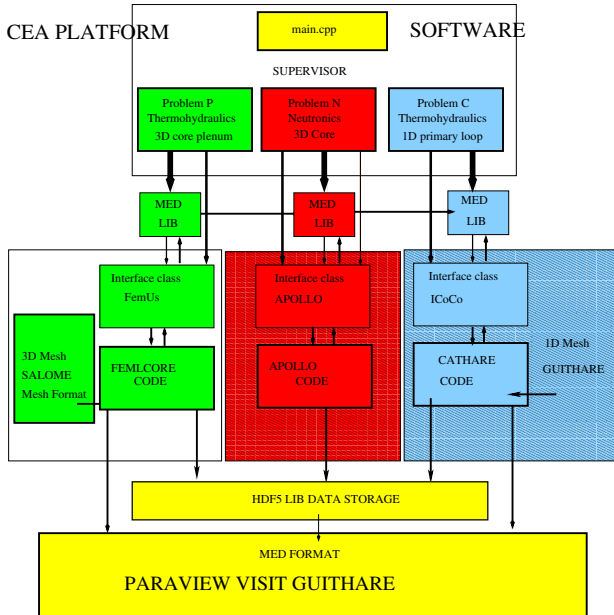
Sviluppo piattaforma CEA



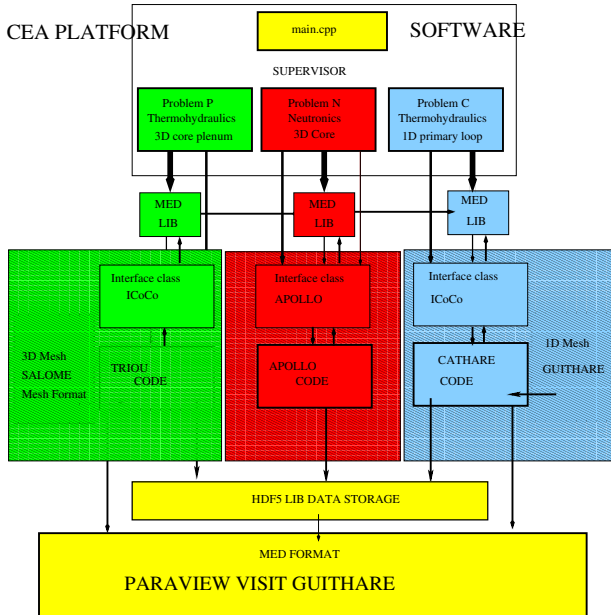
Sviluppo piattaforma CEA



Sviluppo piattaforma CEA



Sviluppo piattaforma CEA



Sviluppo piattaforma SALOME per sistemi LFR

Schema calcolo neutronico multiscala

Schema calcolo termo-idraulico multiscala (DEFECTIVE METHOD)

Test 1 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

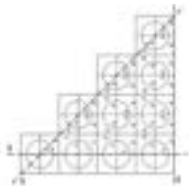
Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Conclusioni



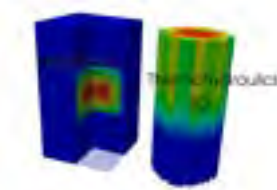
Schema neutronico multiscala (DRAGON-DONJON)

Eq. del trasporto neutronica in geom semplice (DRAGON)



assembly → Dragon → equazione del trasporto
→ metodo delle caratteristiche
per geometrie ripetitive infinite
flusso neutronico → sezioni d'urto medie per
gruppi energetici

Eq. di diffusione neutronica in geometria a reticolo (DONJON)



Neutronica solo Cartesiana → CFD non Cartesiano



Sviluppo piattaforma SALOME per sistemi LFR

Schema calcolo neutronico multiscala

Schema calcolo termo-idraulico multiscala (DEFECTIVE METHOD)

Test 1 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

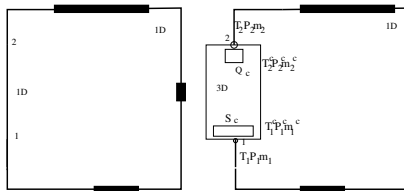
Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Conclusioni



Schema termo-idraulico multiscala (FEMLCORE-CATHARE)

DEFECTIVE METHOD (con mesh sovrapposti 1D e 3D)



CATHARE (circuito completo) FEMLCORE (3D)+CATHARE (1D)

Boundary conditions → 3D FEMLCORE

$T_1 = T_1^c$ temperatura imposta da CATHARE 1D a 3D FEMLCORE

$m_1 = m_1^c$ portata imposta da CATHARE 1D a 3D FEMLCORE

Correzione (FEMLCORE 3D → CATHARE 1D)

$T_2^c = \langle T_2 \rangle^{3D}$ mediante feedback $Q = \alpha(T_2^c - \langle T_2 \rangle^{3D})$

$P_2^c = \langle P_2 \rangle^{3D}$ con $S = \beta(\Delta P_{21}^c + \Delta P_g - \Delta P_{21}^{3D})$



Sviluppo piattaforma SALOME per sistemi LFR

Schema calcolo neutronico multiscala

Schema calcolo termo-idraulico multiscala (DEFECTIVE METHOD)

Test 1 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Conclusioni



Test 1 FEMLCORE(3D)-SALOME-CATHARE(1D)

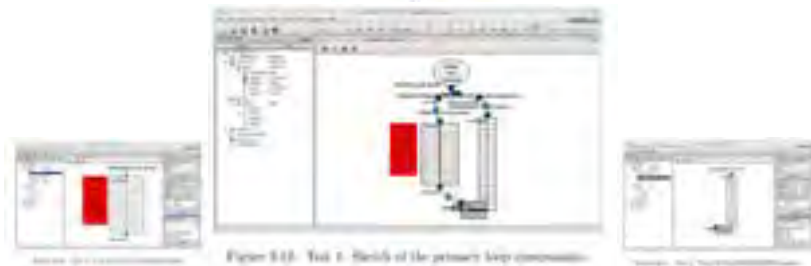
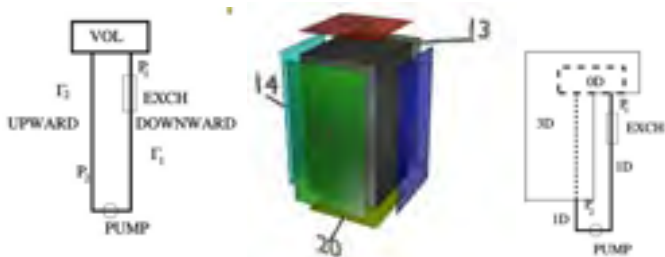


Figure 1.13: Test 1: Schematic of the primary loop components

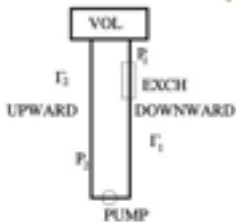
Ramo Upward
poi sostituito dal 3D

CIRCUITO COMPLETO

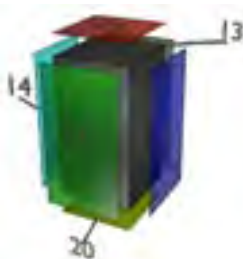
Ramo Downward



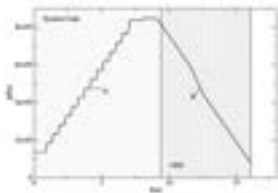
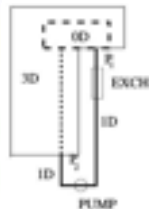
Test 1 FEMLCORE(3D)-SALOME-CATHARE(1D)



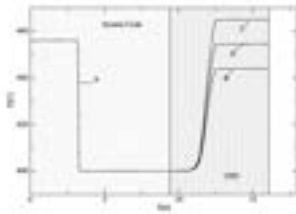
1D circuit CATHARE



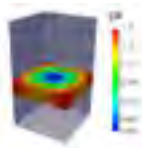
1D CATHARE +3D FEMLCORE



Pressione 1D-3D centerline



Temperatura 1D-3D centerline



Neutronica

Sviluppo piattaforma SALOME per sistemi LFR

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Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

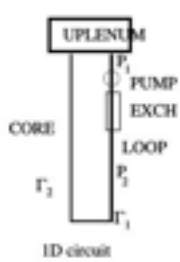
Conclusioni



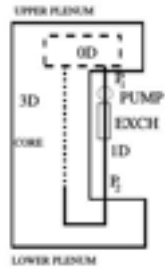
Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)



P=pompa, E=scambiatore

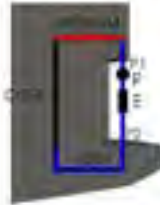


1D circuit CATHARE



1D CATHARE + 3D FEMLCORE

Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)



Schema con algoritmo difettivo: P1 e P2 punti con Sorgenti



Reattore 3D (FEMLCORE)

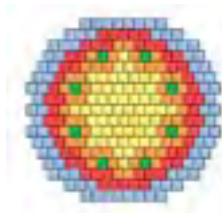


1D circuit CATHARE

(P=pompa, E=scambiatore)

Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)

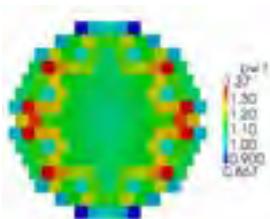
NEUTRONICA - GENERAZIONE CALORE 3D



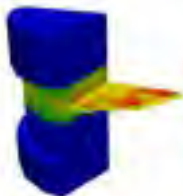
Reticolo reattore



assembly reattore



pk heat generation (orizzontale)



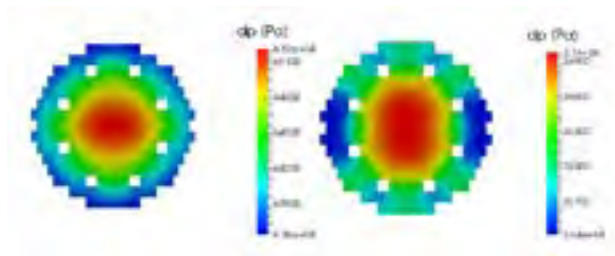
(verticale)



3D reattore

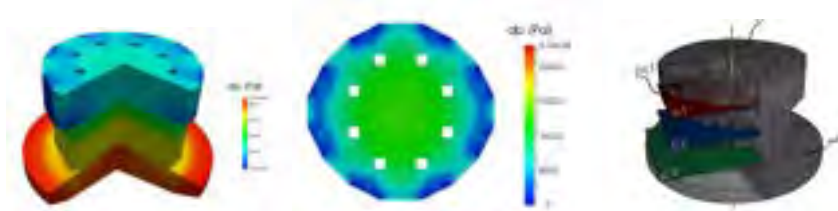
Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)

PRESSIONE FEMLCORE(3D)



Sezione G3

Sezione G2



Complessivo

Sezione G1

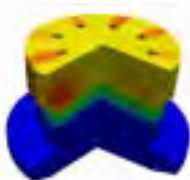
TEMPERATURA FEMLCORE(3D)



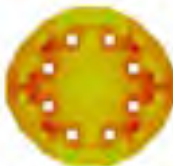
Sezione G3



Sezione G2



Complessivo



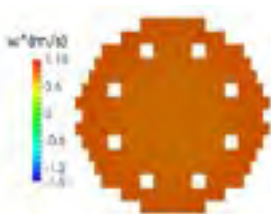
Sezione G1



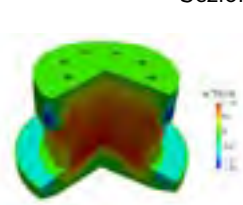
VELOCITÀ FEMLCORE(3D)



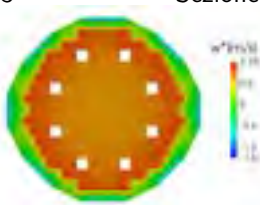
Sezione G3



Sezione G2



Complessivo



Sezione G1



Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)

CIRCUITO 1D (CATHARE)



SCHEMA CALCOLO



UP PLENUM



BOUNDARY CONDITION



RAMO CORE



COMPLESSIVO 1D



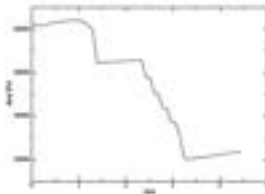
RAMO PRIMARIO

Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)

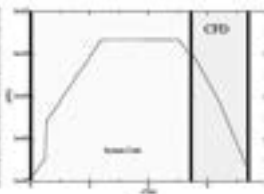
PRESSIONE - TEMPERATURA CATHARE(1D)



GEOMETRIA 3D



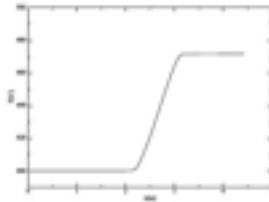
3D centerline



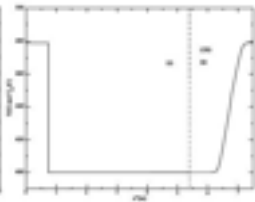
Pressione nel circuito 1D+3D



SCHEMA



3D centerline



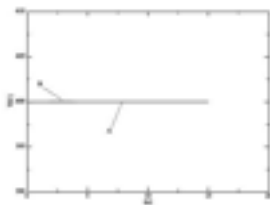
Temperatura nel circuito 1D+3D

Test 2 FEMLCORE(3D)-SALOME-CATHARE(1D)

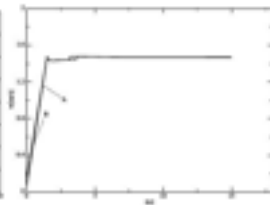
PUNTI FEMLCORE(3D)-CATHARE(1D)



SCHEMA



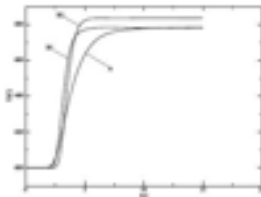
Temperatura P2



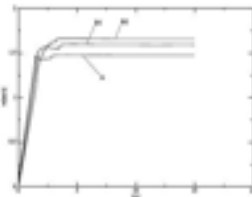
Velocità P2



GEOMETRIA 3D



Temperatura P1



Velocità P1



Sviluppo piattaforma SALOME per sistemi LFR

Schema calcolo neutronico multiscala

Schema calcolo termo-idraulico multiscala (DEFECTIVE METHOD)

Test 1 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Test 2 di integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

Conclusioni



Integrazione SALOME-FEMLCORE(3D)-CATHARE(1D)

- ▶ Integrazione FEMLCORE-SALOME-CATHARE
- ▶ DEFECTIVE method: robustezza rispetto a BC
- ▶ DEFECTIVE method: evidenza errore del 1D rispetto al calcolo 3D
- ▶ Accoppiamento Reattore/Plenum(3D)-Primario(1D)

Sviluppi futuri

- ▶ Test della piattaforma (casi tempo dipendente)
- ▶ Miglioramento degli algoritmi per i codici
- ▶ Miglioramento nel trasferimento dati
- ▶ Inclusione di altri codici





AdP PAR 2014

Revisione della validazione del codice T/H CATHARE2 attraverso il benchmark LACANES

Massimiliano Polidori
massimiliano.polidori@enea.it

PAR 2014 Workshop LP2
Brasimone – 20 Novembre 2015

Laboratori UTFISSM-SICIS (Bologna)

- AdP MSE-ENEA sulla Ricerca di Sistema Elettrico
- Piano Annuale di Realizzazione – PAR 2014
 - LINEA PROGETTUALE 2 – **“Collaborazione internazionale per il nucleare di IV-gen”**
 - C1 – Sperimentazione e modellistica per la termoidraulica dei metalli liquidi

DELIVERABLE LP2.C1

“Revisione della validazione del codice T/H CATHARE2 attraverso il benchmark LACANES”

Ref. Massimiliano Polidori, nessun contributo CIRTEN.

SCOPO

Verifica e validazione del codice T/H di sistema CATHARE-2 per le analisi di sicurezza di sistemi LFR utilizzando dati sperimentali disponibili dal Benchmark OECD LACANES anche attraverso benchmark di calcolo con il codice RELAP5.

- ❖ ENEA partecipa ufficialmente al benchmark LACANES con il codice RELAP5.
- ❖ L'attività si concentrerà nella simulazione di **test in circolazione naturale** di esperimenti condotti sulle facility HELIOS (South-Korea) e NACIE (Brasimone).
- ❖ E' stata utilizzata l'ultima versione di CATHAREv2.5_3 mod2.1, la prima versione provvista di HLM rilasciata ufficialmente dal CEA

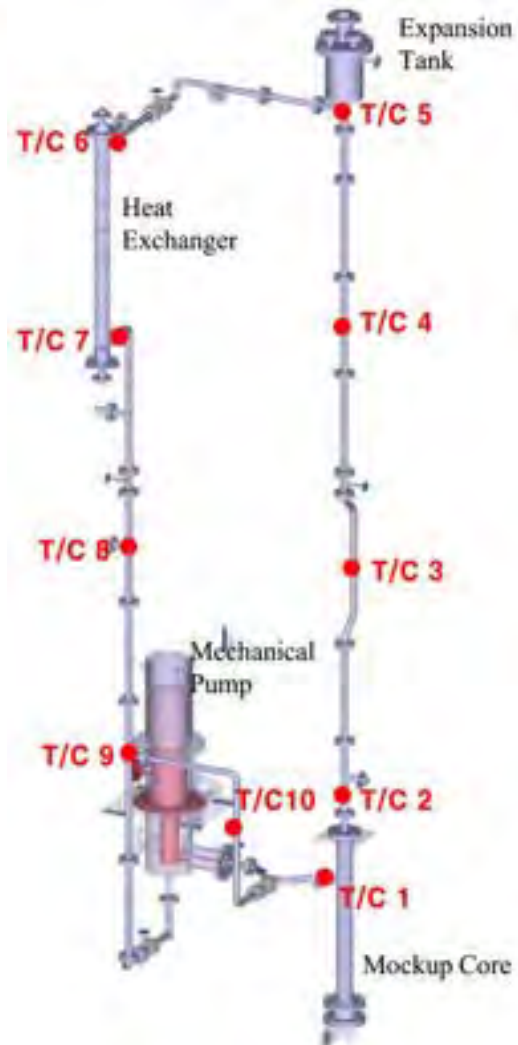
L'attività rappresenta il proseguimento delle precedenti annualità (deliverable ADPFISS – LP2 – 043 del PAR2013).

Nelle precedenti attività all'interno del PAR, CATHARE ha dimostrato buone capacità di simulazione sia in circolazione forzata che naturale.

- Revisione dei modelli HELIOS e NACIE alla luce delle «best practices» acquisite nel benchmark.
- I dati sperimentali di riferimento:
 - A seguito di upgrade alla facility HELIOS, nuovi dati «ufficiali» per i test in circolazione naturale sono stati rilasciati a Marzo 2015. E' stato proposto l'approccio «**calorimetrico**» per la simulazione dei test in N.C., i.e. ricostruzione dei salti entalpici lungo il loop, calibrazione delle pdc e del coeff di scambio termico dell'HX.
 - I dati provenienti dalla campagna di caratterizzazione di un flowmeter a induzione di NACIE, resi disponibili da Brasimone per il benchmark LACANES.
- I risultati ottenuti con CATHARE2 sono stati confrontati anche con i risultati RELAP5 del benchmark con l'uso delle **proprietà TD dell'Handbook OECD (2007)**.

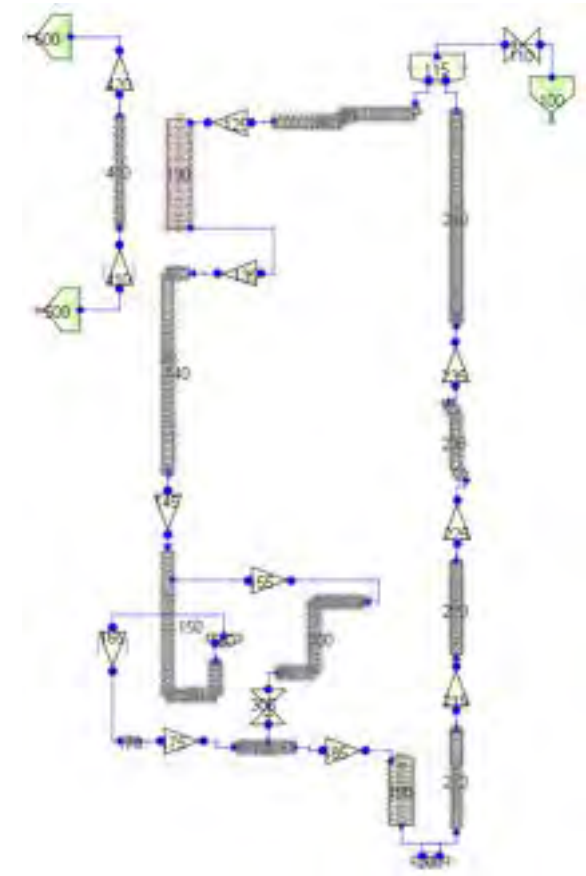
HELIOS Model for Natural Circulation Tests

HELIOS è una facility termoidraulica in scala del reattore PEACER-300 raffreddata a LBE. Olio come fluido termovettore lato secondario.



HELIOS Facility

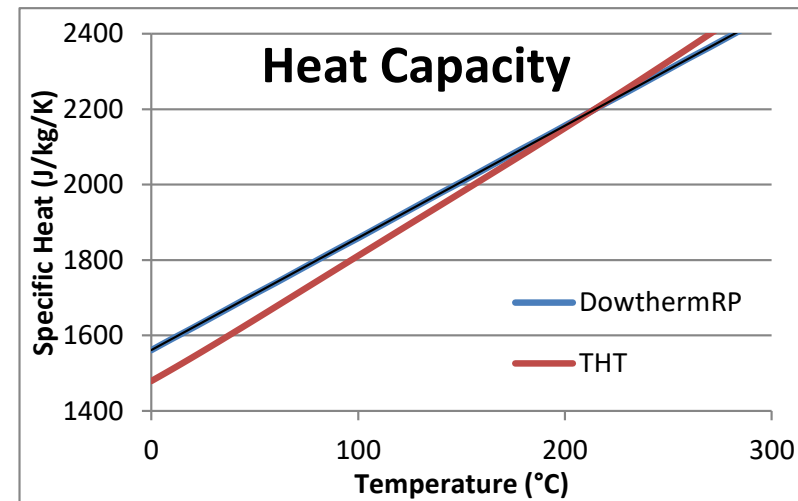
- 1D description of the natural circulation flow path.
- Thermal structures: core rod bundle, HX, piping insulated by glass-wool
- Pumps simulated with time-dependent junctions
- Friction loss coefficients calculated by the code
- K-factor coefficients calculated with Handbook correlations and tuned on experimental data obtained during forced circulation tests.
- Explicit description of the HX secondary side driven by BC.



HELIOS Nodalization

Thermal Exchange Calculation in HX

- The reference **correlations from HANDBOOK** are now available in RELAP5 mod3.3 and are used in present simulations.
- Thermodynamic properties of the **THT oil** (Tetra Hydro Thiophene) **except** the thermal **conductivity** that refers to DowthermRP ($\lambda = 0.169 - 0.00013 \cdot T[K]$). The heat capacity is bit lower, but the calibration of secondary side is not considered at working T



- **Seban-Shimazaky** correlation (LBE side) for convective heat transfer in pipe geometry:

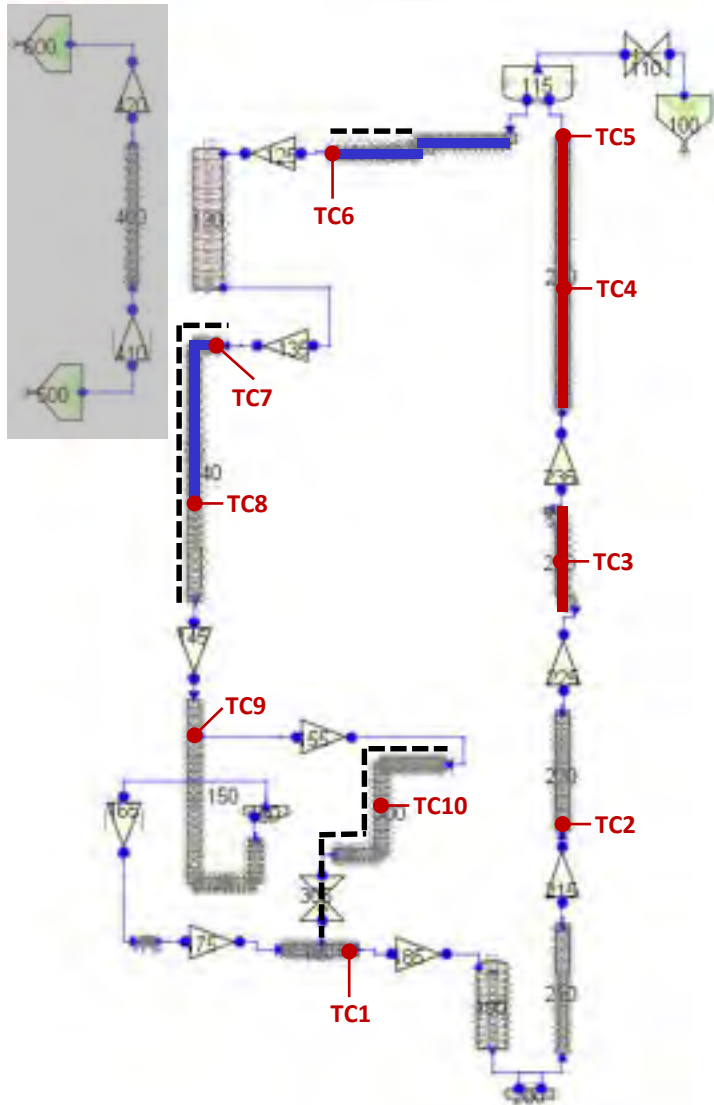
$$Nu = 5.0 + 0.025 Pe^{0.8}$$

- **Dittus-Boelter** standard RELAP5 correlation (Oil side):

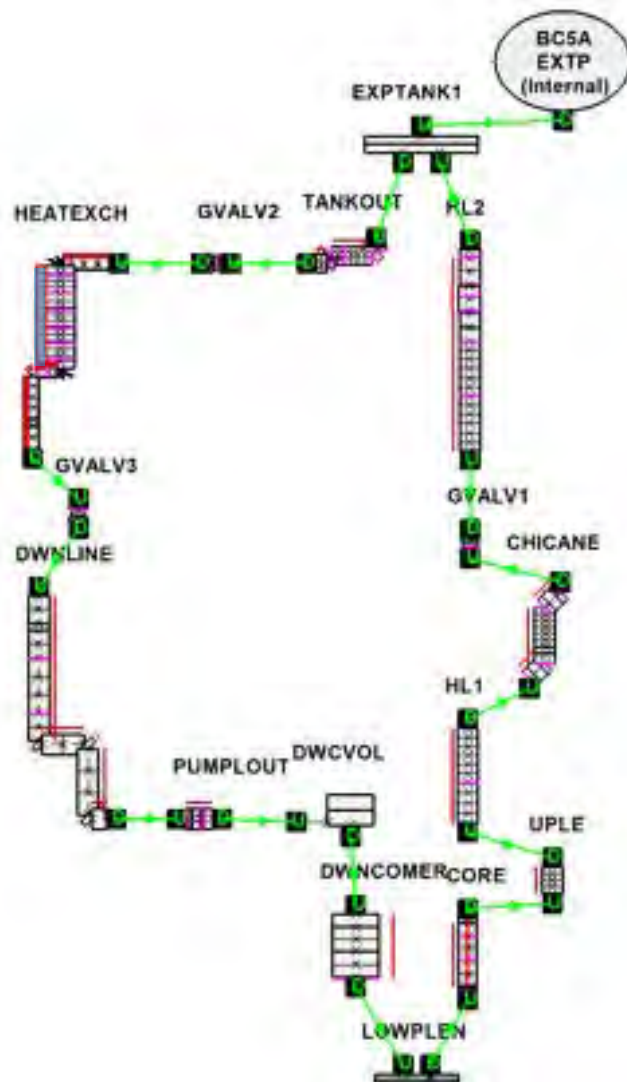
$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

Simulazione degli stati stazionari di due test in circolazione naturale a 15kW e 9.8 kW

- The test at 15 kW is taken as reference
- Two steps calibration suggested by SNU followed
- **STEP1(1): Calibration of primary loop temperatures**
secondary side removed, heat exchanger simulated as heat losses, mass flow imposed at 2.394 kg/s:
 - Sections with heat losses in blue
 - Sections with heat gain in red
 - Other sections considered adiabatic
- **STEP1(2): Calibration of NC mass flowrate**
free LBE mass flowrate
 - *k*-factors roughly removed in black dashed lines
- **STEP2: Calibration of HX heat transfer**
restoration of secondary side
 - Fouling factor on HX heat structure oil side (fouling acts as multiplier for the heat transfer correlation)



Modello HELIOS per CATHARE

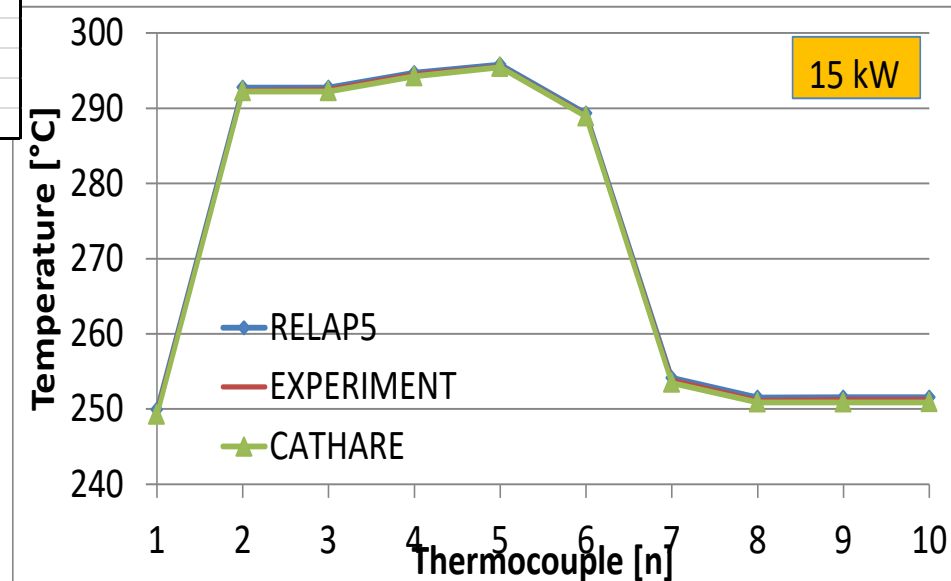


- ❖ Modello dedicato a studi di circolazione naturale (eliminato il ramo con la pompa meccanica)
- ❖ assenza di olio come fluido in CATHARE → Scambio termico nell'HX derivato da RELAP5 e simulato con heat-loss.
- ❖ La calibrazione del modello per CATHARE è stata condotta con l'approccio «calorimetrico» suggerito nel benchmark (ricostruzione delle heat-loss e heat-gain lungo il loop), relativamente ai dati del test a 15 kW.
- ❖ Non è stato necessario calibrare le pressure drops.

Results of NC Test – 15 kW

		EXPERIMENT	RELAP5	CATHARE	Error C2
CORE	TC1	249.5	249.9	249.2	-0.13%
	TC2	292.4	292.8	292.2	-0.04%
	TC3	292.5	292.8	292.2	-0.09%
	TC4	294.5	294.7	294.2	-0.09%
	TC5	295.5	295.8	295.5	-0.02%
HX	TC6	289.0	289.3	288.9	-0.05%
	TC7	253.8	254.1	253.5	-0.14%
	TC8	251.1	251.5	250.9	-0.11%
	TC9	251.3	251.6	250.9	-0.16%
	TC10	251.2	251.6	250.9	-0.15%
	DT_HX	35.2	35.2	35.4	0.62%
	DT_OIL	16.6	17.1	NA	
	PUMP flow		0.0	NA	
	BYPASS flow	2.394	2.392	2.382	-0.49%
	OIL flow	0.29	0.29	NA	
	P_HX_pri	-12332	-12269	-12349	0.14%
	P_core	15000	15000	15000	0.00%
	P_HX_sec	9260	9362	NA	
	Heatloss Mantello	3072	3209.82	NA	
	sec+heatloss mantello	12332	12572.1	NA	
	heatloss loop	2668	2427.9	2651	-0.63%

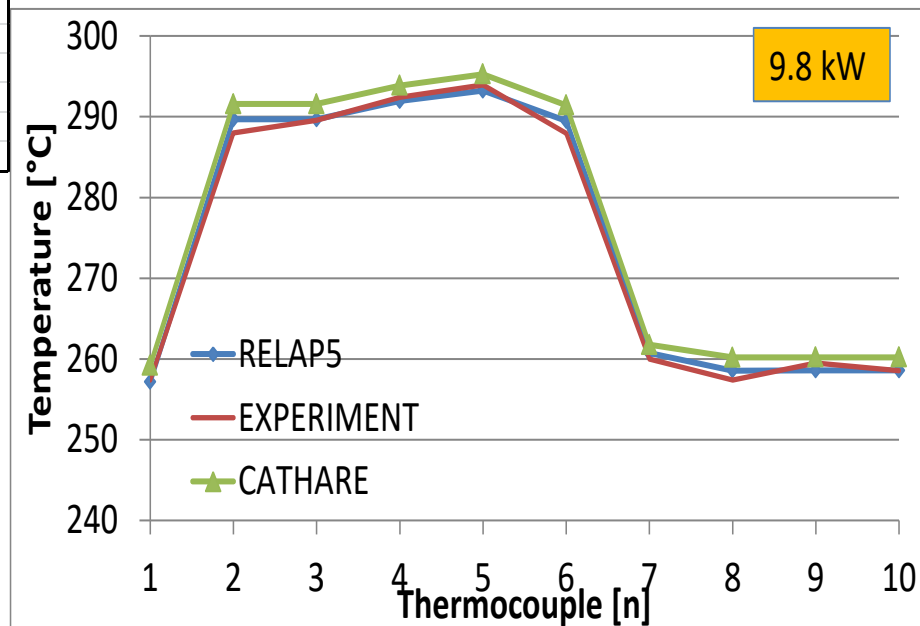
DATA		
Power	15000	W
Tin_oil	113.6	° C
Mflow_oil	0.29	kg/s



Results of NC Test – 9.8 kW

	time = 20000 s	EXPERIMENT	RELAP5	CATHARE	Error
CORE	TC1	257.4	257.2	259.2	0.71%
	TC2	288.0	289.7	291.6	1.24%
	TC3	289.6	289.7	291.6	0.69%
	TC4	292.4	291.9	293.9	0.50%
	TC5	293.9	293.2	295.3	0.46%
HX	TC6	288.0	289.5	291.4	1.21%
	TC7	260.0	260.7	261.8	0.69%
	TC8	257.4	258.6	260.2	1.09%
	TC9	259.5	258.6	260.2	0.28%
	TC10	258.5	258.6	260.2	0.65%
	DT_HX_pri	28.0	28.7	29.7	6.08%
	DT_OIL	25.6	29.2	NA	
	PUMP flow		0.0		
	BYPASS flow	2.100	2.062	2.070	-1.44%
	OIL flow	0.12	0.12	NA	
	P_HX_pri	-8952	-8641	-8985	0.37%
	P_core	9800	9800	9800	0.00%
	P_HX_sec	6224	7044	NA	
	Heatloss Mantello	2728	1764	NA	
	sec+heatloss mantello	8952	8808	NA	
	heatloss loop	848	992	816	-3.82%

DATA	
Power	9800 W
Tin_oil	143.5 ° C
Mflow_oil	0.12 kg/s



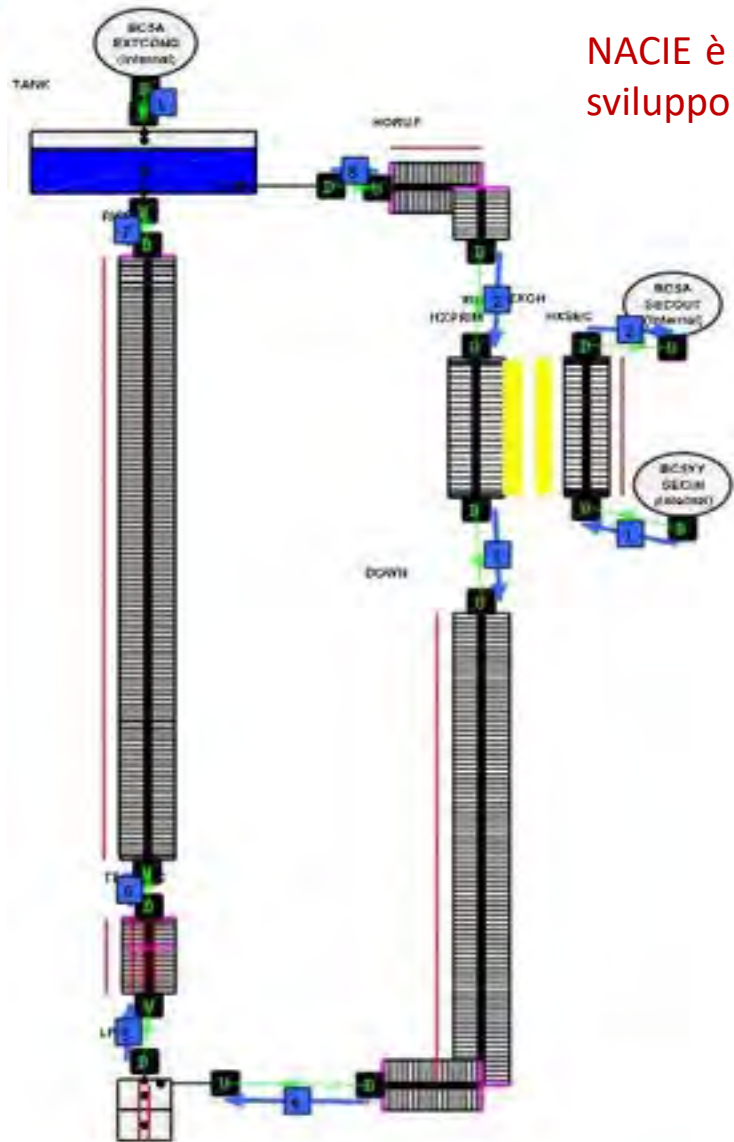
Imposte le condizioni di scambio termico HX di RELAP5

Modello NACIE per CATHARE

NACIE è una facility per esperimenti termoidraulici su metalli liquidi (LBE), sviluppo di componenti e verifica di procedure.

CARATTERISTICHE DEL MODELLO

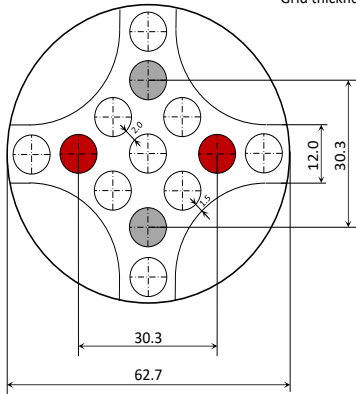
- ❖ Modello monodimensionale
- ❖ Le strutture termiche sono simulate (FPS, dummy, etc)
- ❖ Le perdite di calore sono simulate attraverso i tubi circondati da uno strato di lana di roccia.
- ❖ L'HX è simulato e la conducibilità dello strato di polvere di acciaio è calibrata al 10.5% di AISI304.
- ❖ Circuito secondario (H₂O) limitato all'HX con condizioni al contorno.
- ❖ Revisionate le perdite di carico concentrate calcolate con correlazioni in letteratura (Idelchick) in particolare della griglia superiore della barra scaldante, le stesse usate nel modello RELAP5



Perdite di Carico – Griglia superiore (precedente)

Upper Grid

- Active Rod
- Dummy Rod
- $\phi_{hole} = 8.2 \text{ mm}$
- Grid thickness = 5 mm



Area undisturbed (Ach-A4rod)	2.8744E-03	m2
Grid Area		
Ach-A13holes-A4sect	1.29053E-03	m2
Area flow on the grid (A9holes-A4sect)	1.58389E-03	m2
Ref. Reynolds (core)	50000	

With Rehme

$$k = 2.6311$$

With Idelchick perforated plate (Diag. 3.12)

$$f = F_{or}/F_{gr} = 0.551$$

$\bar{f}$	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.90	1.0
ζ	5.8	4.4	3.5	2.6	2.0	1.7	1.3	0.8	0.5

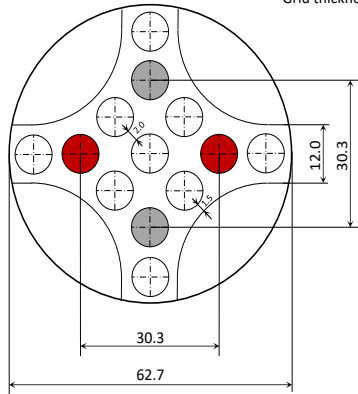
Adopted

$$k = 4.4$$

Perdite di Carico – Griglia superiore (attuale)

Upper Grid

● Active Rod
● Dummy Rod
 $\phi_{hole} = 8.2 \text{ mm}$
Grid thickness = 5 mm



Area undisturbed (Ach-A4rod)	2.8744E-03	m2
Grid Area		
Ach-A13holes-A4sect	1.13855E-03	m2
Area flow on the grid (A9holes-A4sect)	1.73587E-03	m2
Ref. Reynolds (core)	20000	

$$K(w0) = 1.2829$$

152 HANDBOOK OF HYDRAULIC RESISTANCE

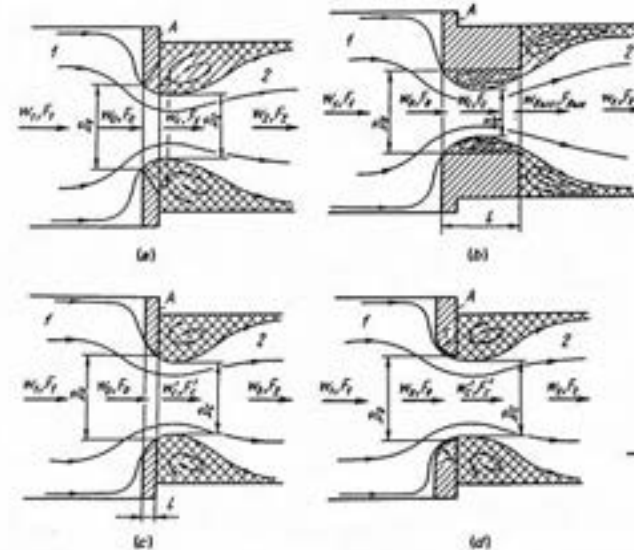


Figure 4-8. General case of flow passage through an orifice in the wall from one volume into another: (a) sharp-edged orifice ($l/D_h = 0$); (b) orifice with thick edges ($l/D_h > 0$); (c) orifice with edges beveled in the flow direction; (d) orifice with edges rounded in the flow direction.

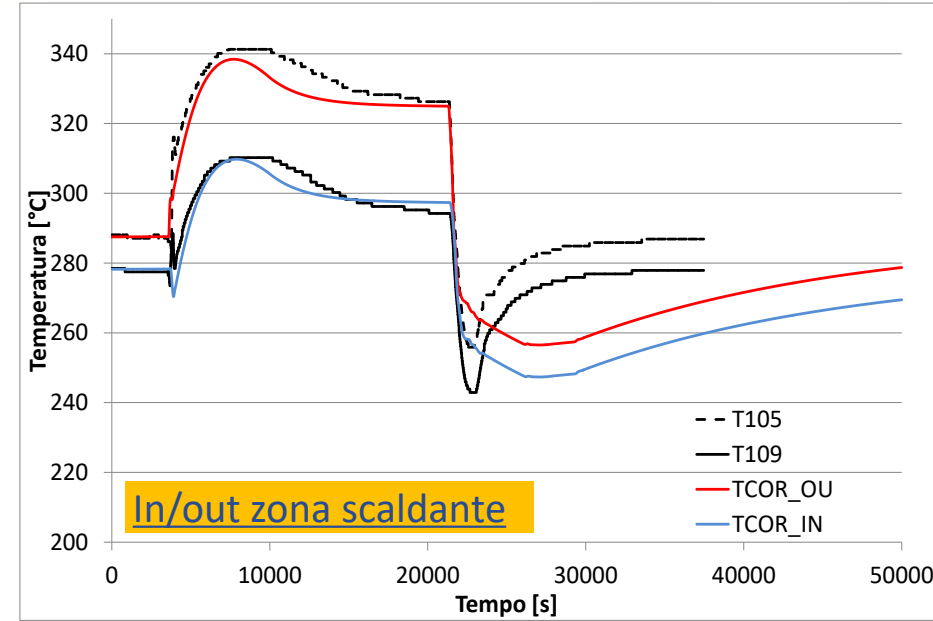
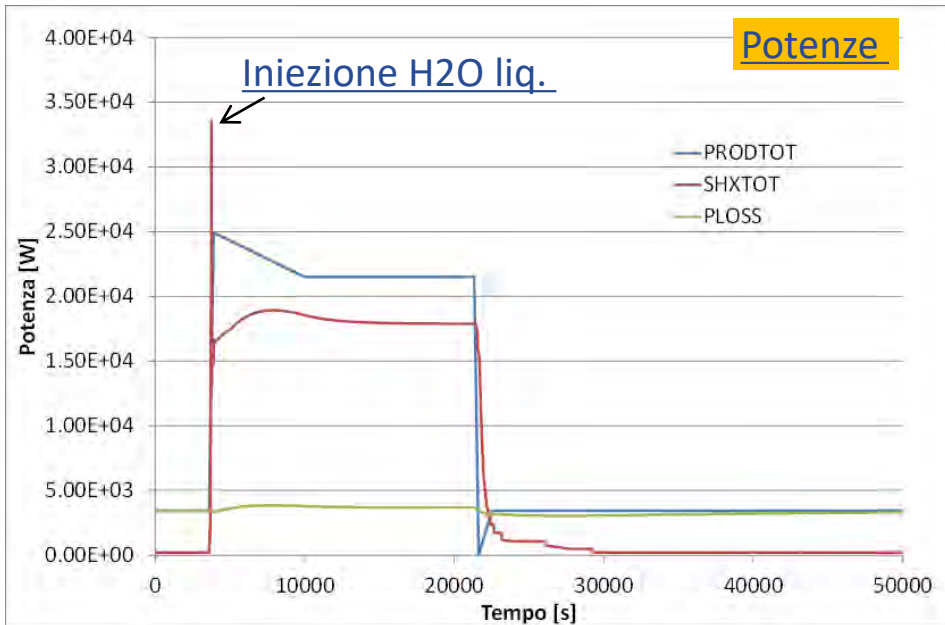
21. The resistance coefficient of the flow passing through orifices in the wall, with edges of any shape and of any thickness, is calculated (in the general case considered under paragraph 18) from the author's generalized formula [13, 14]

$$\xi = \frac{\Delta p}{\rho w_0^2 / 2} = \xi' \left(1 - \frac{F_0}{F_1}\right) + \left(1 - \frac{F_0}{F_2}\right)^2 + \tau \sqrt{1 - \frac{F_0}{F_1}} \left(1 - \frac{F_0}{F_2}\right) + \xi_{tr} \quad (4-5)$$

where ξ' is a coefficient which depends on the shape of the orifice inlet edge and is determined as ξ from Diagrams 3-1 through 3-4 and 3-7; τ is the coefficient representing the effect of the wall thickness, the inlet edge shape of the opening, and conditions of flow passage through the opening with thick edges [it is determined from the curve $\tau = f(l/D_h)$ in Diagram 4-12, while for beveled or rounded edges, it is approximated by $\tau \approx 2\sqrt{\xi'}$]; $\xi_B = \lambda(l/D_h)$ is the friction coefficient over the entire depth of the orifice opening; and λ is the hydraulic friction factor of the opening depth determined from diagrams in Chapter 2. In the case of beveled or rounded edges, ξ_B is assumed to be zero.

Simulazione Dinamica del Test 301

Test301 (circolazione naturale): Accensione del FPS a 21.5 kW seguito dallo spegnimento.



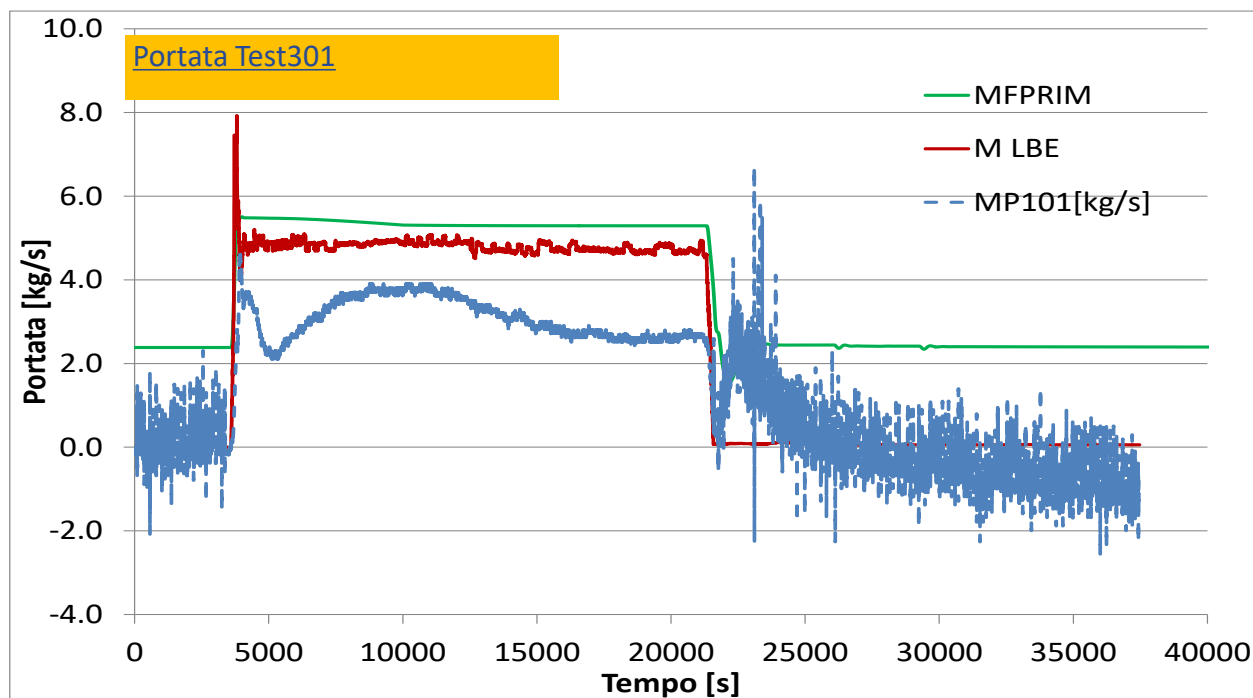
Calibrazione iniziale per compensare le incertezze su misure e procedure:

- potenza iniziale FPS 3.4kW (16%) in funzione di riscaldatore
- conducibilità powder 10.5% AISI304
- perdite di calore
- Il secondario è caricato con vapore a 1.5 bar, pressione costante durante il transitorio

Si assume che all'accensione del FPS, i riscaldatori forniscono ancora una certa potenza (inerzia termica). Rampa di potenza da 16% al 116%.

Simulazione Dinamica del Test 301

- ❖ **Test 301:** Circolazione Naturale, Potenza 21.5 kW, portata stimata con bilancio termico **4.71 kg/s (media su 1h)**. La portata di MP101 è affetta da forti incertezze alle basse portate.



Portate stimate dai partecipanti al benchmark LACANES

Dato sperimentale
da bilancio termico

4.71

ENEA
(RELAP5)

5.15

RSE
(LEGO)

5.30

SNU
(MARS)

5.21

Ansaldo
(RELAP5-3D)

5.19

INEST
(RELAP/SCDAPSIM/MOD4)

5.26

ENEA
(CATHARE)

5.29

- ❖ I modelli di HELIOS e NACIE per il codice T/H CATHARE2 sono stati riveduti (geometria e pdc) per la simulazione di test in circolazione naturale, usando CATHARE versione v2.5_3 mod 2.1.
- ❖ Le perdite di carico sono state valutate avvalendosi delle “best practice” acquisite nella Fase 1 del benchmark LACANES e con correlazioni in letteratura (Idelchik).
- ❖ Nella simulazione degli stati stazionari di due test in circolazione naturale a 15kW e 9.8 kW della facility HELIOS, di cui il primo usato per calibrazione del modello, CATHARE si è dimostrato capace di riprodurre anche il test a 9.8 kW. Rimane il limite di non avere una corretta simulazione dell’HX (olio).
- ❖ Nella simulazione del test 301 in circolazione naturale della facility NACIE si ha una sovrastima della portata in relazione a RELAP5 (come evidenziato in precedenti annualità) ma il valore risulta comunque in linea se comparato ai partner LACANES. Le discrepanze sono dovute a mancanza di informazioni sulle procedure di prova, specialmente sul lato secondario.