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SPES3 Facility: RELAP5 simulations of the DBE and BDBE DVI line DEG break from 65% and 100% power for design support

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SPES3 FACILITY: RELAP5 SIMULATIONS OF THE DBE AND BDBE DVI LINE DEG BREAK FROM 65% AND 100% POWER FOR DESIGN SUPPORT

R. Ferri, SIET

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SPES3 facility: RELAP5 simulations of the DBE and BDBE DVI line DEG break from 65% and 100% power for design support

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This report has been issued in the frame of the ENEA and MSE research program on "Nuovo Nucleare da fissione". It is the deliverable A.1-1 of the task LP2 of the work program 2008-2009 "Verifiche analitiche a supporto del progetto" della facility SPES3.
The document deals with the results of RELAP5 simulations of the DVI line DEG break for design and beyond design basis conditions. It describes the influence of PCC and ADS Stage-II actuation time on accident recovery. A comparison between full power and reduced power steady state conditions is reported together with a comparison between transients starting from such conditions. The results demonstrate that SPES3 facility is suitable to simulate accidental transients starting from reduced power and mass flow conditions with little differences by transients starting from full power.

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III. NOMENCLATURE

ADS	Automatic Depressurization System
ADS-DT	ADS-Double Train
ADS-ST	ADS-Single Train
BAF	Bottom of Active Fuel
BDBE	Beyond Design Basis Event
Bot, bot	Bottom
BC	Base Case
CIRTEN	Consorzio Interuniversitario Nazionale per la Ricerca Tecnologica Nucleare
CRDM	Control Rod Drive Mechanism
CV	Containment Volume
D	Diameter
DBE	Design Basis Event
Di	inner diameter
d	diameter
DC	Downcomer
DEG	Double Ended Guillotine
DP	Differential pressure
DT	Difference of temperature
DTh	Heat transfer Diameter (RELAP5 parameter)
DVI	Direct Vessel Injection
DW	Dry Well
EBT	Emergency Boration Tank
EHRS	Emergency Heat Removal System
FER	University of Zagreb
FF	Fouling Factor (RELAP5 parameter)
FL	Feed Line
FW	Feed Water
GOTHIC	Generation Of Thermal-Hydraulic Information for Containments
HX	Heat Exchanger
IRIS	International Reactor Innovative and Secure
LGMS	Long Term Gravity Make-up System
LM	LOCA Mitigation signal
LOCA	Loss of Coolant Accident
mid	middle
MFIV	Main Feed Isoaltion Valve
MSIV	Main Steam Isolation Valve
n.a.	Not available

NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
P	Pressure
PCC	Passive Containment Cooling
PRZ	Pressurizer
PSS	Pressure Suppression System
PWR	Pressurized Water Reactor
QT	Quench Tank
RC	Reactor Cavity
RC	Concentric reduction (in the geometrical detail tables)
RCCA	Rod Cluster Control Assembly
RELAP	REactor Loss of coolant Analysis Program
RI	Riser
R&D	Research and Development
RPV	Reactor Pressure Vessel
RV	Reactor Vessel
RWST	Refuelling Water Storage Tank
S	Safeguard signal
SC	Sensitivity case
SG	Steam Generator
SIET	Società Informazioni Esperienze Termoidrauliche
SL	Steam Line
SPES	Simulatore Per Esperienze di Sicurezza
T	Temperature
TAF	Top of Active Fuel
WEC	Westinghouse Electric Company

1. SCOPE

The primary goal of this document is to describe the results of SPES3 facility numerical simulations for the DBE and BDBE DVI line DEG break transients.

The BDBE DVI line DEG break transient simulation, with all the EHRSs unavailable, allowed to investigate the PCC performance and actuation logic. Moreover it put in evidence the importance of the ADS-Stage-II actuation time in the accident mitigation and the need of reducing hydraulic resistance of the RC to DVI line to enhance the water back-flow from containment to RPV. The comparison with IRIS results allowed to verify similarity of the main quantities in the facility and in the plant.

The transients were investigated starting from 100% power, for a direct comparison with the IRIS plant, and from 65% power to define the correct test procedure.

In fact, the need of test beginning from 65% power, due to SIET electric supply limit, led to investigate the initial conditions for the tests that, scaling primary and secondary mass flows according to power, allowed to have same fluid enthalpy conditions as if starting from full power. Steady conditions were thus defined.

Both DBE and BDBE DVI line DEG break transients were simulated starting from steady state at 65% power and the similarity to the 100% power transients was verified.

2. INTRODUCTION

The SPES3 facility was designed for testing on SMR with integral layout and it is being built at SIET laboratories. The facility is based on IRIS reactor design and it is suitable to simulate postulated Design and Beyond Design Basis Events, providing experimental data for code validation and plant safety analyses, [1].

The IRIS reactor is an advanced medium size, integral layout, pressurized water reactor developed by an international consortium of utilities, industries, research centres and universities. It is based on the proven technology of PWR with an innovative configuration and safety features suitable to cope with Loss of Coolant Accidents through a dynamic coupling of the primary and containment systems, [2] [3].

The SPES3 facility reproduces the primary, secondary and containment systems of the reactor with 1:100 volume scale, full elevation, prototypical fluid and thermal-hydraulic conditions, [4] [5] [6] [7] [8] [9] [10] [11] [12] [13].

The RELAP5 thermal-hydraulic code was chosen to simulate the whole SPES3 facility: primary and secondary circuits, safety systems and containment. During the SPES3 design, a complex calculation-design feedback process led to optimize model and design up to the present configuration suitable to simulate the IRIS reactor and reproduce the IRIS results obtained by FER at Zagreb University with the RELAP5 and GOTHIC coupled codes [14] [15] [16] [17] [18] [19] [20] [21] [22] [23].

The process included the simulation of all Design Basis Events specified in the test matrix with a greater attention to the DVI line DEG break, considered the most challenging LOCA in IRIS, potentially maximizing RPV mass depletion [1]. The first simulated Beyond Design Basis Event, specified in the test matrix, was the DVI line DEG break with all the EHRS unavailable. This allowed to verify PCC performance and actuation logic and to investigate ADS Stage-II influence on on accident mitigation.

The need of testing SPES3 starting from 65% nominal power, due to the limit on SIET power supply, led to search for steady conditions with reduced power and mass flows, suitable to maintain the same full power fluid enthalpies. New steady conditions were found as compromise among hardware choices, boundary conditions and acceptable differences by IRIS steady state. The DBE and BDBE DVI line DEG break were simulated starting from 65% power steady state in order to have a direct comparison with 100% power transients.

Work, described in detail in this document, is part of SPES3 facility design review and transient analyses that led to further updating of the facility nodalization and design with particular focus on the SG tube number, the PCC tube bundle and cooling circuit, the RC to DVI line pressure drops and accident mitigation strategies with optimization of PCC and ADS Stage-II actuation time.

3. SPES3 AND IRIS MODELS

This section reports the schemes of the SPES3 facility and the RELAP5 nodalization utilized for the cases described in the following chapters. The IRIS schemes and nodalizations for RELAP5 and GOTHIC codes are reported too.

3.1 SPES3 schemes and RELAP5 nodalization

The general view of SPES3 is reported in Fig.3. 1. The SPES3 flow diagram for primary loop, secondary loop B and containment system is reported in Fig.3. 2. The flow diagrams for secondary loops A and C are reported in Fig.3. 3.

The details of SPES3 base nodalization are reported in [15]. The calculation-design feedback process, carried out to optimize the SPES3 design to better simulate the IRIS plant, led to model updates as described in [18]. Two models, SPES3-146 and SPES3-147, came out of the design review, the first one with 14 tubes SGs and the second one with 13 tubes SGs. The DVI line DEG break calculation results showed that both solutions were valid for IRIS simulation if starting from 100% power. The search for steady conditions to run the facility at 65% power led to choose the case with 13 tubes SGs that showed more adequate heat transfer surface suitable to provide core inlet and outlet temperature close to IRIS ones, with mass flow scaled on power (the 14 tubes SG case resulted in the same core ΔT but primary average temperature 5 K lower). SPES3-147 nodalization was the staring point for the present analysis.

Updates to SPES3-147 nodalization concerned the PCC cooling loop model, for the BDBE simulation, and resizing of RC to DVI line orifice. Fig.3. 4, Fig.3. 5, Fig.3. 6 report the updated SPES3 RELAP5 nodalization.

3.2 IRIS RELAP5 and GOTHIC nodalization

The general view of the IRIS RPV and Containment System are reported in Fig.3. 7 and Fig.3. 8. IRIS Engineered Safety Features are sketched in Fig.3. 9.

Details of IRIS base nodalizations are reported in [20]. The comparison with SPES3 simulation results and system optimization, led to update the IRIS nodalization as reported in [21] up to the IRIS-HT6_rwstc case. Later modifications of some details furthermore updated the nodalization in IRIS-HT6_rwstc1a case as reported in [24].

Fig.3. 10 and Fig.3. 11 report the IRIS RELAP5 and GOTHIC nodalizations.

Fig.3. 1 – SPES3 general view

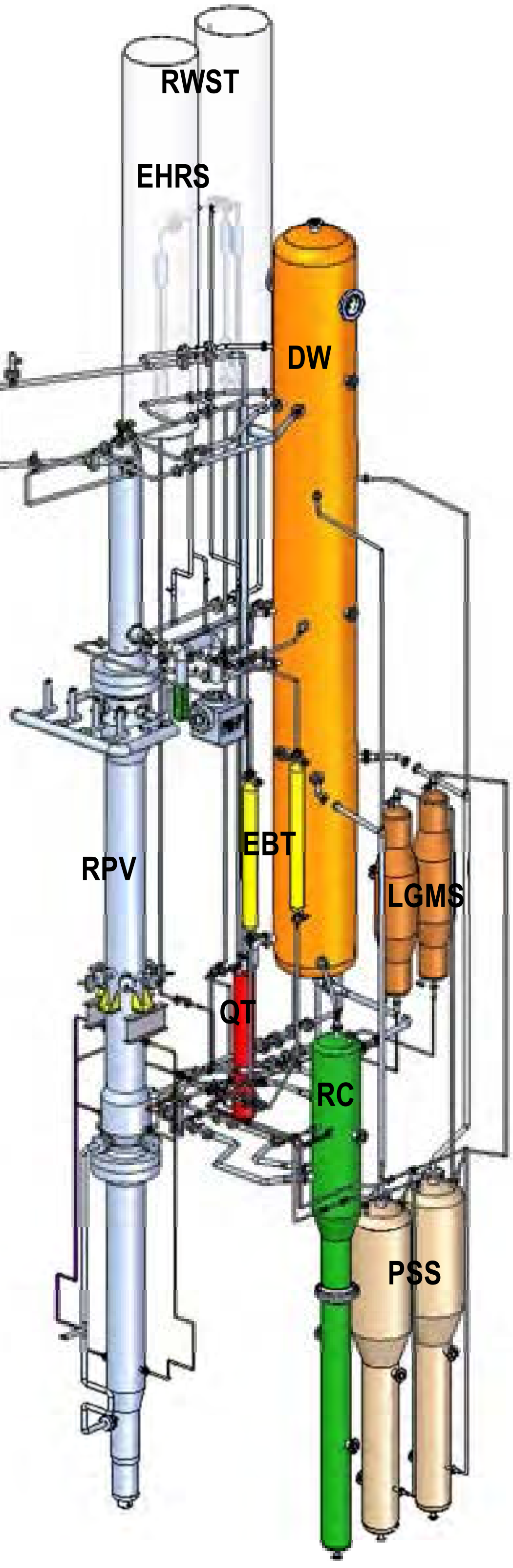


Fig.3. 2 – SPES3 primary, secondary loop B, and containment system layout

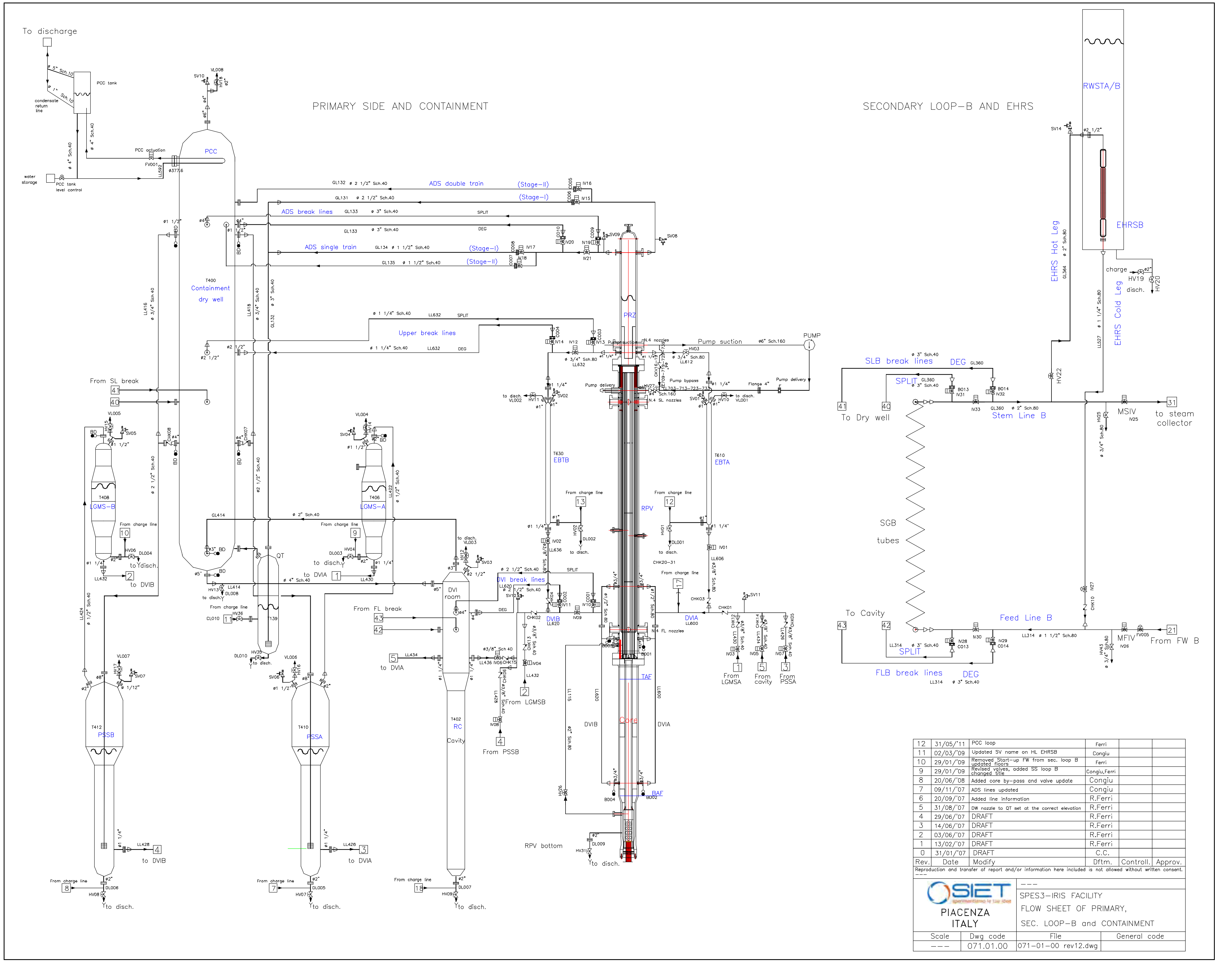


Fig.3. 3 – SPES3 secondary system A and C layout

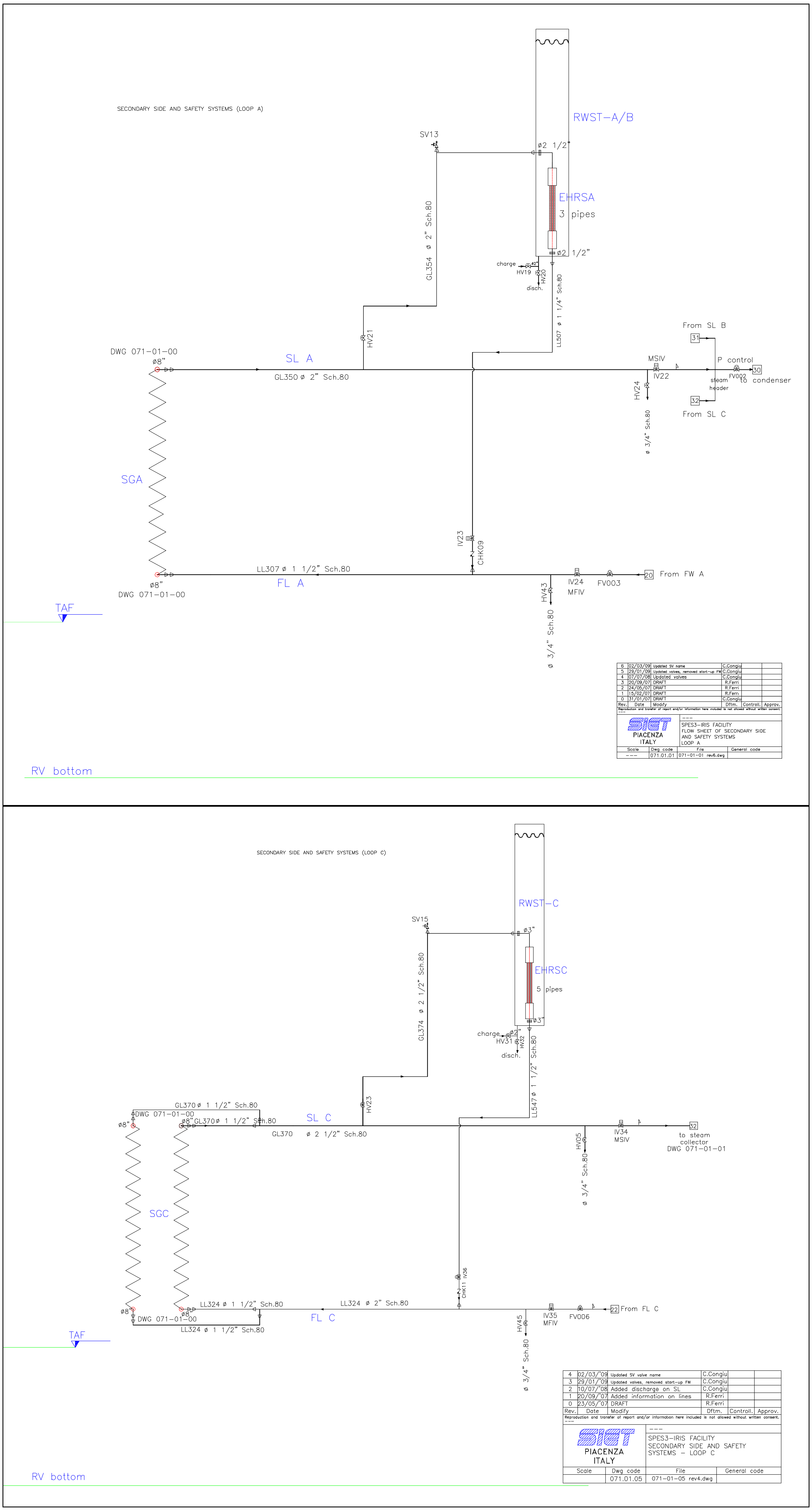


Fig.3. 4 – SPES3 Primary System RELAP5 nodalization

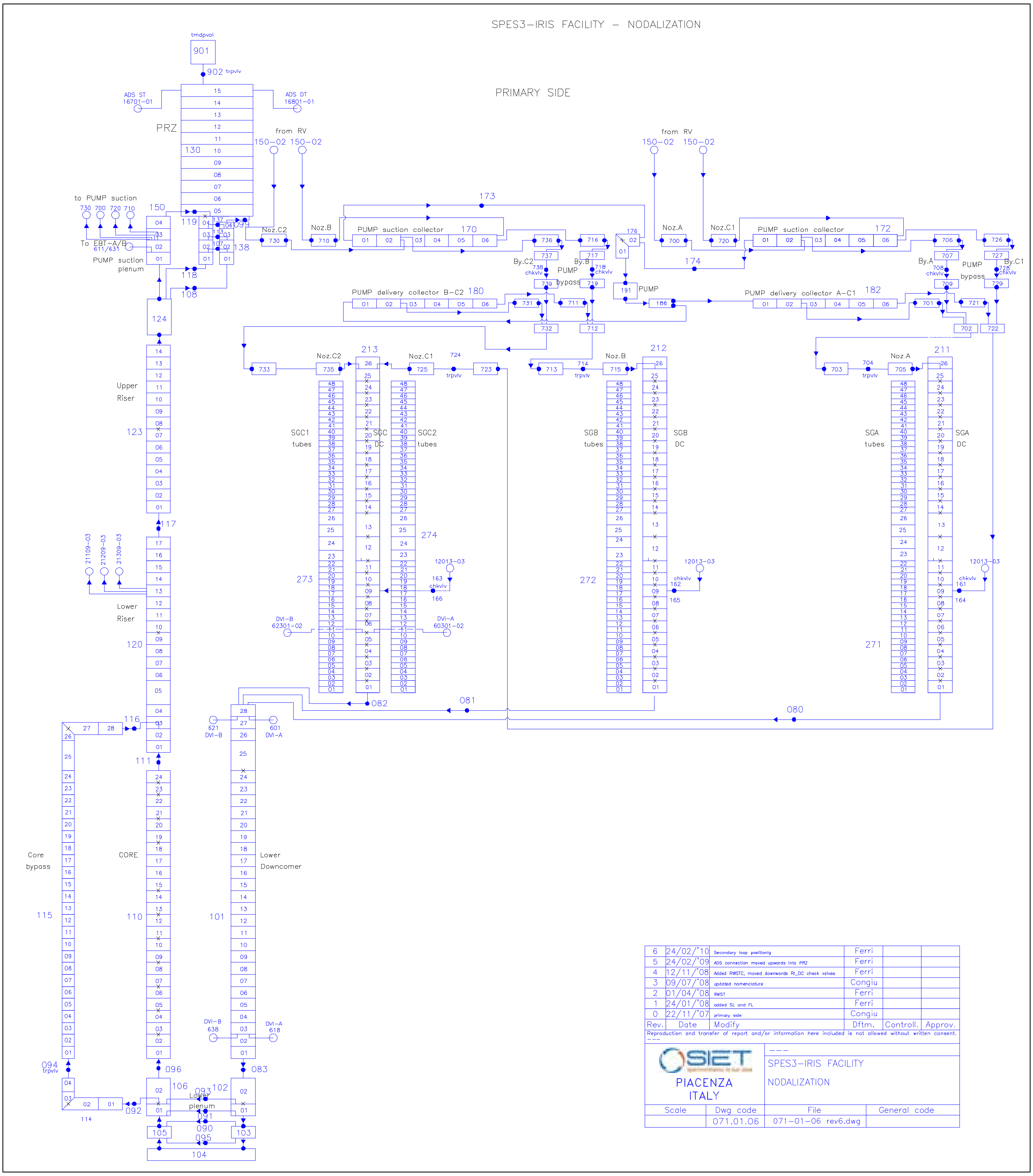


Fig.3. 5 – SPES3 Secondary Systems and EHRSs RELAP5 nodalization

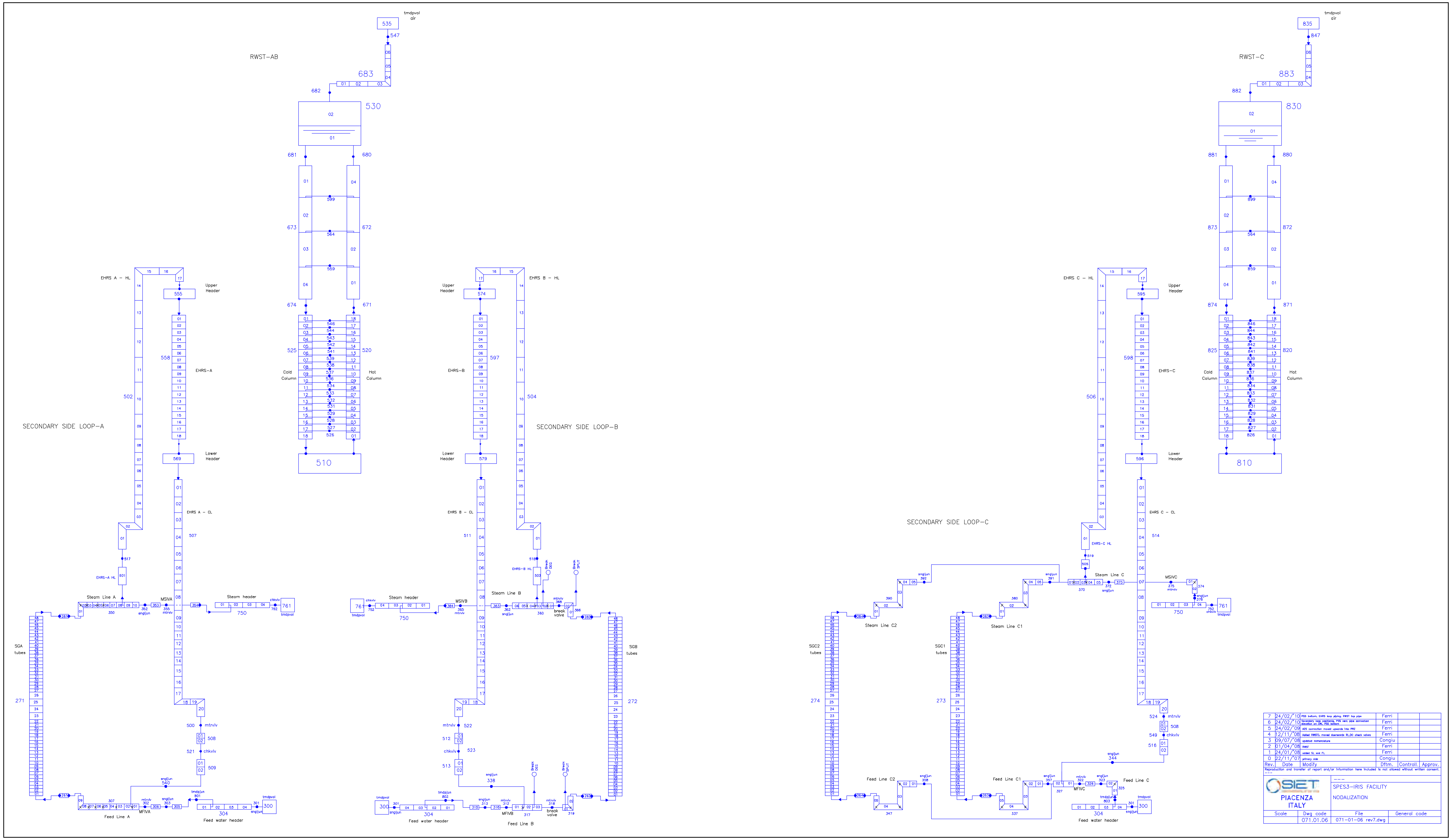


Fig.3. 6 – SPES3 Containment System RELAP5 nodalization

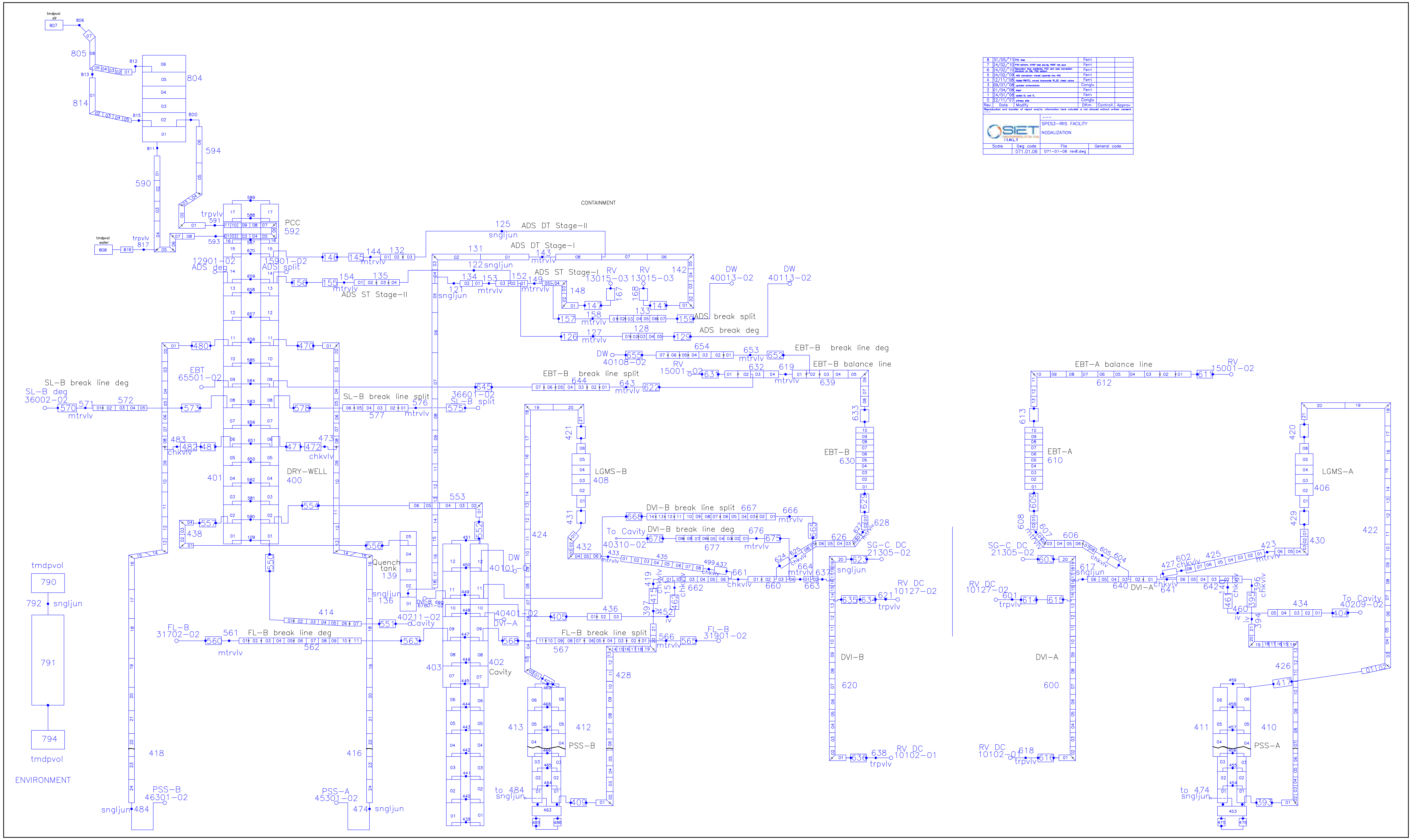


Fig.3. 7 – IRIS Reactor Pressure Vessel general view

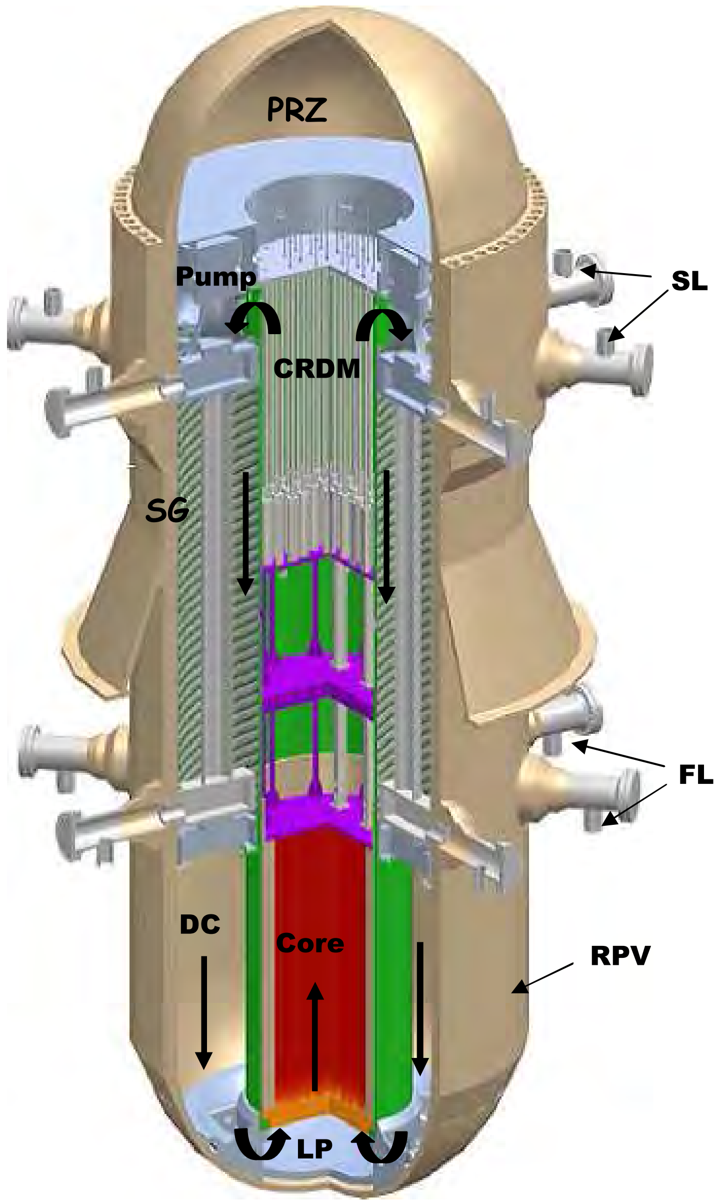


Fig.3. 8 – IRIS Containment System general view

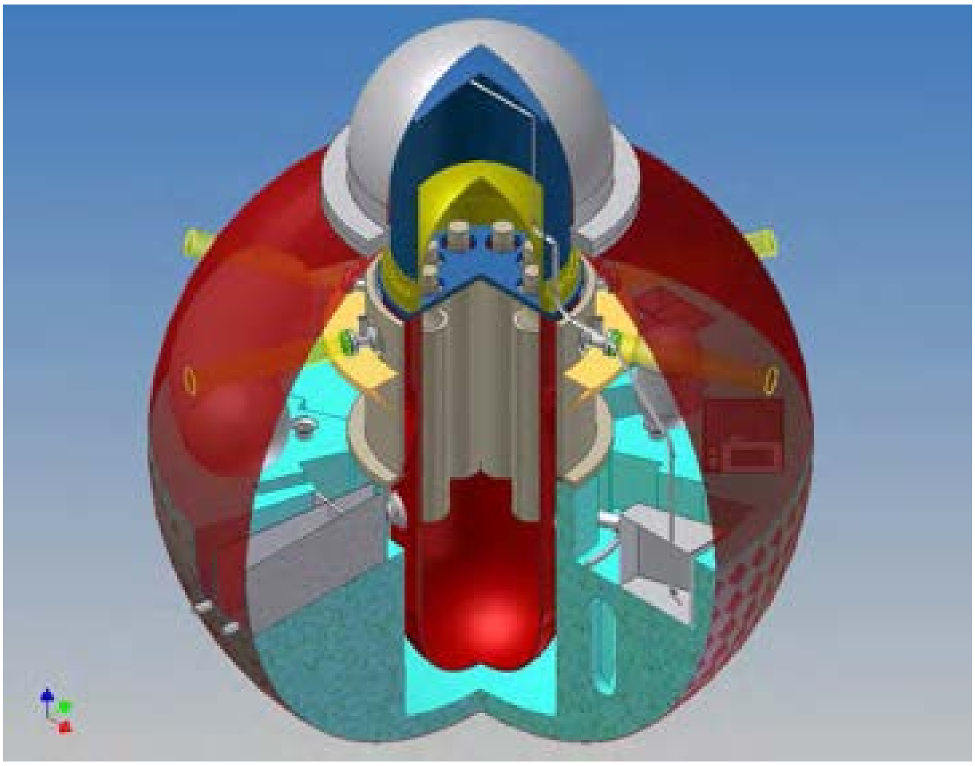


Fig.3. 9 – IRIS Engineered Safety Feature scheme

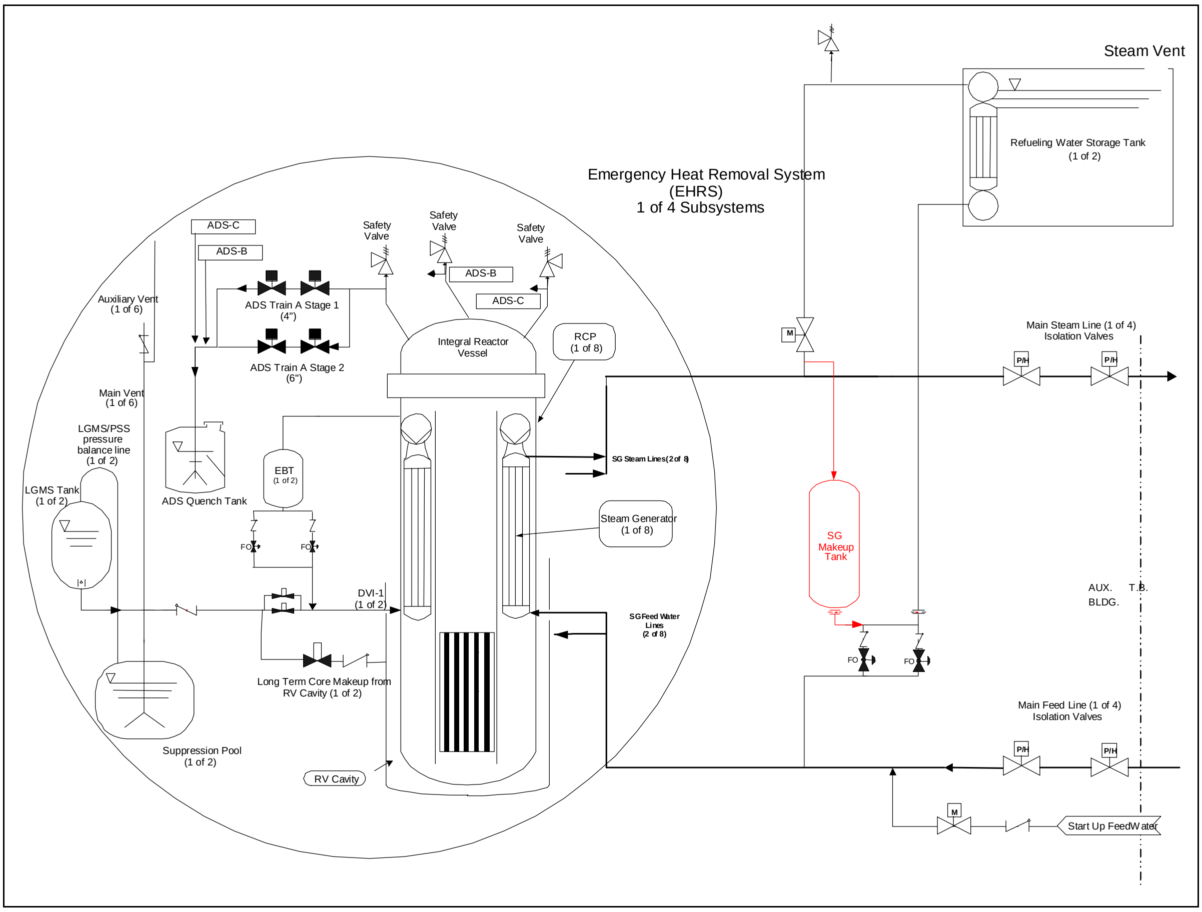


Fig.3. 10 – IRIS Primary, Secondary and EHRS systems RELAP5 nodalization

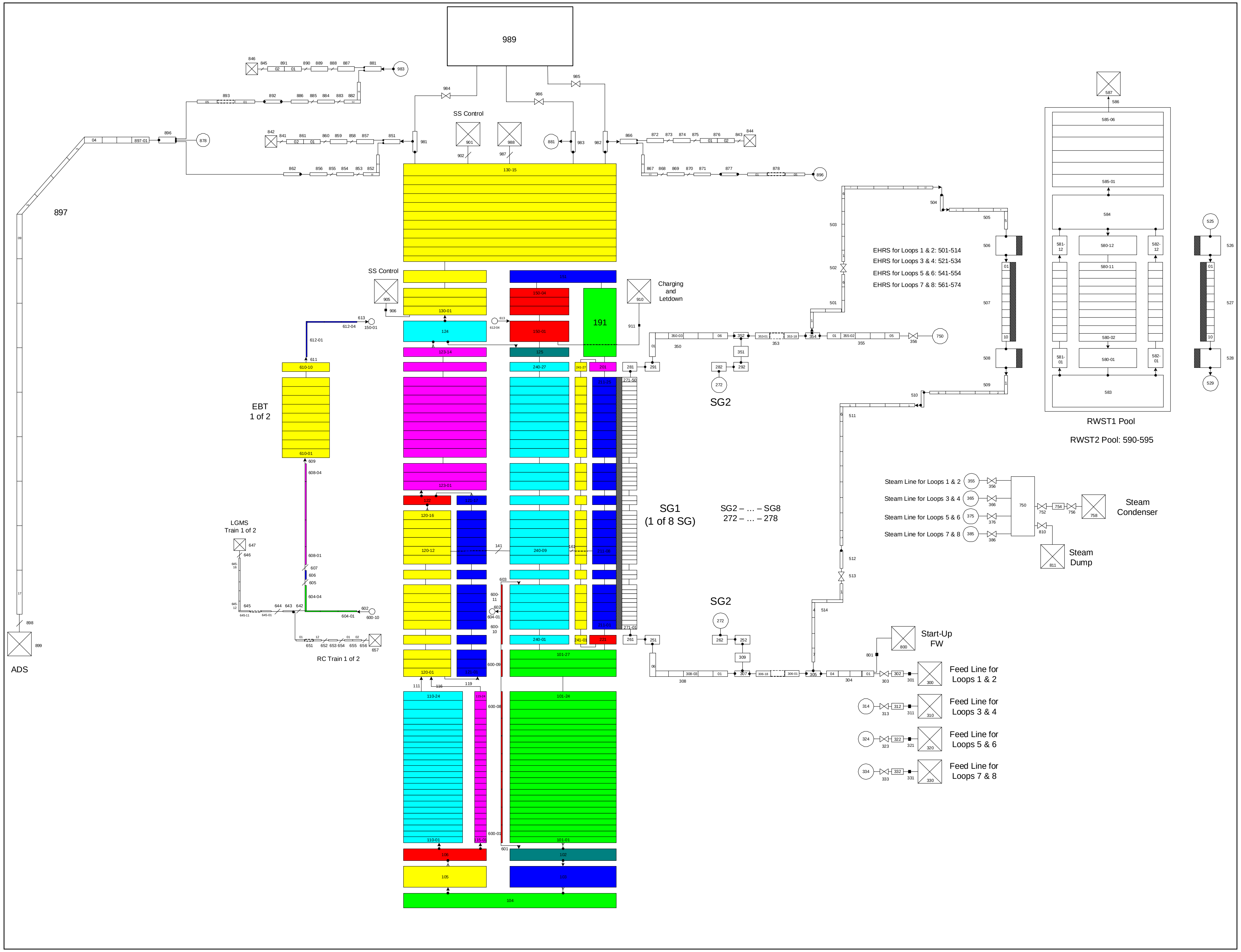
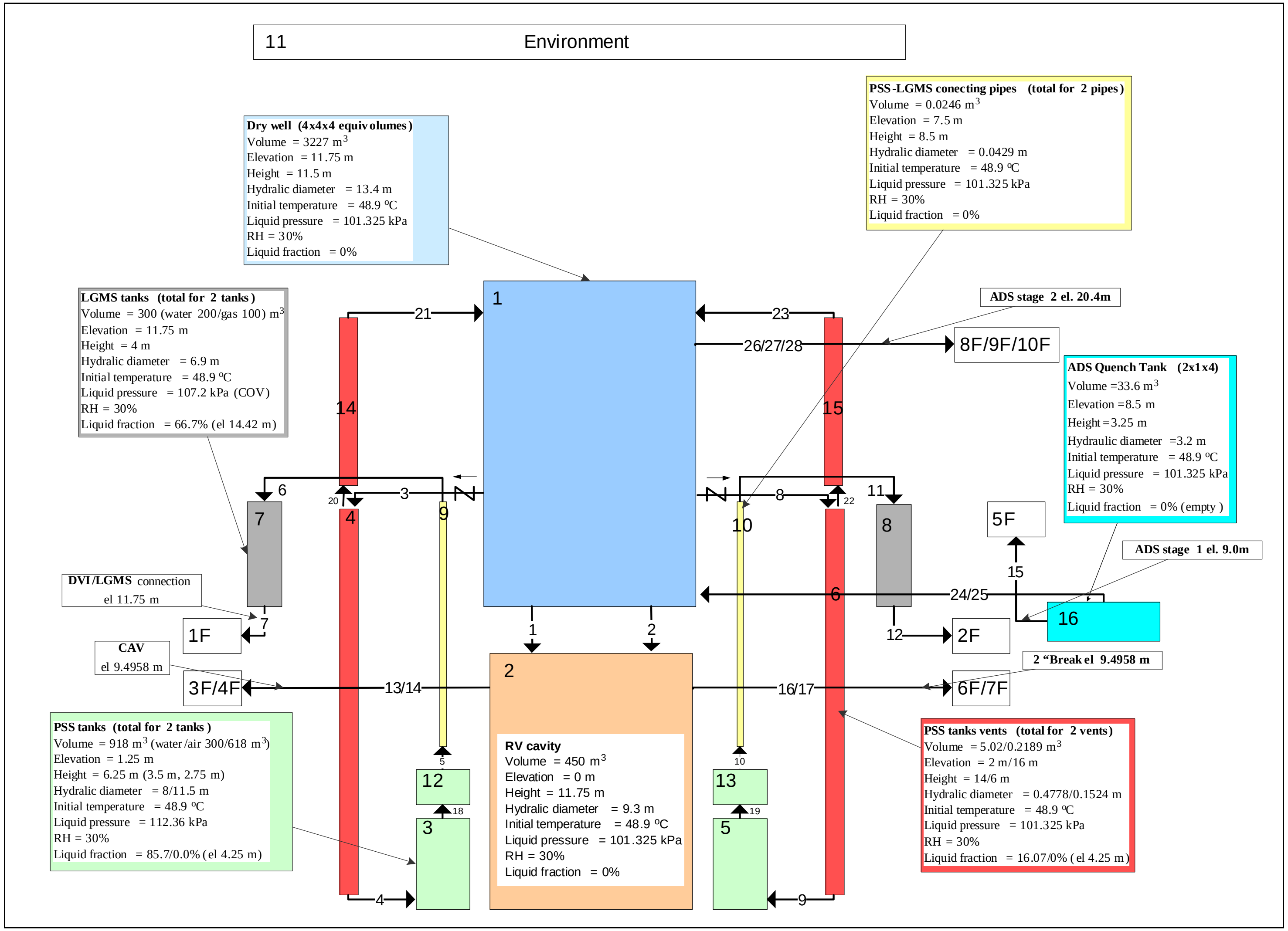


Fig.3. 11 – IRIS Containment system GOTHIC



4. BDBE DVI LINE DEG BREAK: SPES3-160

The calculation-design feedback process led to optimize SPES3 design and nodalization on the basis of the DBE DVI line DEG break, as described in [18]. The test matrix for SPES3 experimental program foresees execution of both Design Basis and Beyond Design Basis Events [1]. All transients must be numerically simulated to identify eventual criticalities in the design, not evidenced in the DBE analyses, and possibly intervene before the completion of the facility construction.

The BDBE 2-inch equivalent DVI line DEG break is a very challenging transient for IRIS, with all EHRS unavailable and PCC the only device to remove decay power and maintain the plant in safe conditions.

SPES3-160 case is based on SPES3-147 nodalization, with 13 tube SGs, as come out of the facility design review described in [18]. The model was updated with an optimized PCC tube bundle and cooling circuit as shown in Fig.3. 6. PCC actuation logic was optimized too. PCC water flow was triggered according to the following logic: reaching of 0.9 MPa containment pressure AND 1800 s delay on LM-signal, assuming such delay as time required to fill-up the containment refuelling cavity that provides the heat sink for passive containment cooling system. PCC is designed to maintain the containment pressure between 0.8 and 0.9 MPa.

The PCC final design includes an horizontal 20 tubes bundle (1-inch Sch. 10, 3.58 m average length) installed at the DW top [9]. The bundle is connected to a water tank at upper elevation. A cold line feeds the bundle with water and a hot line drives steam back to the tank, Fig.3. 2. The tank acts as steam condenser/separator and includes a make-up system suitable to maintain water level at the specified set-point of 0.7 m.

Steady conditions of SPES3-147 case, compared to IRIS ones, showed some differences mostly related to average primary circuit temperature, about 3 °C higher than IRIS, due to the 13 tubes SG reduced heat transfer surface with respect to SPES3-146 with 14 tubes SGs [18]. For SPES3-160 case, some boundary conditions were optimized to get closer to IRIS steady state. In particular, SG mass flow was increased by 0.8%, which allowed to improve also superheating at SG outlet and SG collapsed level.

The RELAP5 nodalization used for SPES3-160 case is shown in Fig.3. 4, Fig.3. 5, Fig.3. 6. The details of changes, with respect to SPES3-147, are listed below:

- Modified PCC tube bundle with 20 tubes (they were 12);
- Added PCC cooling loop, tank and control system (PCC mass flow was imposed as a boundary condition);
- PCC actuation logic on 0.9 MPa containment pressure AND 1800 s delay on LM-signal (it was only on pressure);
- Modified the trip sequence to exclude the EHRS intervention;
- Increased SG-A and B mass flow to 1.260 kg/s (it was 1.250 kg/s) and SG-C mass flow to 2.520 kg/s (it was 2.50 kg/s);
- Corrected the control variables related to SG secondary side mass for 13 SG tubes (they were for 14 tubes).

The following paragraphs describe the BDBE DVI line DEG break transient results and put in evidence possible interventions to optimize design and accident management procedures.

4.1 SPES3-160

Full power steady conditions, starting point for the transient, are summarized in Tab.4. 1. IRIS conditions for HT6_rwstc case are reported as well for a direct comparison.

The list of the main events occurring during the transient, with timing and quantities, is reported in Tab.4. 2.

4.1.1 Transient phases and description

The first 10 s of SPES3 data (-10 s to 0 s) are steady state conditions.

All times of the events are given with respect to the break time assumed as time 0 s.

The main phases of the transient are shortly summarized here, while a more detailed description is provided in the followings.

- The break opening causes RPV blowdown and depressurization, containment pressurization and steam dumping into PSS with air build-up at PSS top;
- the S-signal triggers the reactor scram and secondary loop isolation. EHRS-A and B actuation fails;
- the low PRZ water level signal triggers the pump coastdown and natural circulation in the core is guaranteed until RPV water level is above the check valves connecting riser and downcomer at one third of SG height;
- the LM-signal, triggers the ADS Stage-I to help RPV depressurization and EBT intervention to inject cold borated water into the primary circuit. EHRS-C actuation fails;
- PCC water flow is actuated when 0.9 MPa containment pressure threshold is reached and after 1800 s since the LM-signal;
- PCC depressurizes the containment and, when PSS pressure is sufficiently high to win the gravity head of PSS vent pipes, cold water flows from PSS to DW increasing containment depressurization and RC flooding;
- the low differential pressure signal between RPV and DW triggers LGMS injection into the DVI line and opens the valves connecting RC and DVI line to increase water back-flow from containment to primary system;
- PCC maintains DW pressure between specified set points;
- the low LGMS mass signal (20% of initial mass) opens ADS Stage-II connecting primary and containment systems at high elevation in the plant. PRZ and DW pressure equalizes and water flows from RC to RPV driven by containment water gravity head;
- in the long term, PCC maintains the system at limited pressure values by condensing steam exiting the RPV, with a water back-flow from RC to RPV.

Break

Break line mass flow, RPV side (SPLIT) and containment side (DEG), is shown in Fig.4.1 and Fig.4.2. The peak of 1.33 kg/s is observed at 2 s, RPV side. Around 1000 s, water level in the RPV decreases below the DVI line elevation, uncovering the break, with a steeper reduction of loss of mass.

Mass flow, containment side, is first related to the safety injection of EBT in the broken loop (starting at 253.65 s) and later to LGMS injection (starting at 6439.05 s), Fig.4.3, Fig.4.4.

Reverse flow from containment (RC) to RPV is observed through the SPLIT line, after ADS Stage-II is opened and RPV and containment pressures are equalized, Fig.4.5, Fig.4.6.

Blowdown, RPV depressurization, containment pressurization

The blowdown phase depressurises RPV with mass and energy transfer to the containment.

SPES3 PRZ pressures is shown in Fig.4.7 and Fig.4.8.

While PRZ depressurises, containment pressure increases as shown in Fig.4.6, Fig.4.9, Fig.4.10. The increase in the pressurization rate at 253.65 s is due to ADS Stage-I intervention that discharges mass and energy into the DW, Fig.4.11, Fig.4.12. After that, pressure increases up to reach the peak of 1.35 MPa at 2060 s.

After the peak, pressure decreases thanks to PCC intervention which removes power from the containment and brings pressure to oscillate between set points of 0.8 and 0.9 MPa, Fig.4.13, Fig.4.14.

At 2290 s, depressurization rate increases due to water flow from PSS to DW that contributes to steam condensation, Fig.4.15, Fig.4.16.

At 6440 s, LGMS cold water injection into RPV (through the intact DVI line) and into RC (through the broken DVI line) helps PCC to maintain the system at specified pressure, Fig.4.4, Fig.4.9.

Steam dumping into PSS

Containment space (DW and RC) pressurization causes the transfer of steam-gas mixture from DW to PSS through the PSS vent lines, starting at 15 s and lasting until PCC intervention and subsequent DW depressurization, Fig.4.15, Fig.4.9.

Within 1000 s, almost all DW non-condensable gas is transferred to PSS, as shown in Fig.4.17 and Fig.4.18. Steam is dumped underwater through the PSS sparger and air pressurizes PSS and LGMS gas space, Fig.4.19, Fig.4.20, Fig.4.21, Fig.4.22. After PSS to DW injection start, PSS and LGMS pressure follows the DW depressurization until PSS pressure is no more sufficient to win the PSS vent pipe gravity head and push water upwards into the DW, Fig.4.15, Fig.4.23, Fig.4.24. Fig.4.25 and Fig.4.26 show water level in the PSS vent pipes that reaches the pipe top elevation only for a few cycles allowing water to be transferred to DW, Fig.4.15. PSS and DW volumes remain separated from pressure point of view until the PSS vent pipes empty and the PSS sparger remains covered. Between about 10000 s and 15000 s, PSS and DW pressures are coupled and follow the oscillations determined by PCC, Fig.4.24.

An non-symmetric behaviour of PSS level is observed since about 15000 s, Fig.4.27, Fig.4.28: PSS-B fills-up again. The reason is LGMS injection into the DVI line, started at 6440 s, that in loop B (the broken loop) enters the RC, through the break line, and contributes to fill-up DW and QT, Fig.4.4, Fig.4.29, Fig.4.30, Fig.4.31, Fig.4.32, Fig.4.33. Even if collapsed DW level does not reach the PSS vent line connections, the fast component fill-up pushes steam into the PSS vent lines. Mass flow from DW to PSS can be observed in Fig.4.16, grater toward PSS-B than PSS-A, probably for lower pressure drops in the pipe. PSS mass is shown in Fig.4.34. Slow, but continuous and cyclic mass increase is observed in both PSS. It is related to cyclic DW pressurization between 0.8 and 0.9 MPa, that anytime causes a mass transfer to PSS through the vent pipes. This phenomenon, slowly stores water in the PSS, making it no more available to be injected into the RPV. It may be a critical point if the amount of water above the core is little.

After ADS Stage-II opening at 35719.18 s, primary and containment system pressures are equalized and PSS and DW pressures oscillate accordingly.

PSS water temperature increases thanks to mass transfer from DW, Fig.4.35, Fig.4.36, Fig.4.16.

Both liquid and gas temperatures are reported in Fig.4.35 and Fig.4.36 and they are very similar. Temperatures always remain below saturation (maximum temperature reached at pressure peak of 1.32 MPa is 428 K (Tsat 465 K) while maximum temperature at minimum pressure of 0.8 MPa is 436 K (Tsat 443.6 K)).

S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure

The high containment pressure set-point (1.7e5 Pa) is reached at 33.36 s and it triggers the S-signal.

The S-signal (Safeguard) starts the reactor SCRAM and isolates the three secondary loops. EHRS-A and B actuation is assumed to fail.

Power released to fluid in the core is shown in Fig.4.37 and Fig.4.38. After the reactor isolation, no power is removed through the SGs toward EHRSs, as failed, Fig.4.39.

The MFIV and MSIV of the secondary loops are contemporarily closed in 5 s and secondary loop mass flows set to zero, Fig.4.40.

Secondary side pressures are shown in Fig.4.41 and Fig.4.42. After isolation, pressure increases up to about 11.3 MPa, due to heat transfer from the primary side and tube water evaporation. Water evaporation causes tube level decrease as shown in Fig.4.43, Fig.4.44. SG pressure trend is related to RPV mass inventory, Fig.4.42. The first peak of minimum pressure is related minimum RPV mass. Pressure increases after LGMS injection starts and RPV mass recovery enhances heat transfer to the secondary side. Pressure increase is stopped when water transfer from RC to RPV is enhanced by ADS Stage-II actuation. Primary side water removes heat from SGs up to reach pressure balance.

Pump coastdown and primary circulation through RI-DC check valves

PRZ level is shown in Fig.4.45. Early phase of level decrease, until ADS Stage-I intervention (253.65 s), is due to loss of mass from the break. Level increase after ADS Stage-I actuation is due to water swelling and suction toward the QT, Fig.4.11. Due to loss of mass from the break, the pump uncovers soon, Fig.4.46.

The pump coastdown is triggered by the Low PRZ level signal delayed of 15 s (136.78 s + 15 s). Soon after the pump suction is uncovered, RPV natural circulation through the pump interrupts.

Core inlet flow is shown in Fig.4.47 and Fig.4.48. Natural circulation lasts until the RI to DC check valves are covered (1130 s) and heat transfer is present, Fig.4.49. In the long term, even if RPV mass is recovered, no circulation occurs as the primary and secondary sides are in thermal equilibrium, Fig.4.50.

LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure, PCC actuation counter start.

The LM-signal (LOCA mitigation) occurs at 253.65 s, when the low PRZ pressure set-point (11.72e6 Pa) is reached, Fig.4.7.

EHRS-C actuation on LM-signal is assumed to fail. Failure of EHRS-C starts the counter for PCC actuation with 1800 s delay on LM-signal. Such delay is assumed as time required to fill the containment refuelling cavity, heat sink for PCC.

The LM-signal triggers the ADS Stage-I and the EBT actuation valves.

ADS Stage-I trains are actuated contemporarily and the valves are fully open in 10 s. ADS Stage-I mass flows are shown in Fig.4.11 and Fig.4.12. Two-peak trend is related to liquid fraction at ADS nozzles. The first peak is due to steam flowing toward the QT. At ADS intervention, water is sucked upwards and PRZ level increases, Fig.4.45. The second ADS mass flow peak is caused by increasing liquid fraction at PRZ top that decreases when PRZ empties.

The LM-signal triggers the EBT valves that are fully open in 15 s. EBT injection mass flows are shown in Fig.4.3. EBT injection into the broken DVI line is initially about 14 times grater than injection into the intact one, due to presence of the break. EBT masses and levels are shown in Fig.4.51 and Fig.4.52, respectively.

Soon after EBT actuation, liquid circulation from RPV toward EBT starts at EBT balance connection to RPV, then, after such connection is uncovered, steam replaces water contained in the EBT top lines and tanks, Fig.4.53, Fig.4.54. The broken loop EBT is empty at 550 s while the intact loop EBT is empty at 3030 s, Fig.4.52.

EBT actuation is responsible for mass flow through the break line, containment side, starting at 254 s, Fig.4.1.

RPV saturation

Fast RPV depressurization and loss of mass from the break, Fig.4.7, Fig.4.1, Fig.4.2, rapidly cause flashing in the primary circuit and void begins at core outlet at 257 s, Fig.4.55. At high level in the core, very low liquid fractions are reached, and only after ADS Stage-II opening (35719.18 s), which enhances back-flow from containment to primary side, high liquid fraction is definitively restored in the RPV, Fig.4.56.

Inlet and outlet core temperatures are shown in Fig.4.57 and Fig.4.58.

Core heater rod surface temperatures are shown in Fig.4.59 and Fig.4.60 for the normal and hot rods, respectively. Strong and long lasting surface temperature excursions, up to 917 K, are evidenced, corresponding to low RPV mass inventory condition, Fig.4.61. The rods are definitively rewetted only after ADS Stage-II intervention that enhances water inlet from RC to RPV through the RC to DVI line and through the break line, RPV side.

RC to DVI line mass flow is shown in Fig.4.62. Water injection into the RPV occurs only through the intact loop. After ADS Stage-II opening, it assumes meaningful values with oscillatory trend linked to the cyclic actuation of PCC.

DVI line mass flows at RPV connections are shown in Fig.4.63 and Fig.4.64 for the intact and broken loop. Water flow into the RPV, through the intact loop, is due to EBT and LGMS injection. The negative values of broken loop mass flow, represent water lost from the break; the positive values represent water back-flow from containment to RPV, driven by primary to containment differential pressure. Mass flow assumes meaningful values only after ADS Stage-II opening and primary and containment pressure equalization.

It is important to note that mass flow entering RPV through the break line is about 20 times grater than RC to DVI line flow and core rewetting mostly occurs thanks to it, Fig.4.62, Fig.4.2.

PCC actuation

The containment pressure peak of 1.35 MPa occurs at 2060 s, Fig.4.9.

Pressure is rapidly dumped thanks to PCC intervention at 2053.66 s (i.e. 1800 s delayed on LM-signal). After that, pressure is maintained between 0.8 MPa and 0.9 MPa, accordingly to PCC actuation logic, Fig.4.13, Fig.4.14.

PCC tube mass flow is shown in Fig.4.65. The tubes discharge into and are fed by the PCC tank that operates as steam condenser and water supply. PCC tank level is controlled by a PI (proportional-integral) control system, 0.7 m level set-point, that injects cold water into the feed line from an auxiliary circuit Fig.4.66. PCC inlet and outlet temperatures are shown in Fig.4.67. Water enters slightly subcooled and exits saturated with a liquid fraction at the outlet of about 0.2, Fig.4.68, Fig.4.69.

Low DP RPV-Containment signal, LGMS and RC to DVI valve actuation

The “Low DP RPV-Containment” signal set point of 50 kPa is reached at 6439.05 s.

Combination of LM-signal AND Low DP RV-Containment signal actuates the LGMSs and opens the valves on the lines connecting RC to DVIs.

The SPES3 LGMS isolation valves are fully open in 2 s as well as the RC to DVI line isolation valves.

LGMS injection into the DVI line is mostly due to gravity. In fact, at the moment of LGMS injection, pressurization for air build-up at LGMS top, through PSS to LGMS balance lines (during RPV blowdown into

RC and DW), is extinguished, for PSS to DW injection with PSS sparger uncovering DW, PSS and LGMS pressure equalization. LGMS injection mass flow is shown in Fig.4.4. LGMS mass is reported in Fig.4.70. LGMS injection into the RPV, through the intact loop DVI line occurs when DVI pressure is lower than LGMS pressure, accordingly to PCC operation, and this explains the oscillatory trend of injection, Fig.4.71, Fig.4.72, Fig.4.4.

PSS water flow to DW, RC flooding

At 2290 s, PSS pressure overcomes the hydrostatic head of water in the PSS vent lines and water is pushed toward the DW through the vent line extensions, Fig.4.15, Fig.4.16. PCC intervention at 2053.66 s and DW depressurization cause discontinuous water injection according to differential pressure between PSS and DW, Fig.4.23.

Since about 7000 s, RPV and DW pressure are coupled, with RPV always at higher pressure. Only after ADS Stage-II opening, at 35719.18 s, RPV and containment pressures are definitively coupled, Fig.4.6.

RC level, initially increased for break and ADS Stage-I mass flow collection, rapidly increases in correspondence of PSS to DW injection up to complete fill-up at 3300 s (11 m level from bottom), Fig.4.29, Fig.4.30.

The QT, initially empty, is partially filled-up by the ADS Stage-I discharge, Fig.4.32. Later fill-up, around 13990 s, is related to rapid increase of the DW level, mostly due to LGMS water injection, Fig.4.31, Fig.4.4.

Low LGMS mass signal: ADS Stage-II actuation, Containment and RPV pressure equalization, reverse flow from containment to RPV

The broken loop LGMS low mass signal is reached at 23345.68 s, when mass decreases to 198 kg (20% of initial mass); the intact loop one at 35719.18 s, Fig.4.70.

Reaching of both LGMS low mass signals actuates the ADS Stage-II valves, fully open in 10 s, Fig.4.5.

At 6433.76 s, the RC to DVI line valves are opened and, as RC level is above the DVI line elevation, water back-flow from RC to RPV is allowed when RPV pressure is lower than containment one (after ADS Stage-II actuation), Fig.4.62. Being the break line at the same DVI line elevation, water back-flow from RC to RPV is allowed through it as well, Fig.4.2.

Long term conditions

In the long term of the transient, system pressure is maintained between 0.8 and 0.9 MPa by the PCC.

Core power, average value between 100000 and 150000 s, is 45.36 kW.

PCC removed power, average value between 100000 and 150000 s, is 25.20 kW.

The difference of about 20 kW is due to facility heat losses to the environment. This value of estimated heat losses can be compensated during the tests by increasing provided core power.

4.1.2 Case conclusions

The detailed analysis of the BDBE DVI line DEG break transient on the SPES3 facility allowed to investigate the phenomena related to the plant behavior in case of total EHRS failure.

It showed weakness of the system in case the ADS Stage-II actuation signal is maintained on the low LGMS mass signal that causes a late ADS actuation. Late ADS Stage-II opening postpones pressure balance between primary and containment systems and delays water back-flow from RC to RPV. The delay of water back-flow determines long period of core uncovering with high rod clad temperature excursions and possible damages.

Further investigations of PCC and ADS Stage-II actuation time are described in the next chapters.

Tab.4. 1 – SPES3-160 and IRIS-HT6_rwstc steady state conditions

SPES3-160	Primary/Core	SG-A	SG-B	SG-C	EBTA/B	QT	DW	PSSA/B	RC	LGMSA/B	RWSTAB	RWSTC
Pressure (MPa)	15.55 (PRZ) 0.104 (pump head)	5.83 (out)	5.83 (out)	5.87 (out)	Primary	Cont.	0.1013	Cont.	Cont.	Cont.	0.1013	0.1013
Tin (°C)	292.5	223.9	223.9	223.9	48.9	48.9	48.9	48.9	48.9	48.9	20	20
Tout (°C)	329.9	318.0	315.0	315.0								
DT (°C)	37.4	94.1	91.1	91.1								
Superheating (°C)		44.25 (Tsat 273.75)	41.25 (Tsat 27 3.75)	40.8 (Tsat 274.2)								
Mass flow (kg/s)	45.64 (2.14 in by-pass)	1.26	1.26	2.52								
Power (MW)	10	2.509	2.497	4.990								
Level (m) -collapsed-	2.233 (PRZ)	1.68	1.85	1.88	3.14 full	empty	empty	3.77	empty	2.454	6.961	6.954
Mass (kg)	3319 (RV)				127			1480		985	11869	11876

IRIS HT6_rwstc	Primary/Core	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8	EBTA/B	QT	DW	PSSA/B	RC	LGMSA/B	RWST1	RWST2
Pressure (MPa)	15.5 (PRZ) 0.129 (pump head)	5.81 (out)	5.79 (out)	5.79 (out)	5.78 (out)	5.78 (out)	5.79 (out)	5.79 (out)	5.81 (out)	Primary	Cont.	0.1013	Cont.	Cont.	Cont.	0.1013	0.1013
Tin (°C)	291	223.7	223.7	223.7	223.7	223.7	223.7	22 3.7	223.7	48.9	48.9	48.9	48.9	48.9	48.9	20	20
Tout (°C)	329	318.05	316.24	318.22	316.52	316.52	318.22	316.24	318.05								
DT (°C)	38	94.35	92.54	94.52	92.82	92.82	94.52	92.5 4	94.35								
Superheating (°C)		44.55 (Tsat 273.5)	43.04 (Tsat 273.2)	45.02 (Tsat 273.2)	43.42 (Tsat 273.1)	43.42 (Tsat 273.1)	45.02 (Tsat 273.2)	43.04 (Tsat 273.2)	44.55 (Tsat 273.5)								
Mass flow (kg/s)	45.24 (2.13 in by-pass)	1.257	1.257	1.257	1.257	1.257	1.257	1.257	1.257								
Power (MW)	10	1.24	1.26	1.24	1.26	1.26	1.24	1.26	1.24								
Level (m) -collapsed-	2.019 (PRZ)	1.93	1.99	1.92	1.98	1.98	1.92	1.99	1.93	3.14 full	empty	empty	3.00	empty	2.668	9.099	9.099
Mass (kg)	3254 (RV)									127			1453		989	11942	11942

Tab.4. 2 – SPES3-160 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	**SPES3-160**		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.36	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.36		
7	MFIV-A,B,C closure start	33.36		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.36		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.36		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.86	9e6 Pa	
11	SG-A high pressure reached	46.86		
12	SG-B high pressure reached	48.30		
13	SG-C high pressure reached	47.86		
14	Secondary loop pressure peak	72 70 71	111e5 Pa A 113e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.65	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.65		
21	ADS Stage-I opening start (3 trains)	253.65		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	265	1.364 kg/s	ST 0.470 kg/s; DT 0.894 kg/s
23	ADS Stage-I second peak flow (3 trains)	328	2.003 kg/s	ST 0.663 kg/s; DT 1.340 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.65		EBT valve stroke 15 s
25	Break flow peak (Containment side)	273		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	311		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	306		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	1001.89	0.9 MPa	
31	PCC actuation	2053.66		LM-signal + 1800 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	2060	13.5e5 Pa	
33	DW pressure lower than PSS pressure	2090		
34	Water starts to flow from PSS to DW	2290		
35	RC level at DVI elevation	2740		
36	EBT-A empty (intact loop)	3030		
37	RC full of water	3300		
38	**Low DP RV-Containment**	6439.05	50e3 Pa	
39	LGMSA/B valve opening start	6439.05		LM + low DP RV-cont. LGMS valve stroke 2 s.
40	RC to DVI line valve opening	6439.05		RC to DVI valve stroke 2 s.
41	LGMS-B starts to inject into RC through DVI broken loop	6440		
42	LGMS-A starts to inject into RV through DVI intact loop	6440		
43	QT fill-up starts from DW connection	13990		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
44	**Low LGMS mass**	23345.68	20% mass (198 kg)	LGMS B (broken loop)
45		35719.18	20% mass (198 kg)	LGMS A (intact loop)
46	ADS Stage-II start opening	35719.18		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
47	LGMS-B empty (broken loop)	28590		
48	Water starts to flow from RC to DVI-A	35740		
49	Containment and RV pressure equalization	35990		
50	LGMS-A empty (intact loop)	38990		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		45.36 kW	Average between 100000 s and 150000 s
53	PCC removed power		25.20 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Fig.4.1 – SPES3-160 DVI line break flow (window)

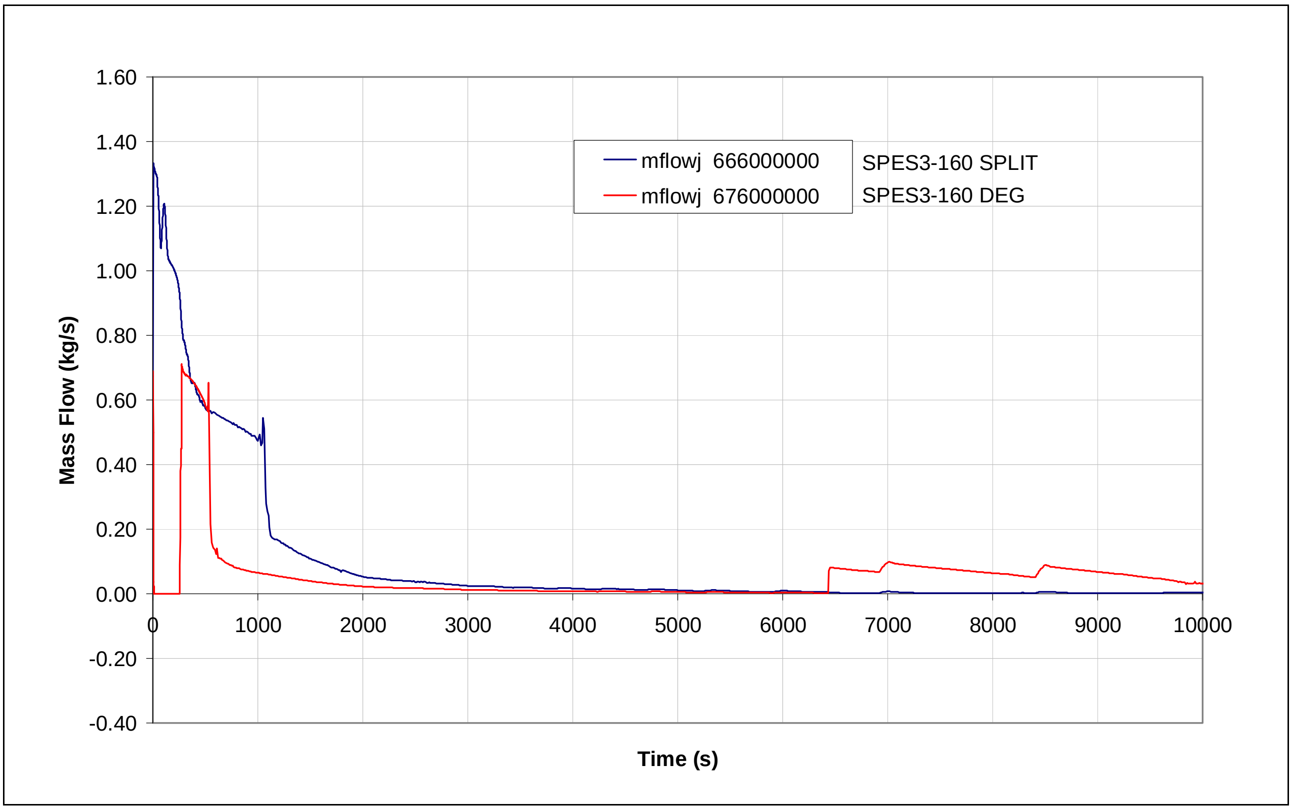


Fig.4.2 – SPES3-160 DVI line break flow

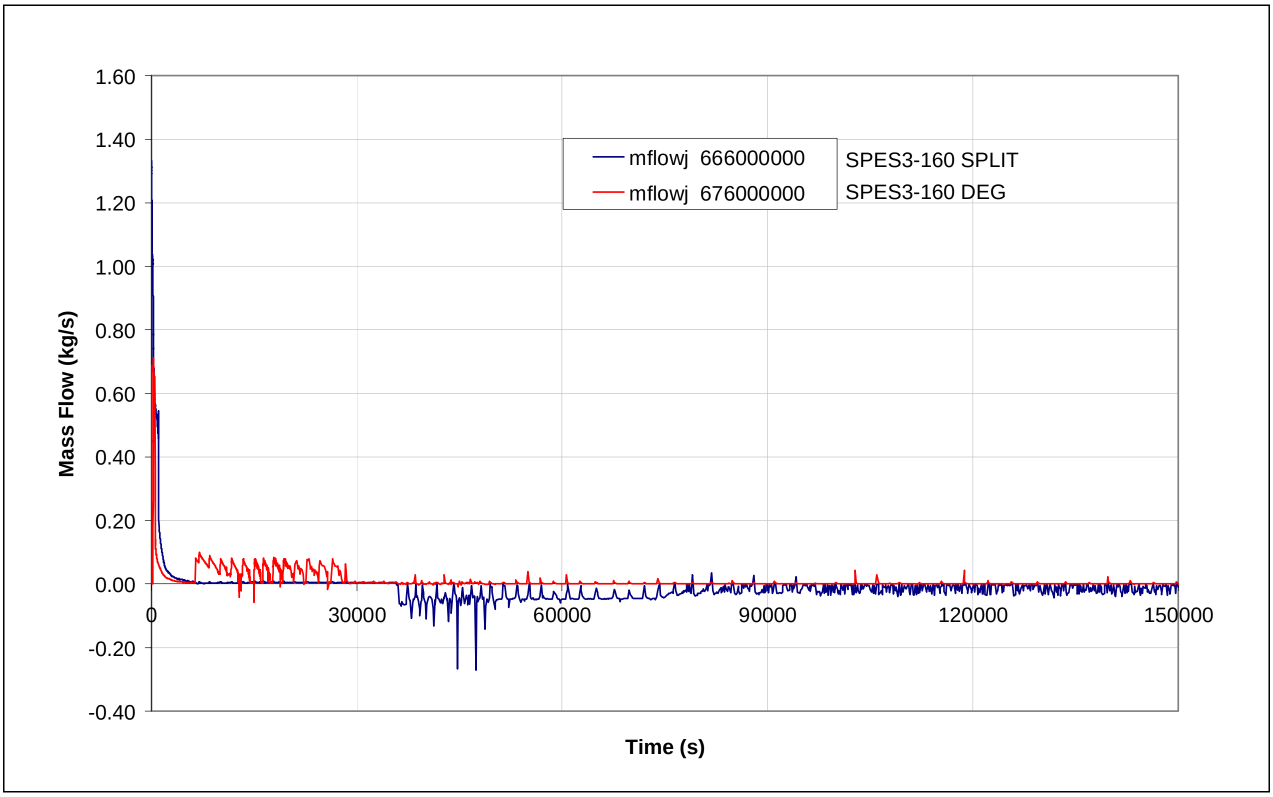


Fig.4.3 – SPES3-160 EBT injection mass flow (window)

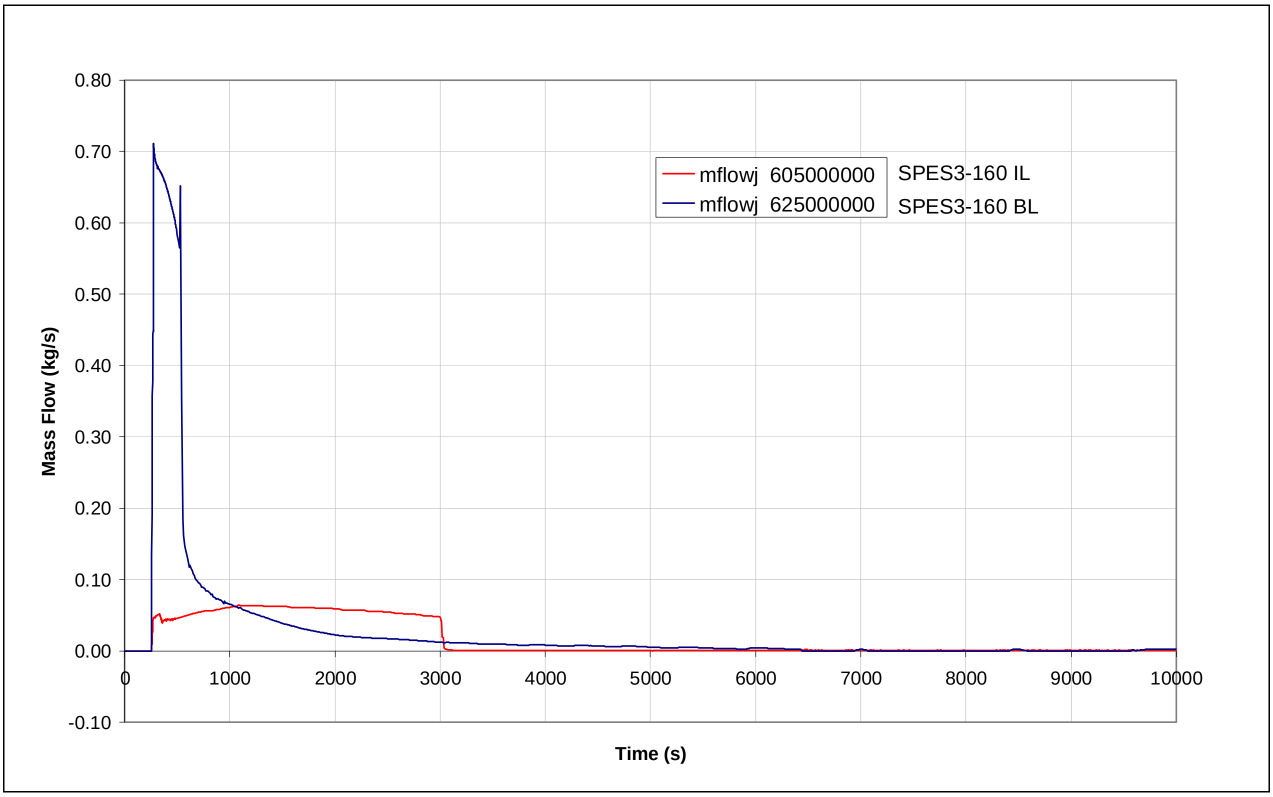


Fig.4.4 – SPES3-160 LGMS injection mass flow

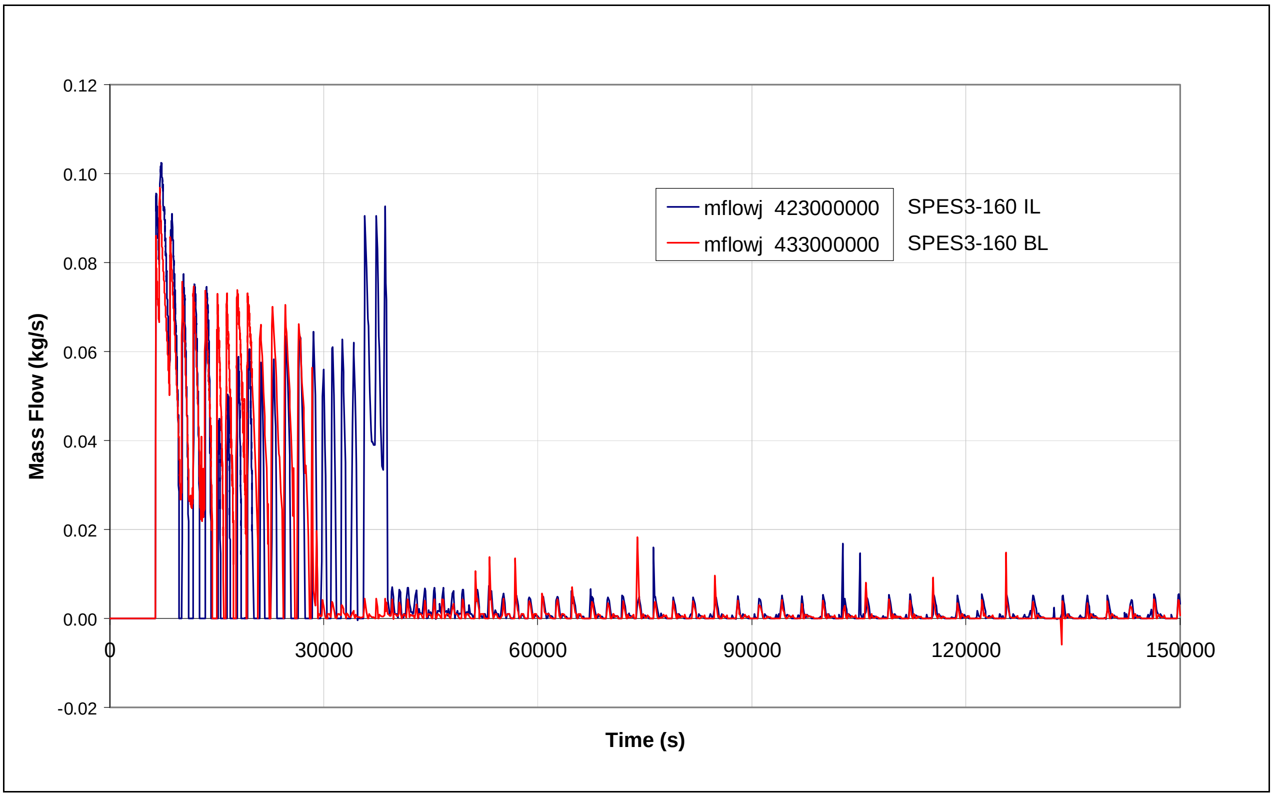


Fig.4.5 – SPES3-160 ADS Stage-II mass flow

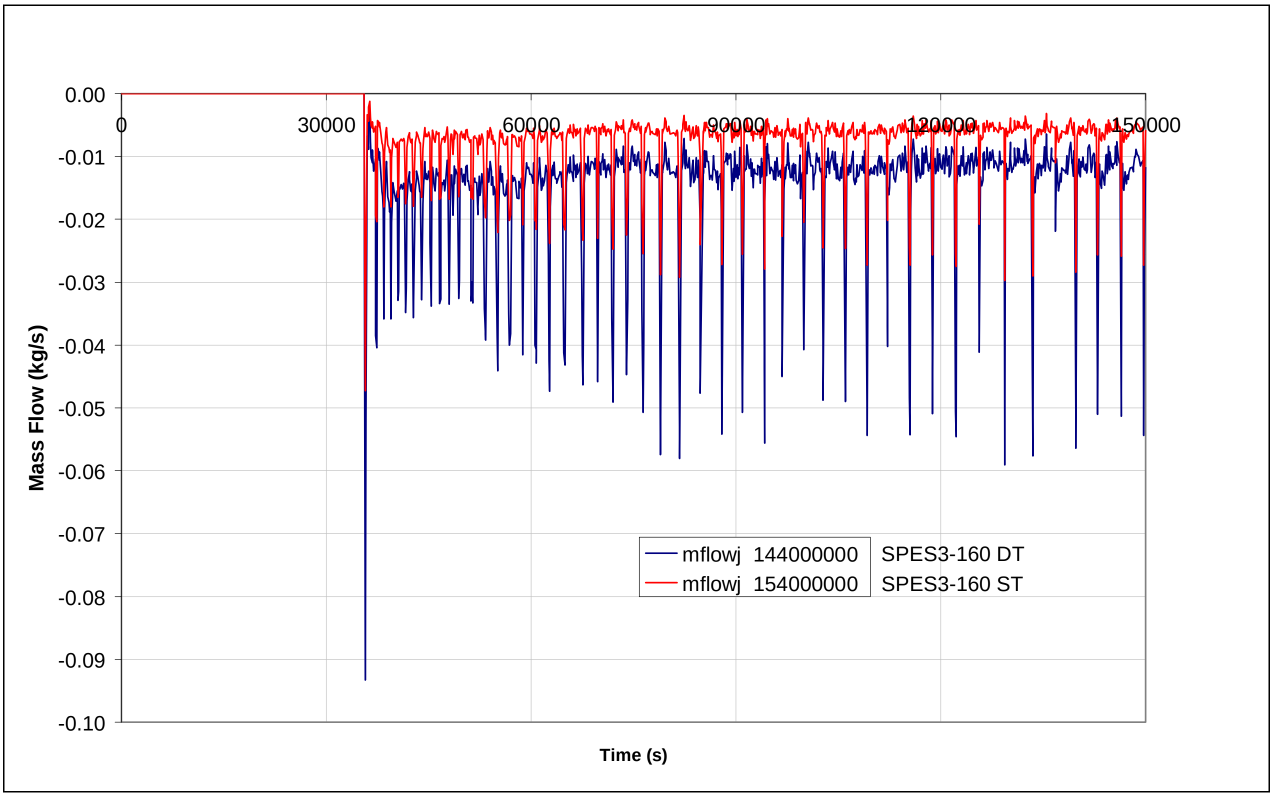


Fig.4.6 – SPES3-160 PRZ and DW pressures (window)

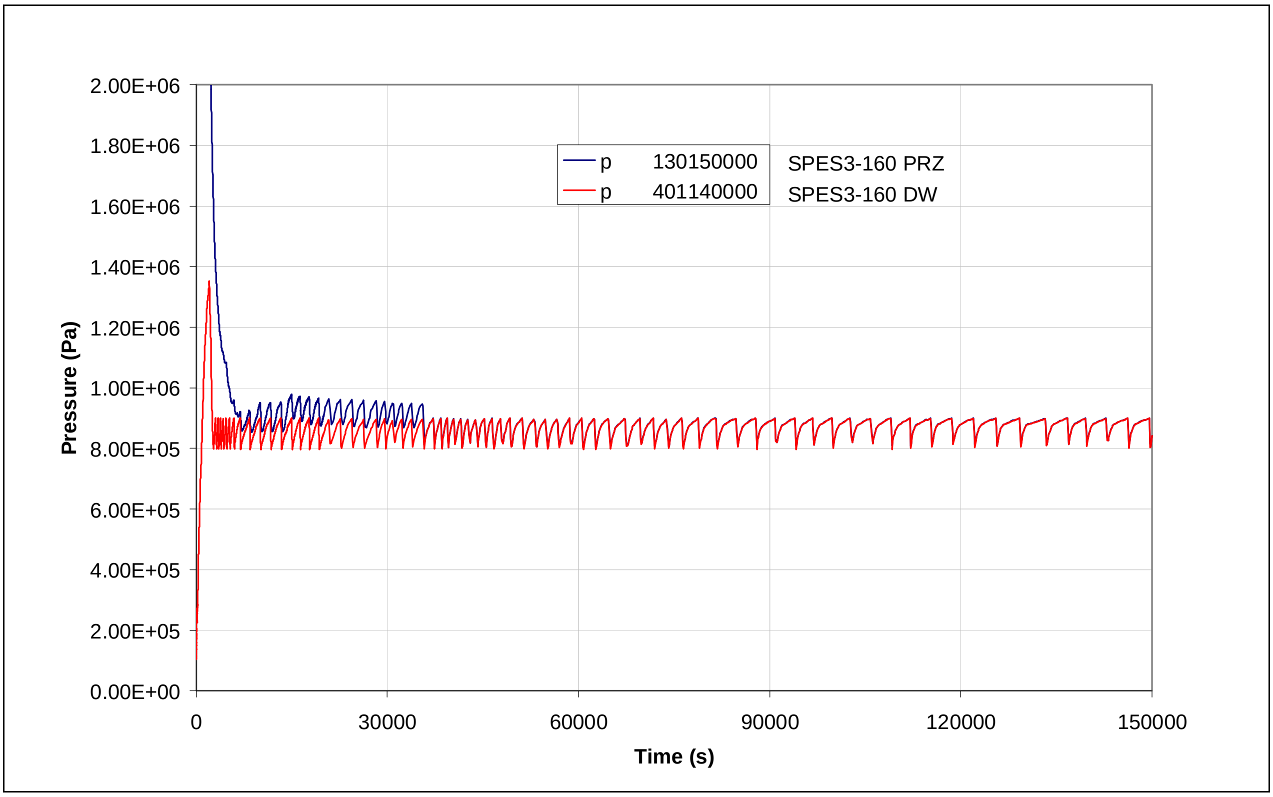


Fig.4.7 – SPES3-160 PRZ pressure (window)

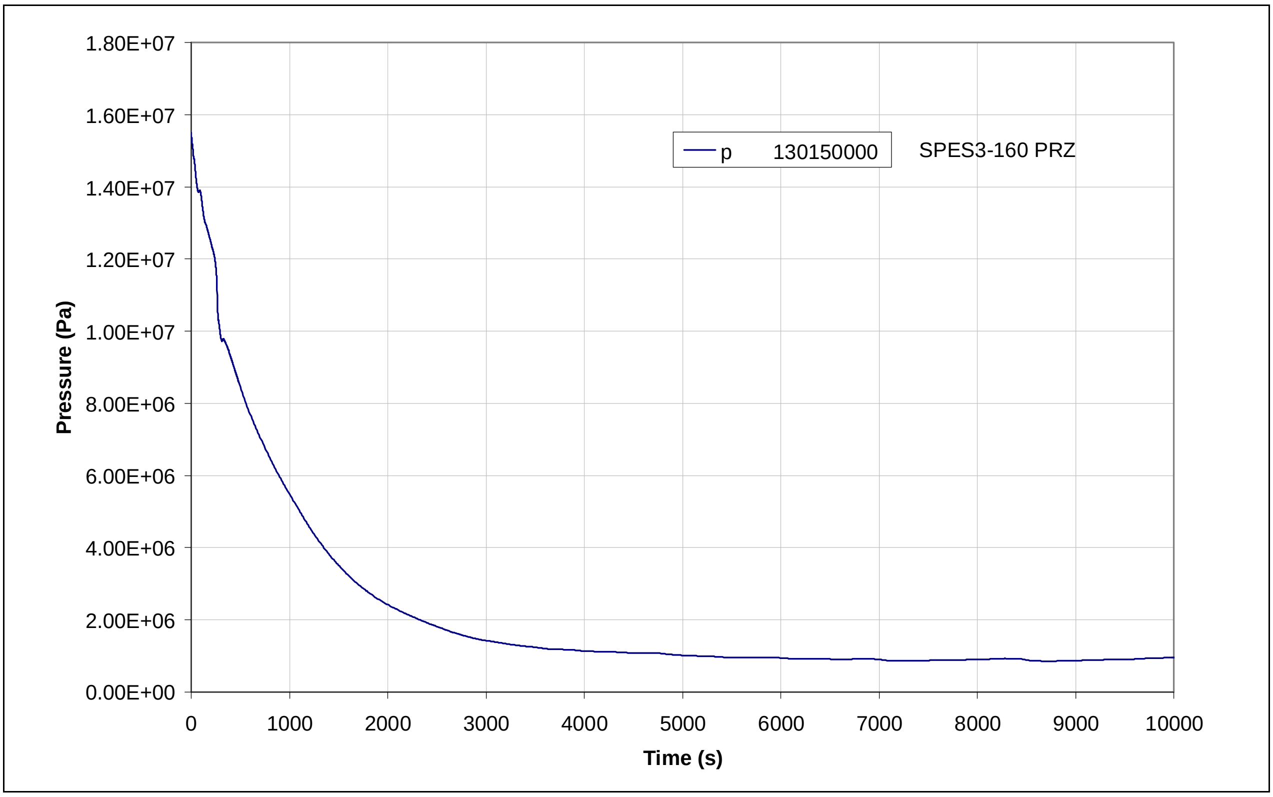


Fig.4.8 – SPES3-160 PRZ pressure

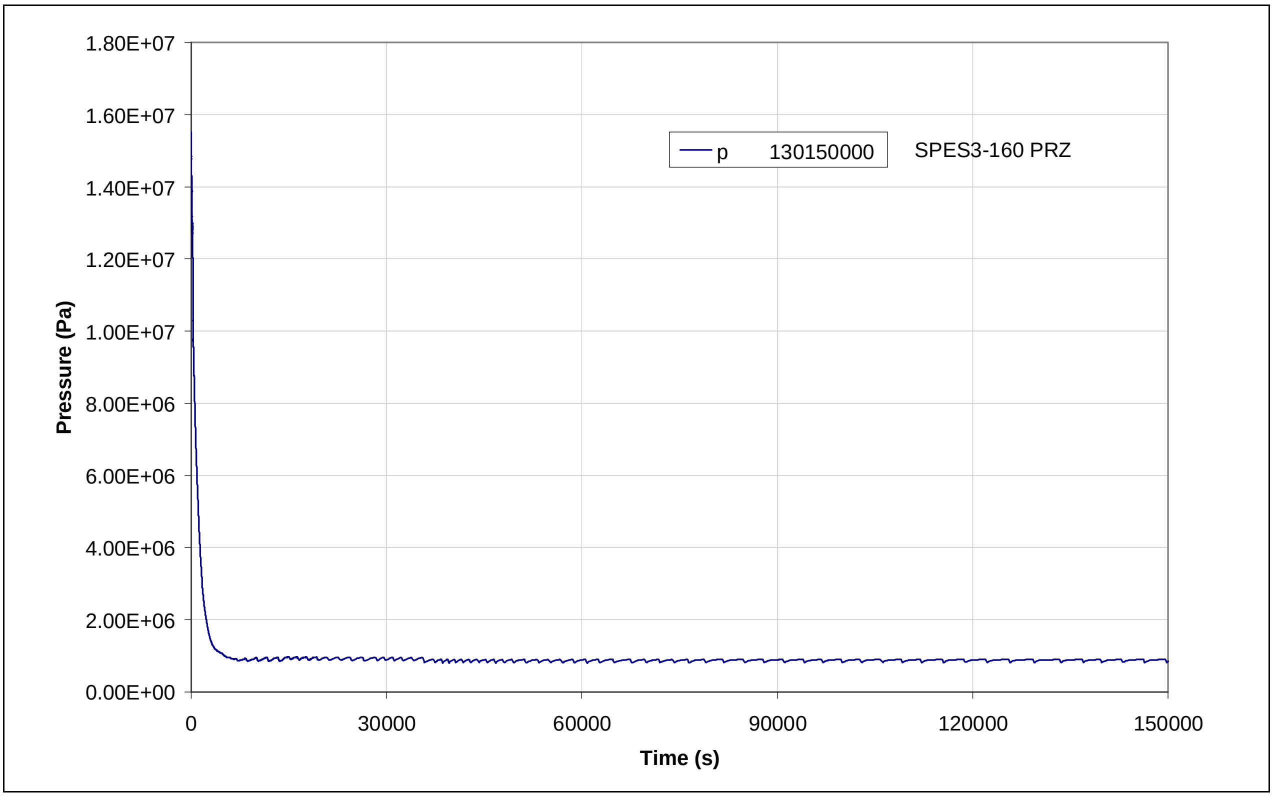


Fig.4.9 – SPES3-160 DW pressure (window)

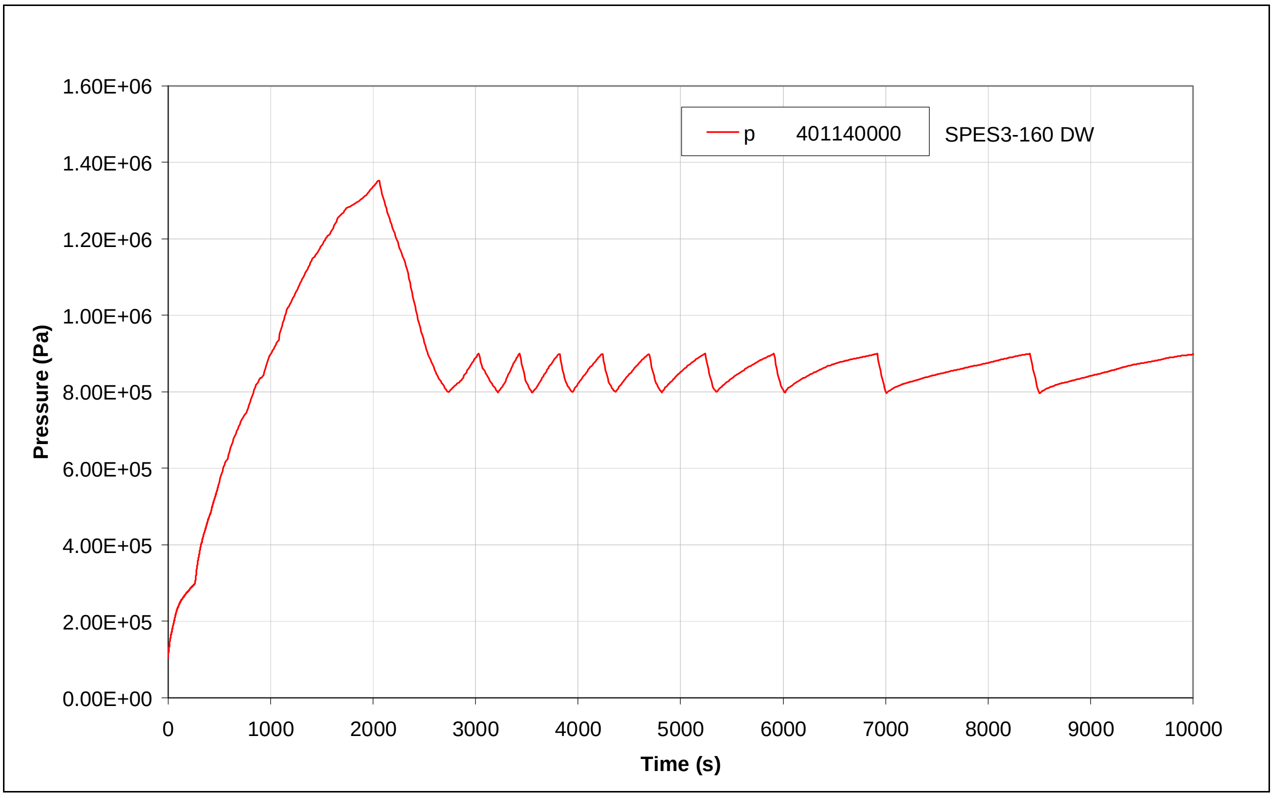


Fig.4.10 – SPES3-160 DW pressure

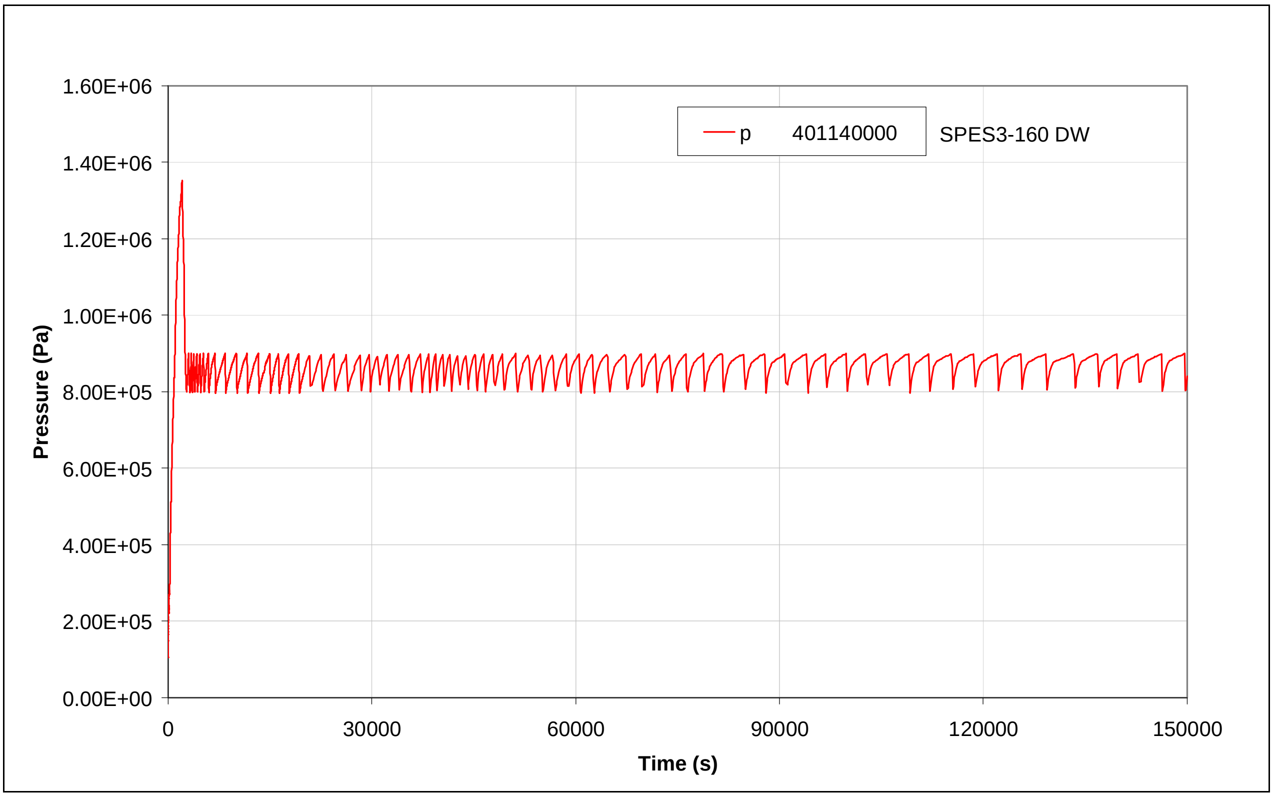


Fig.4.11 – SPES3-160 ADS Stage-I mass flow (window)

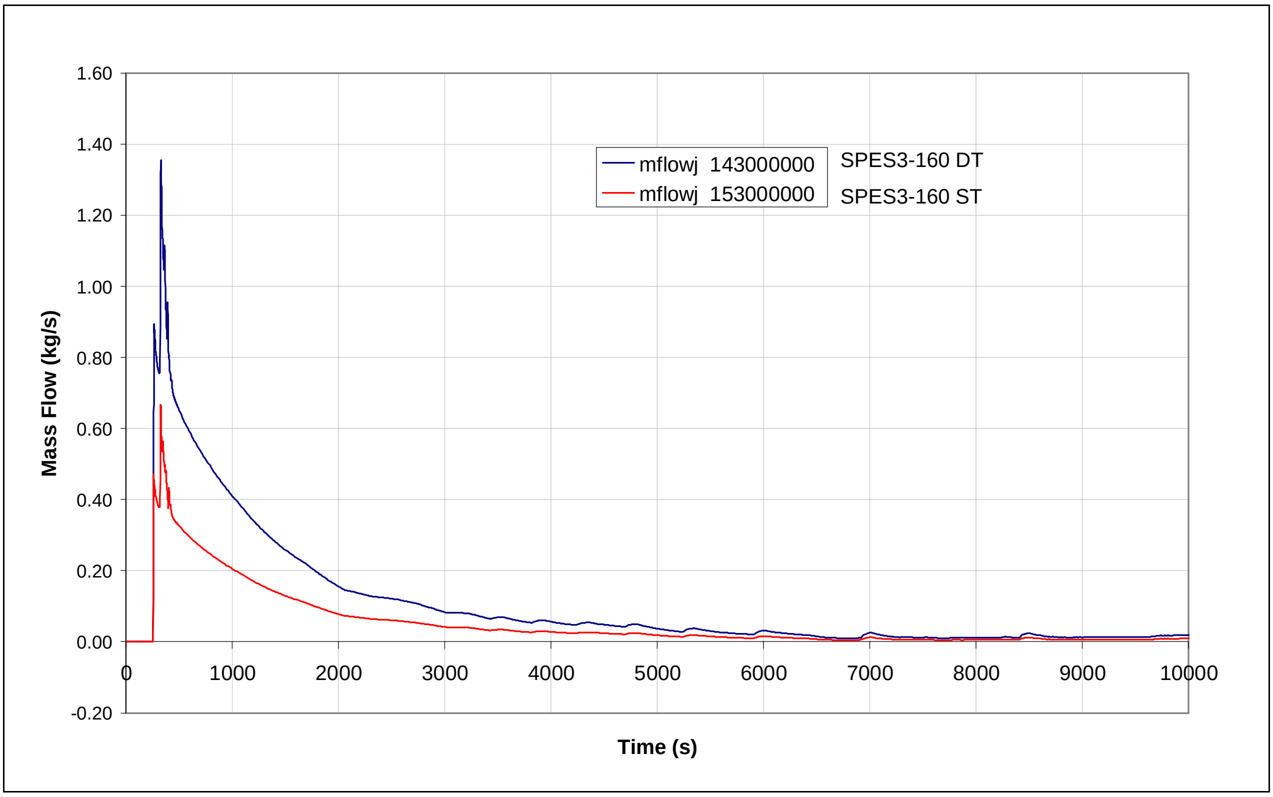


Fig.4.12 – SPES3-160 ADS Stage-I mass flow

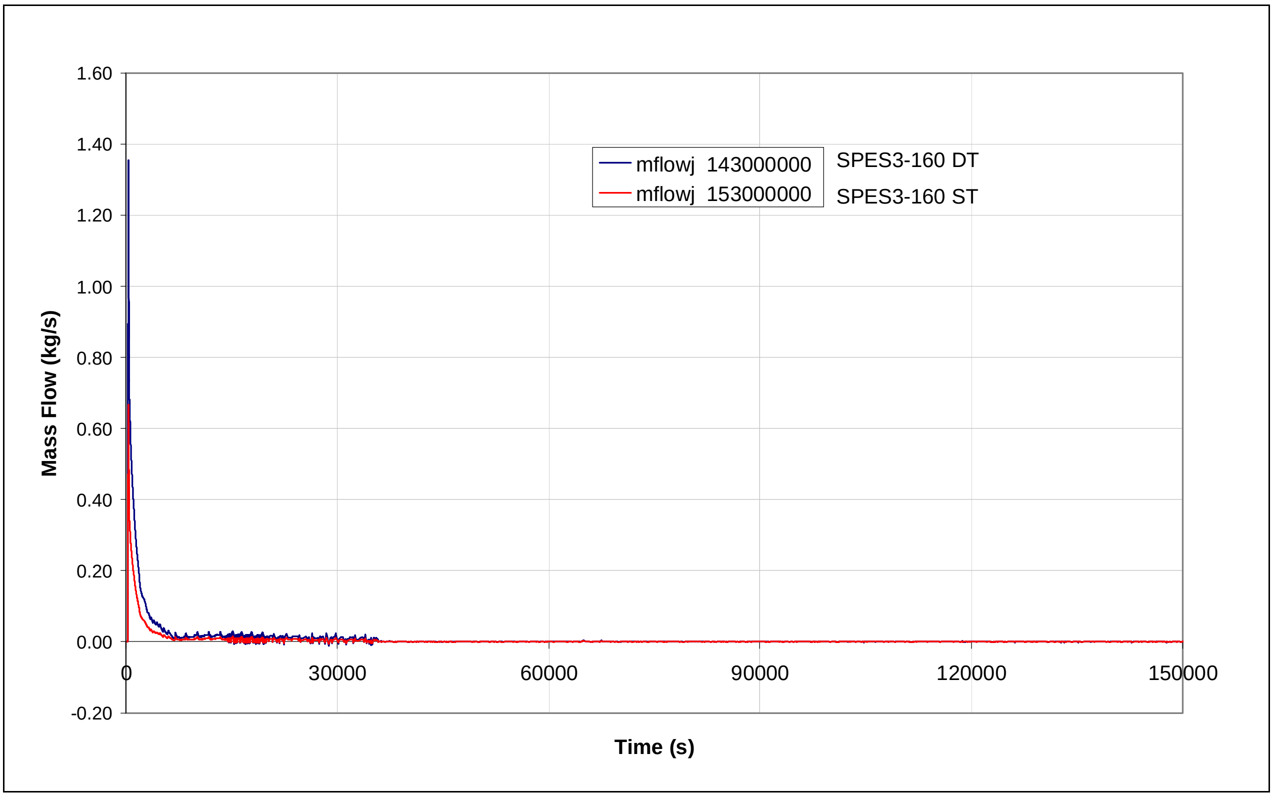


Fig.4.13 – SPES3-160 PCC power (window)

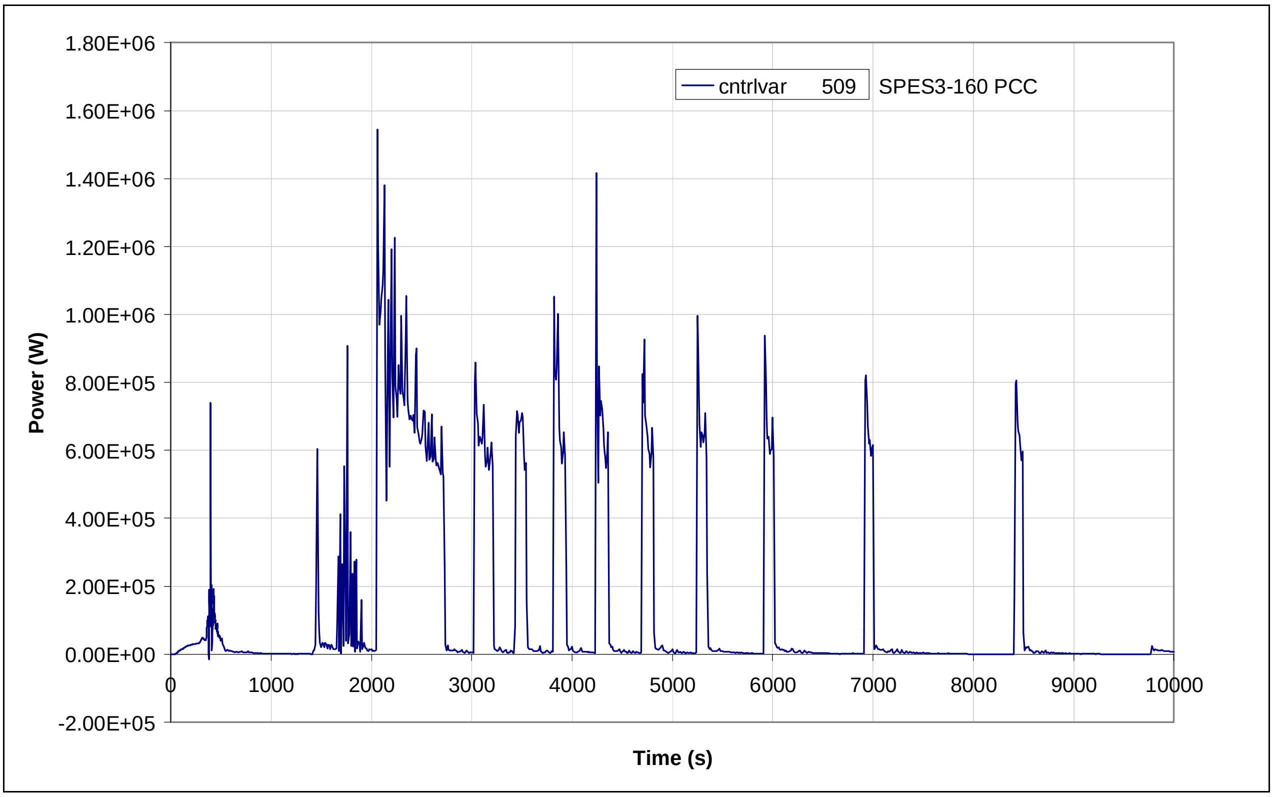


Fig.4.14 – SPES3-160 PCC power

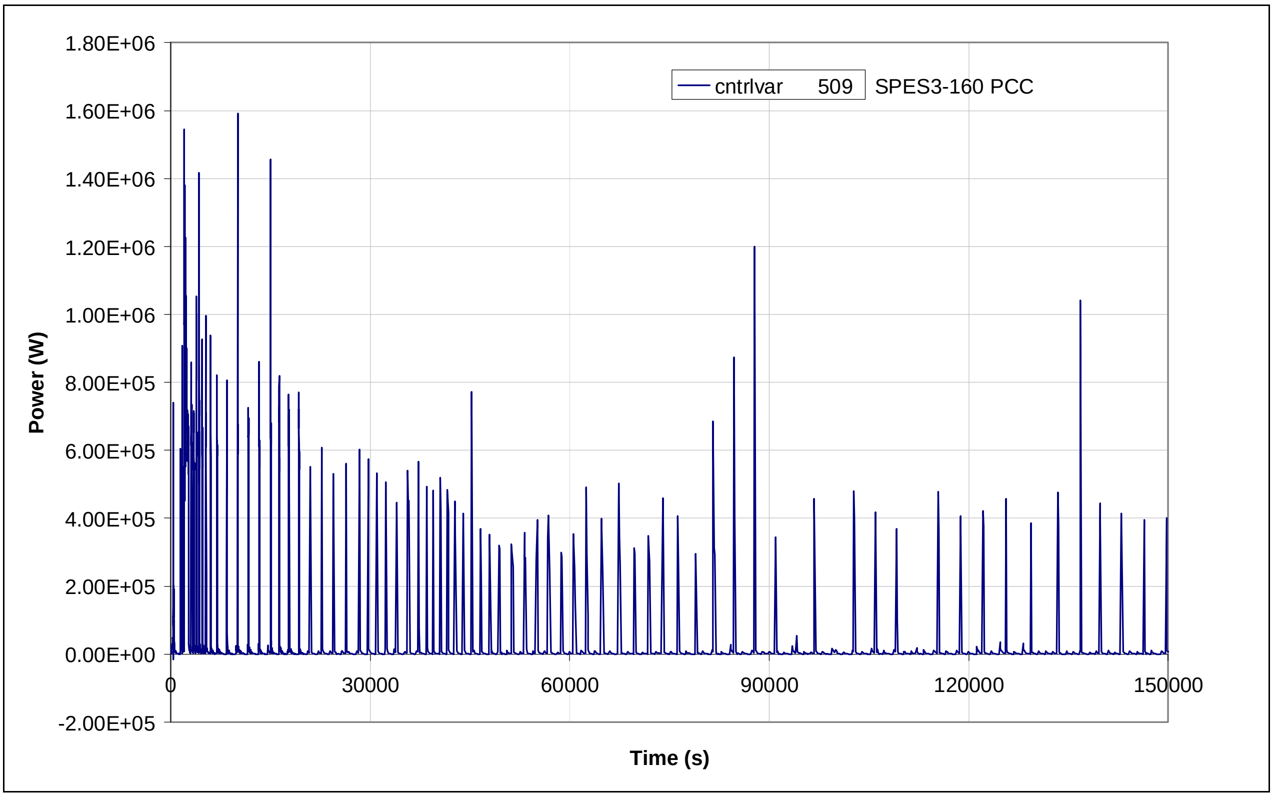


Fig.4.15 – SPES3-160 PSS to DW flow (window)

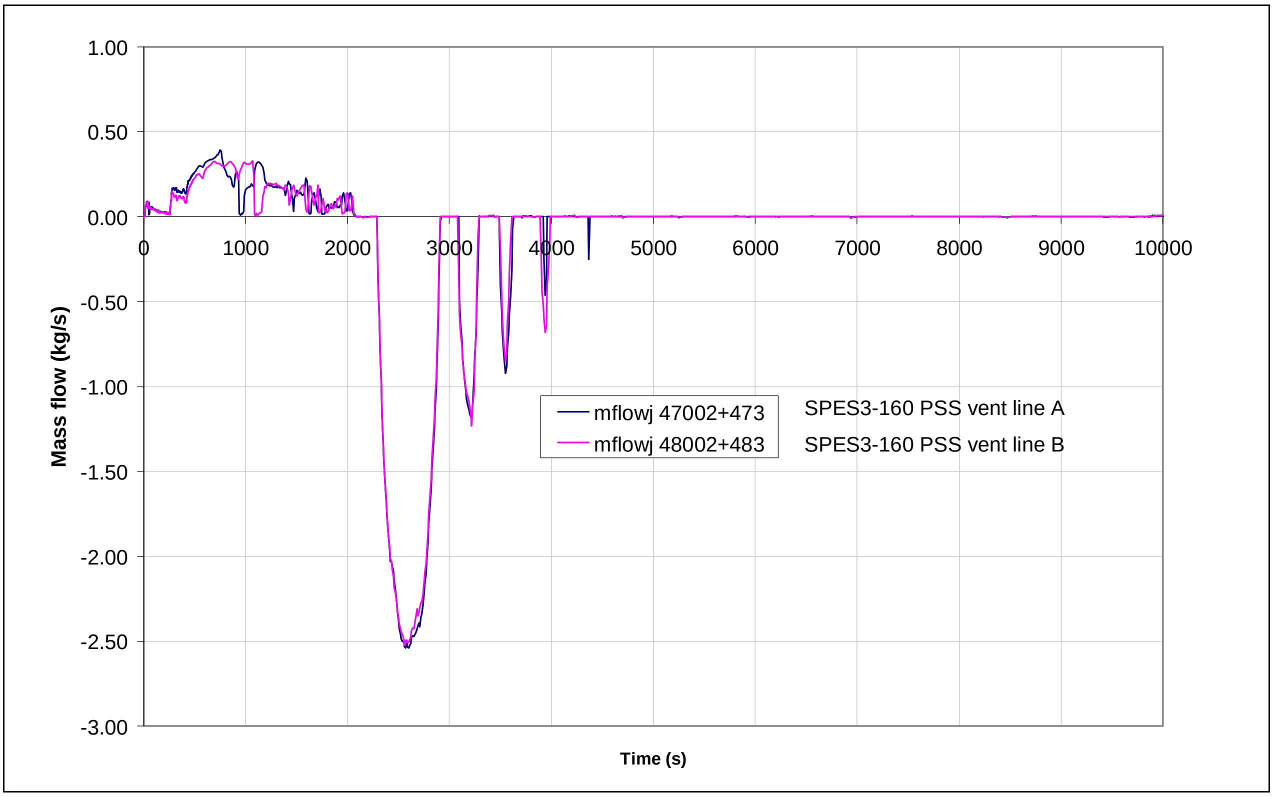


Fig.4.16 – SPES3-160 PSS to DW flow

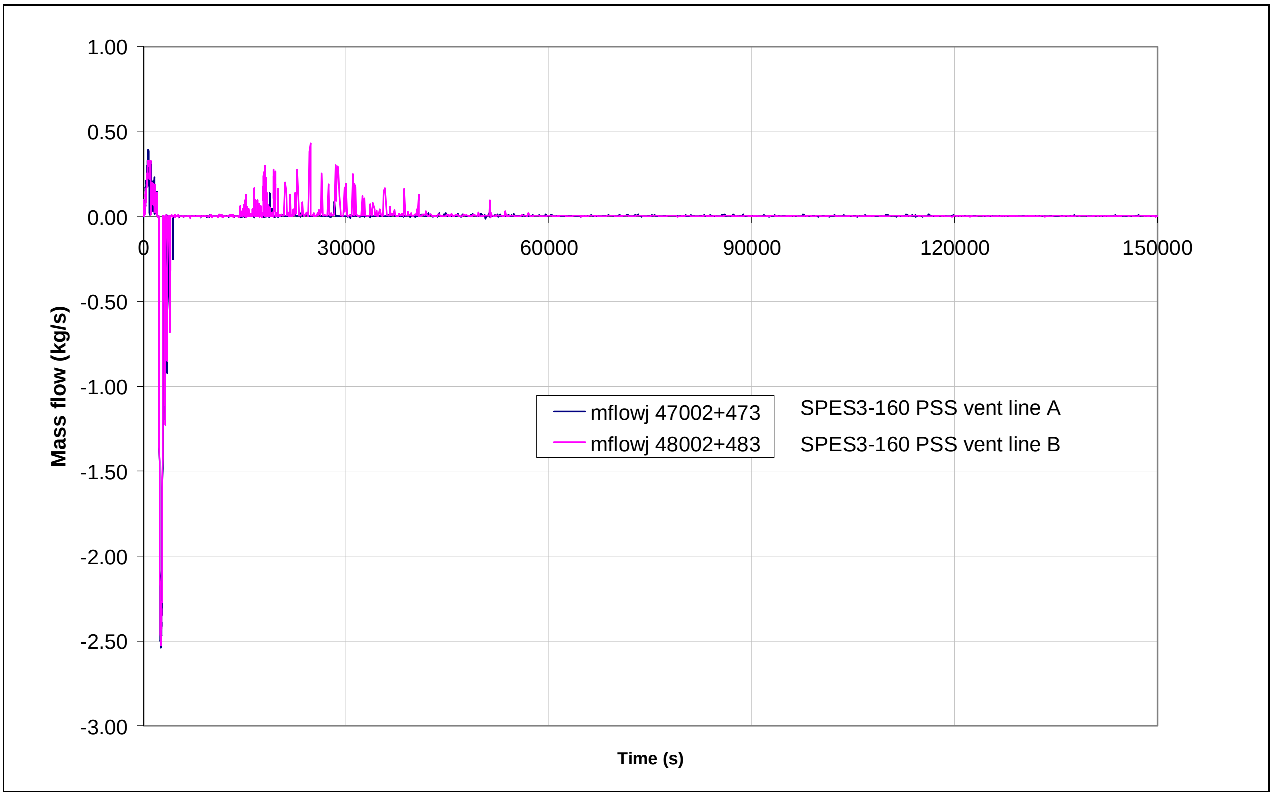


Fig.4.17 – SPES3-160 DW non-condensable gas quality (window)

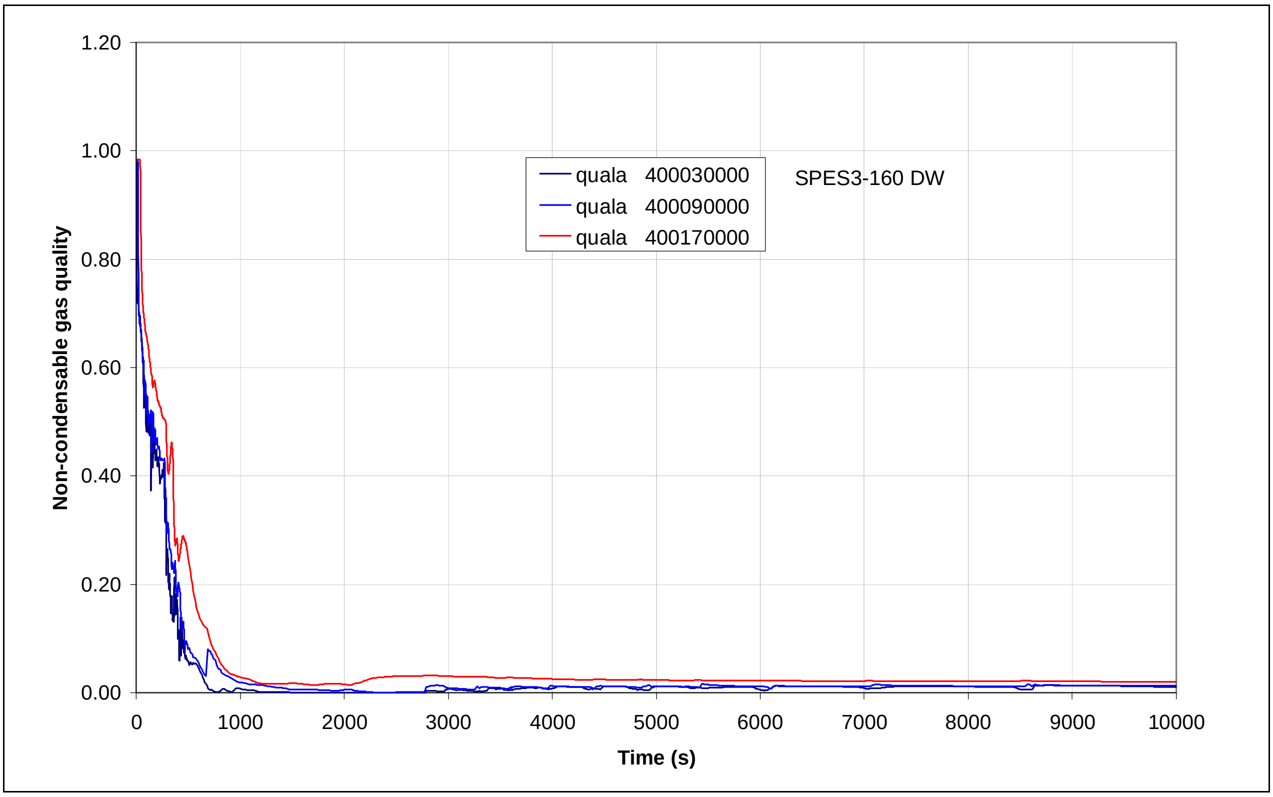


Fig.4.18 – SPES3-160 DW non-condensable gas quality

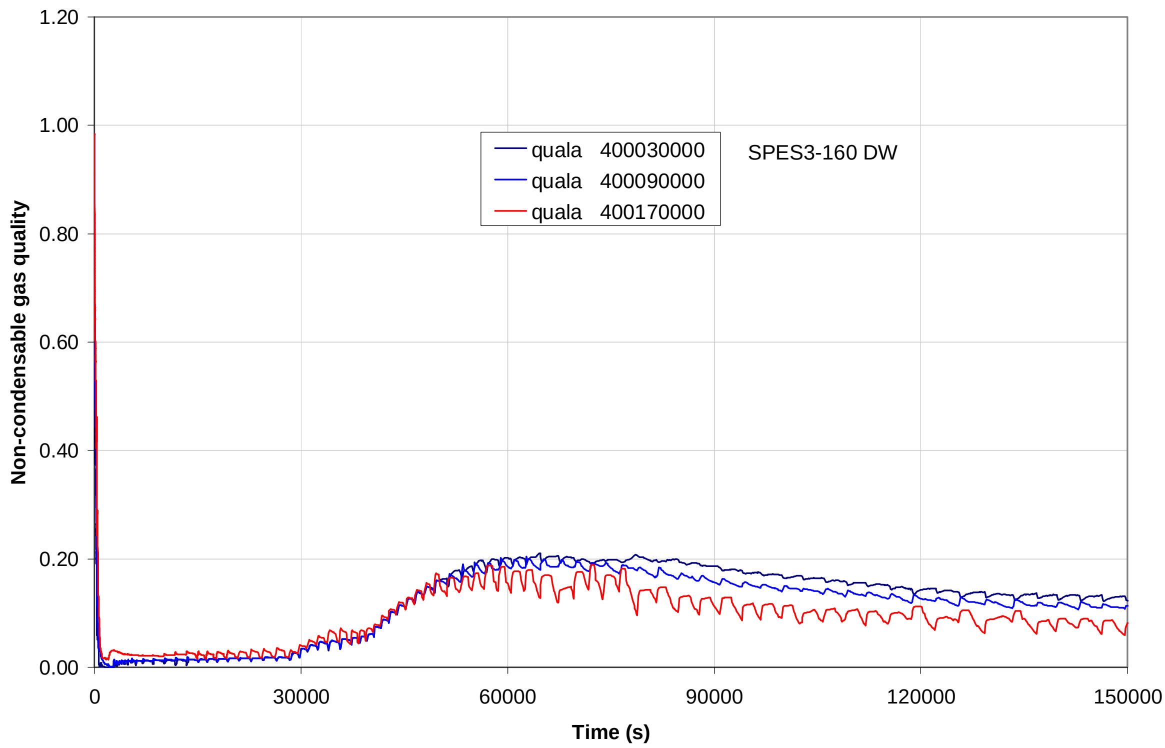


Fig.4.19 – SPES3-160 PSS pressure (window)

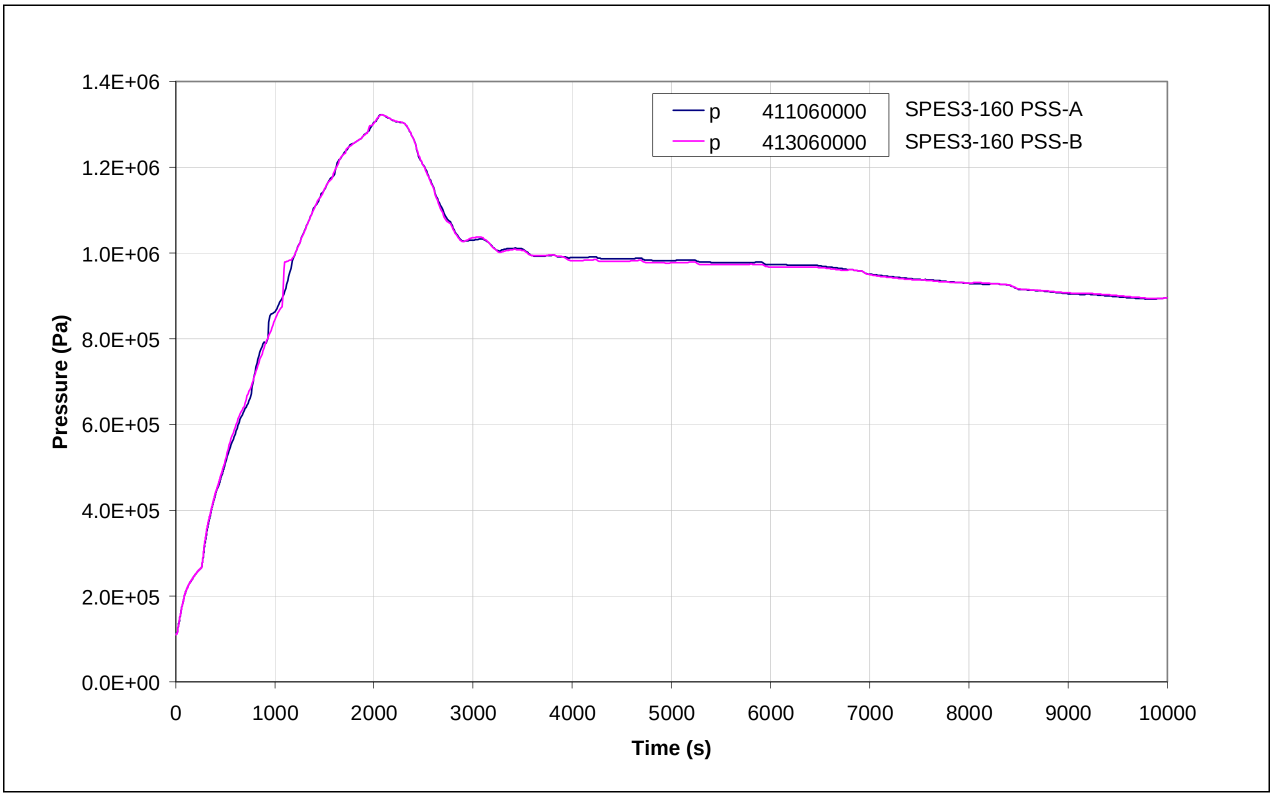


Fig.4.20 – SPES3-160 PSS pressure

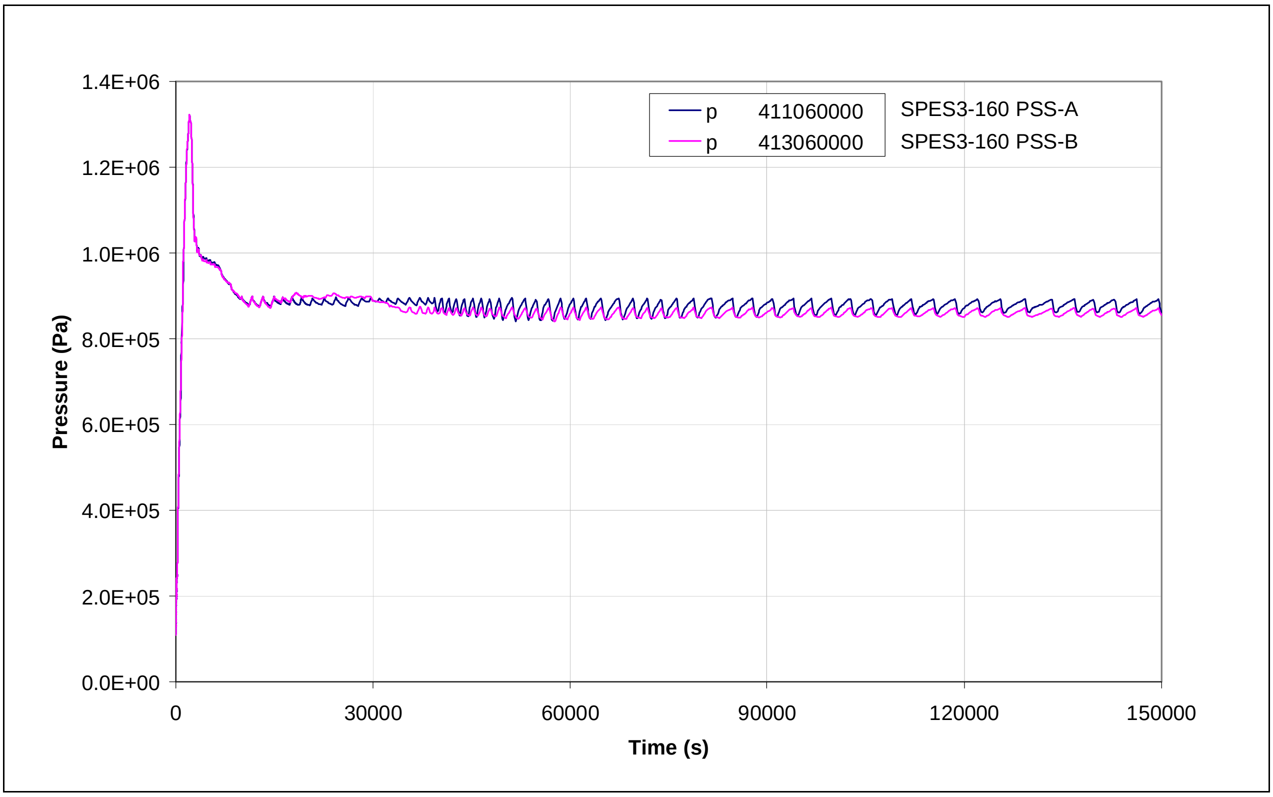


Fig.4.21 – SPES3-160 LGMS pressure (window)

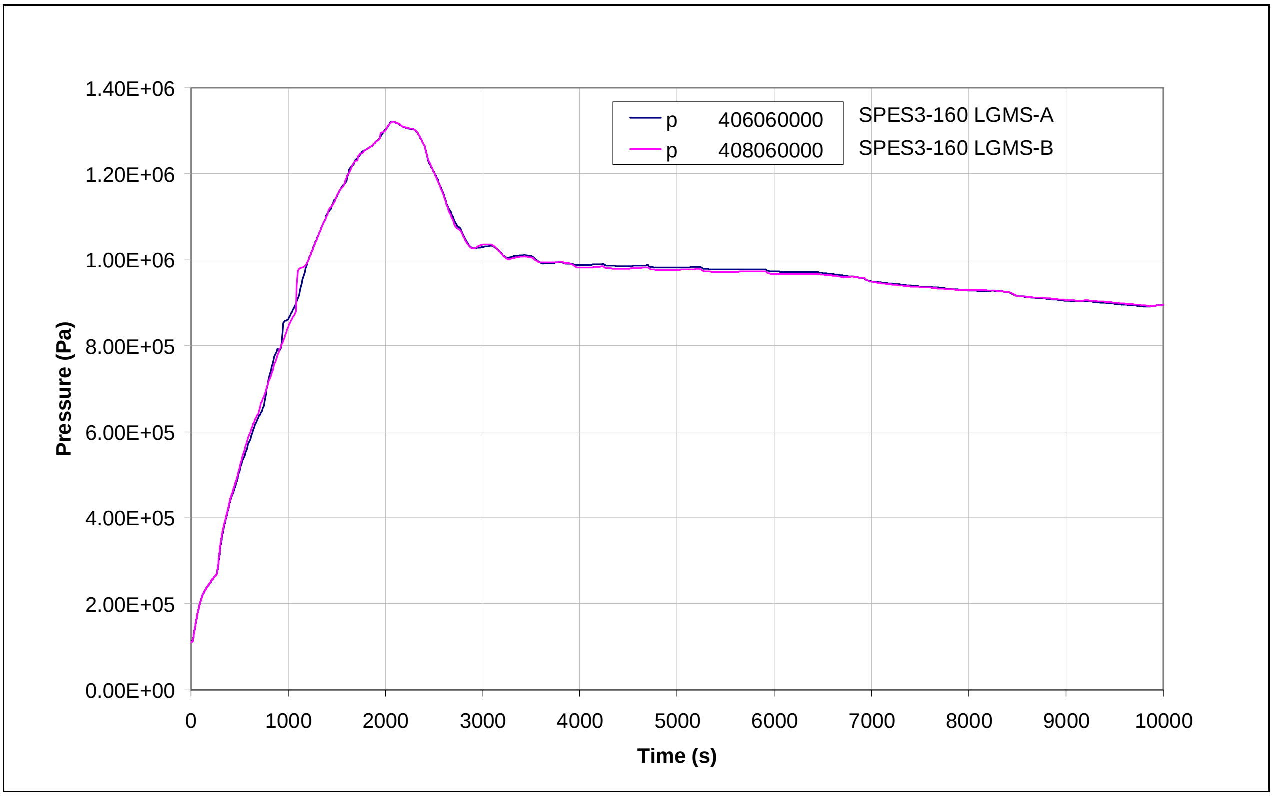


Fig.4.22 – SPES3-160 LGMS pressure

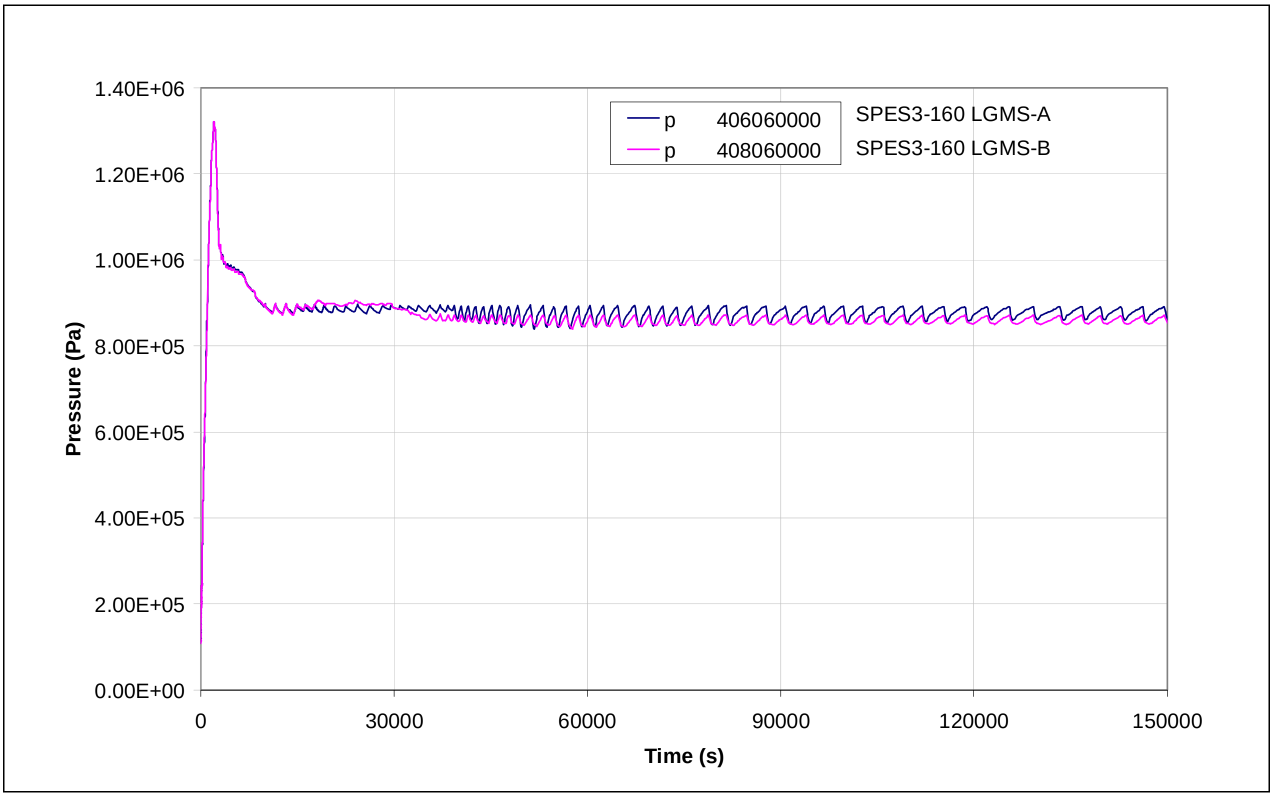


Fig.4.23 – SPES3-160 PSS and DW pressure (window)

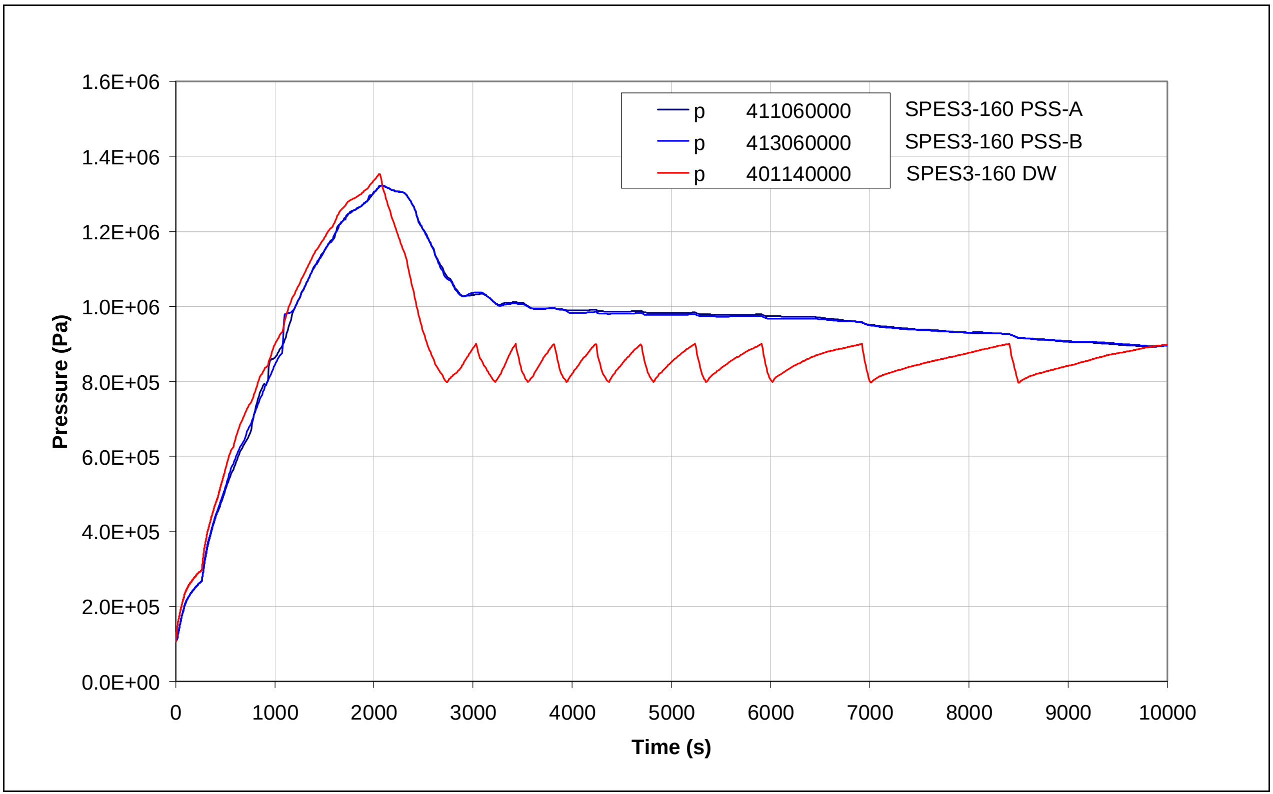


Fig.4.24 – SPES3-160 PSS and DW pressure

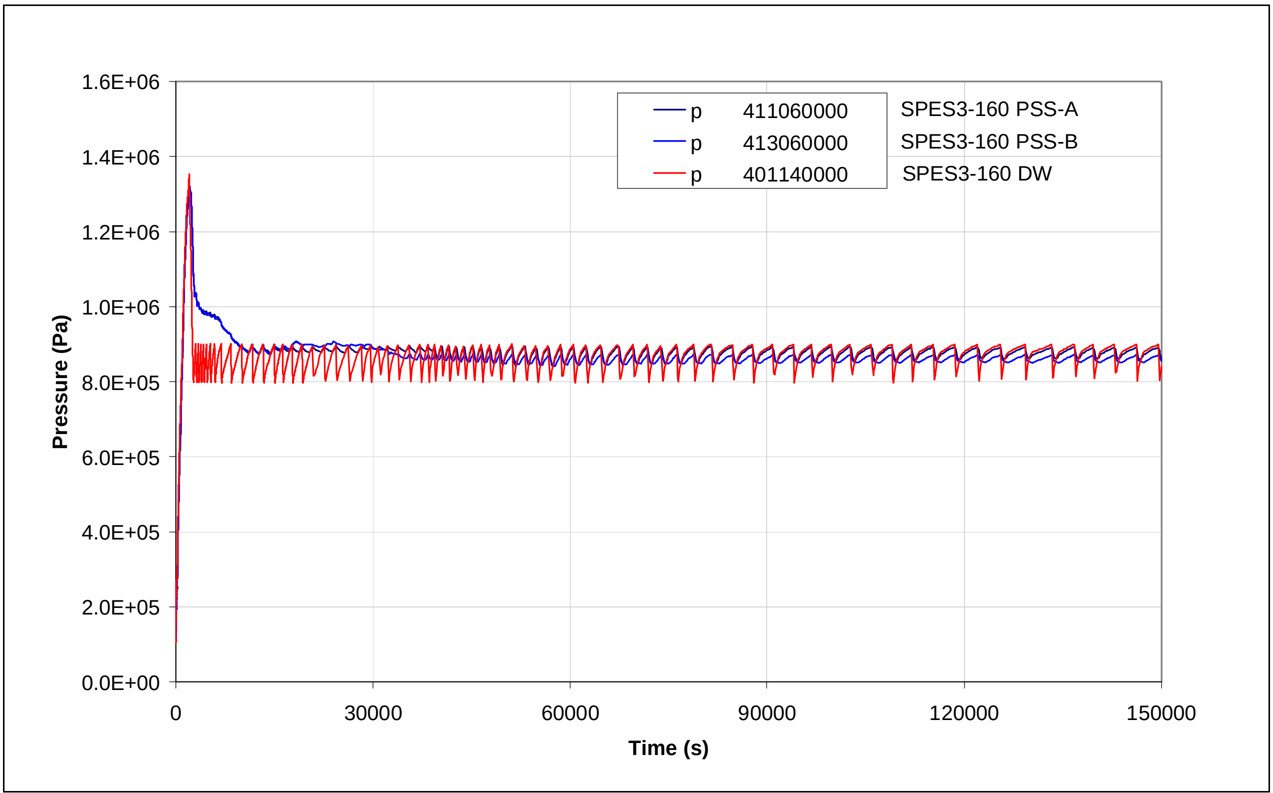


Fig.4.25 – SPES3-160 PSS vent pipe level (window)

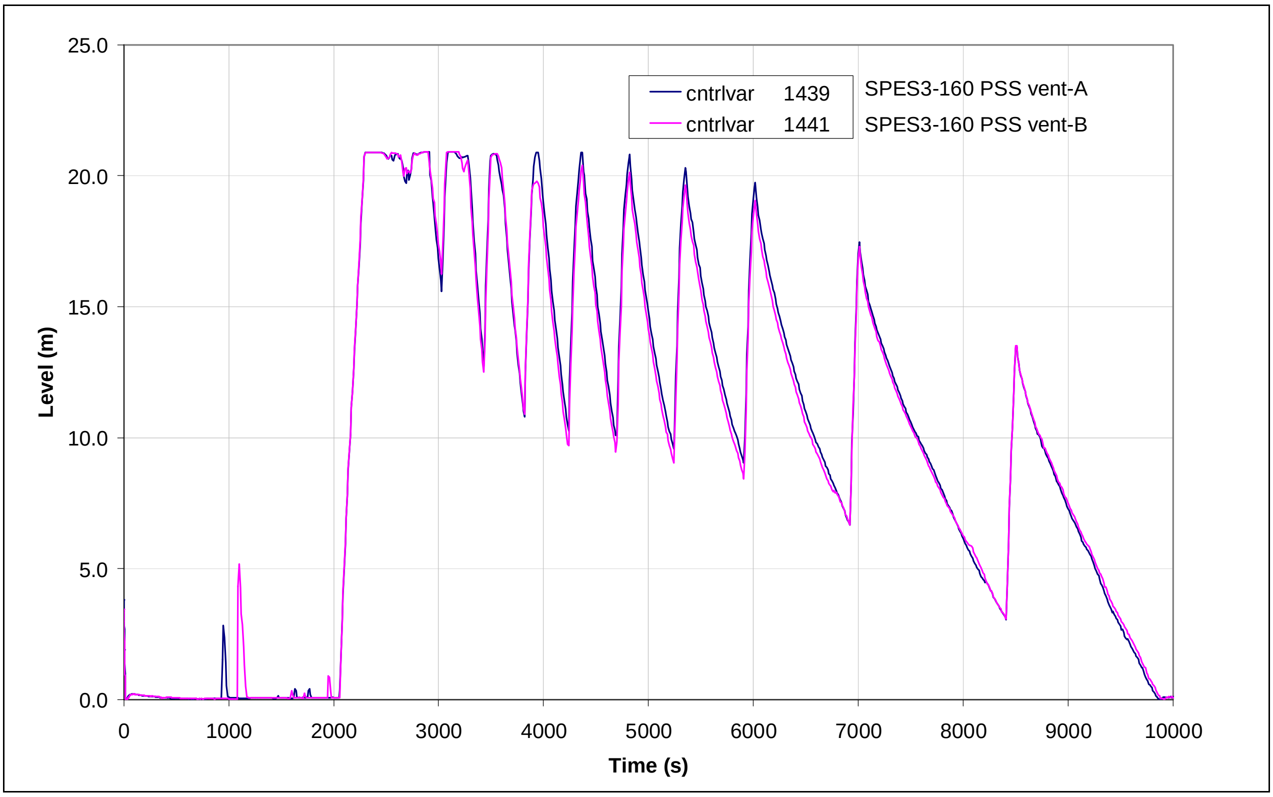


Fig.4.26 – SPES3-160 PSS vent pipe level

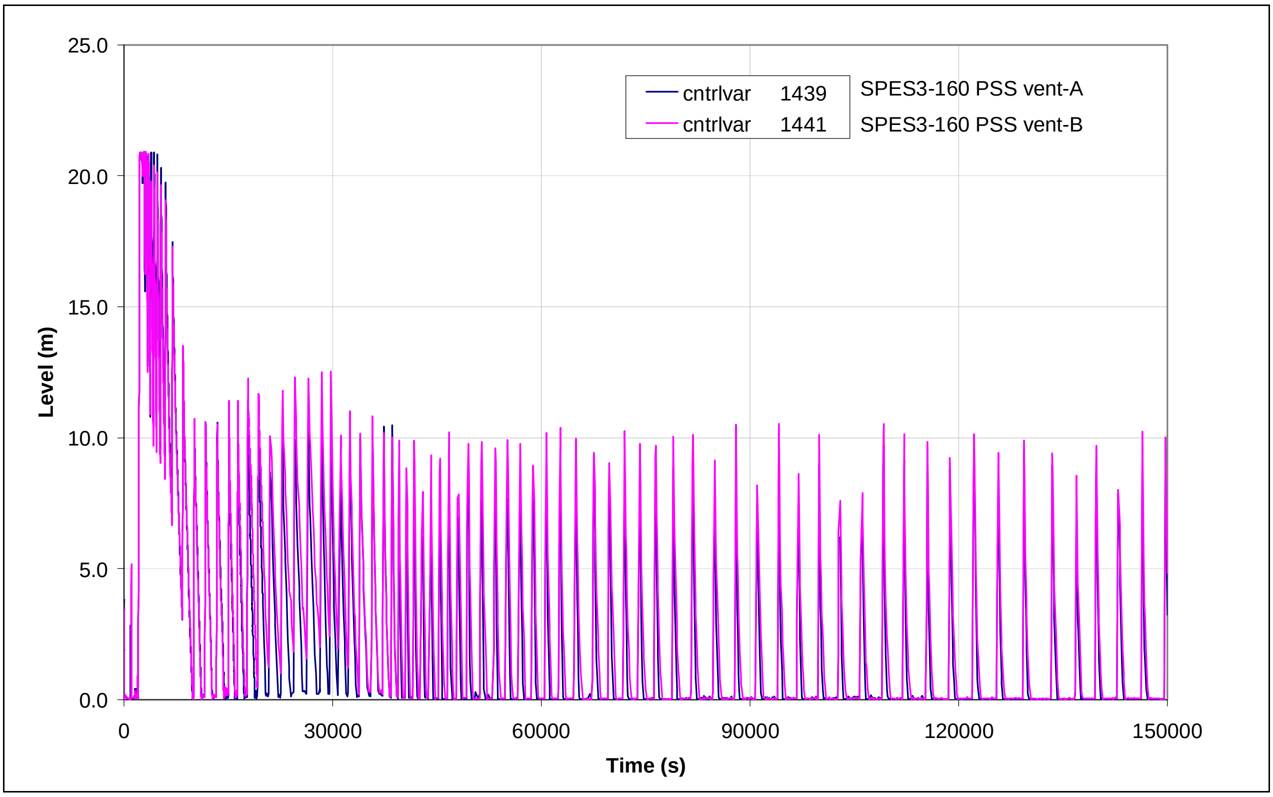


Fig.4.27 – SPES3-160 PSS level (window)

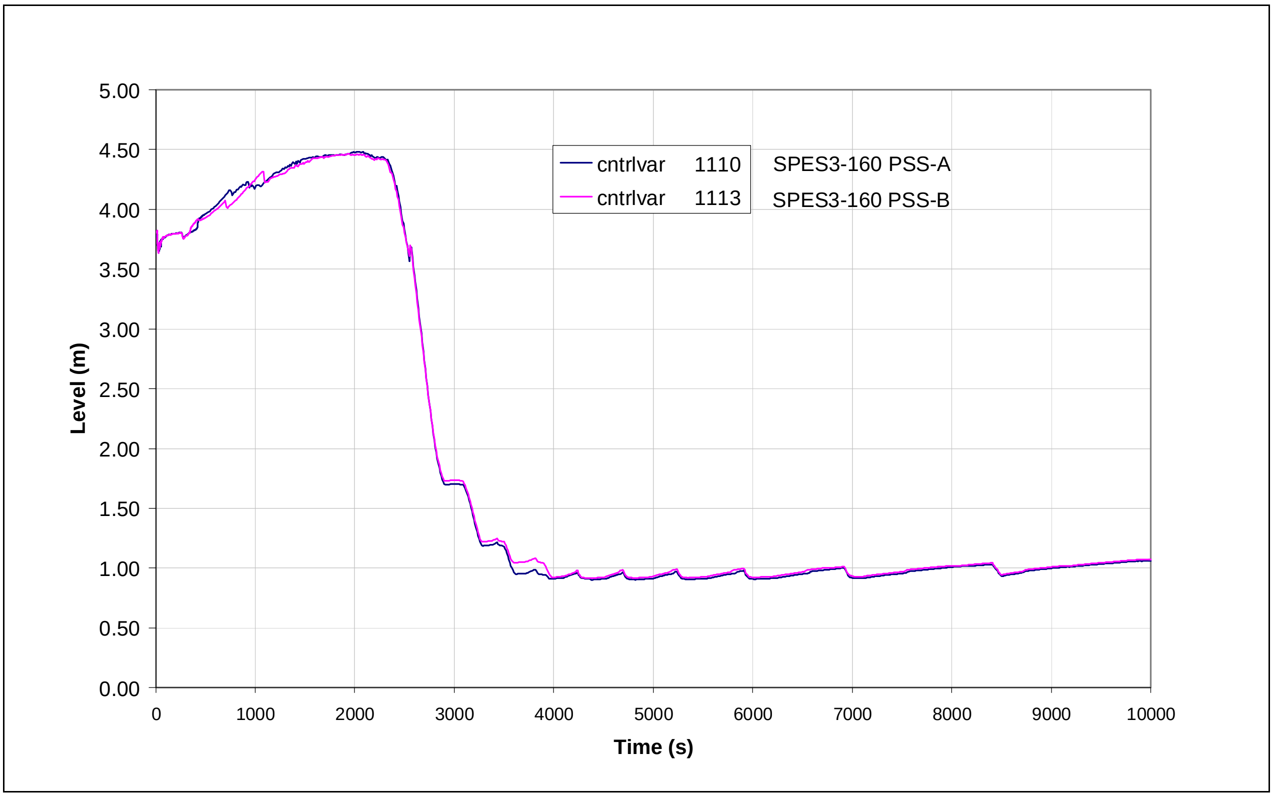


Fig.4.28 – SPES3-160 PSS level

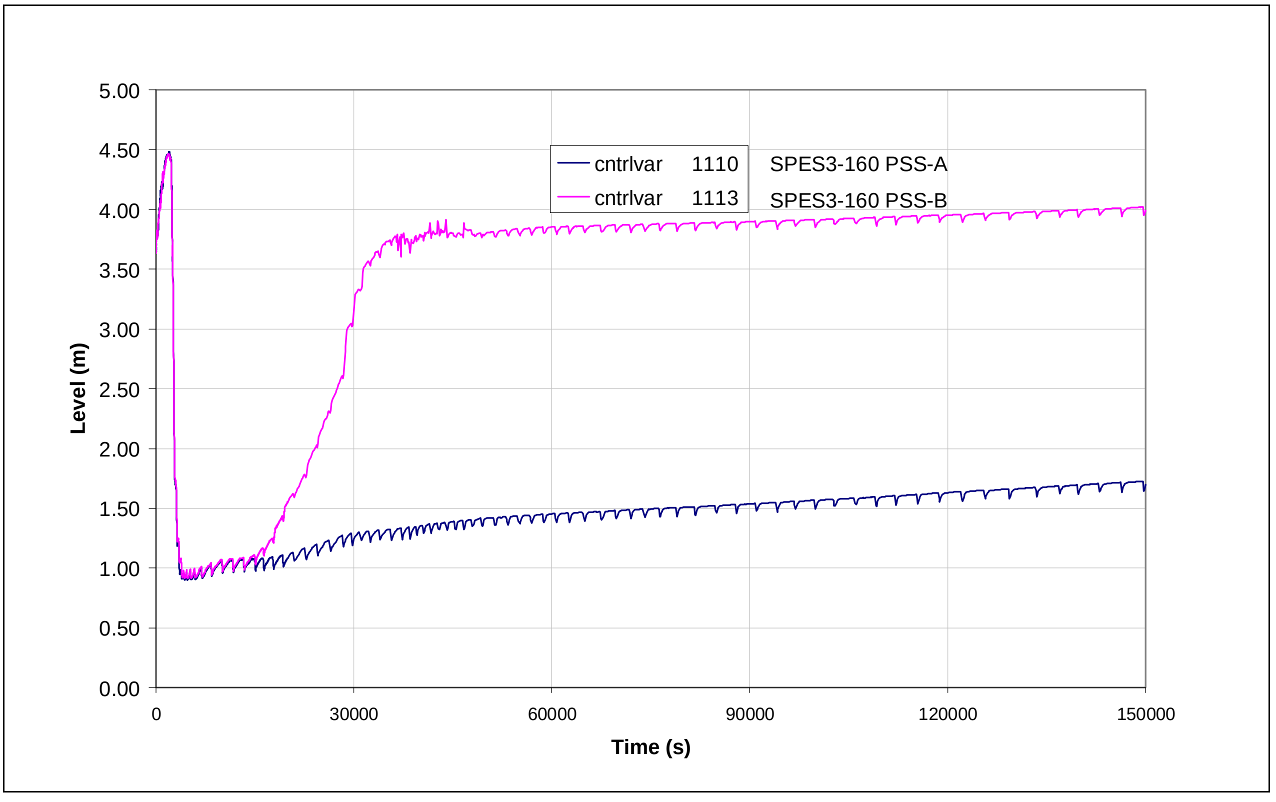


Fig.4.29 – SPES3-160 RC level (window)

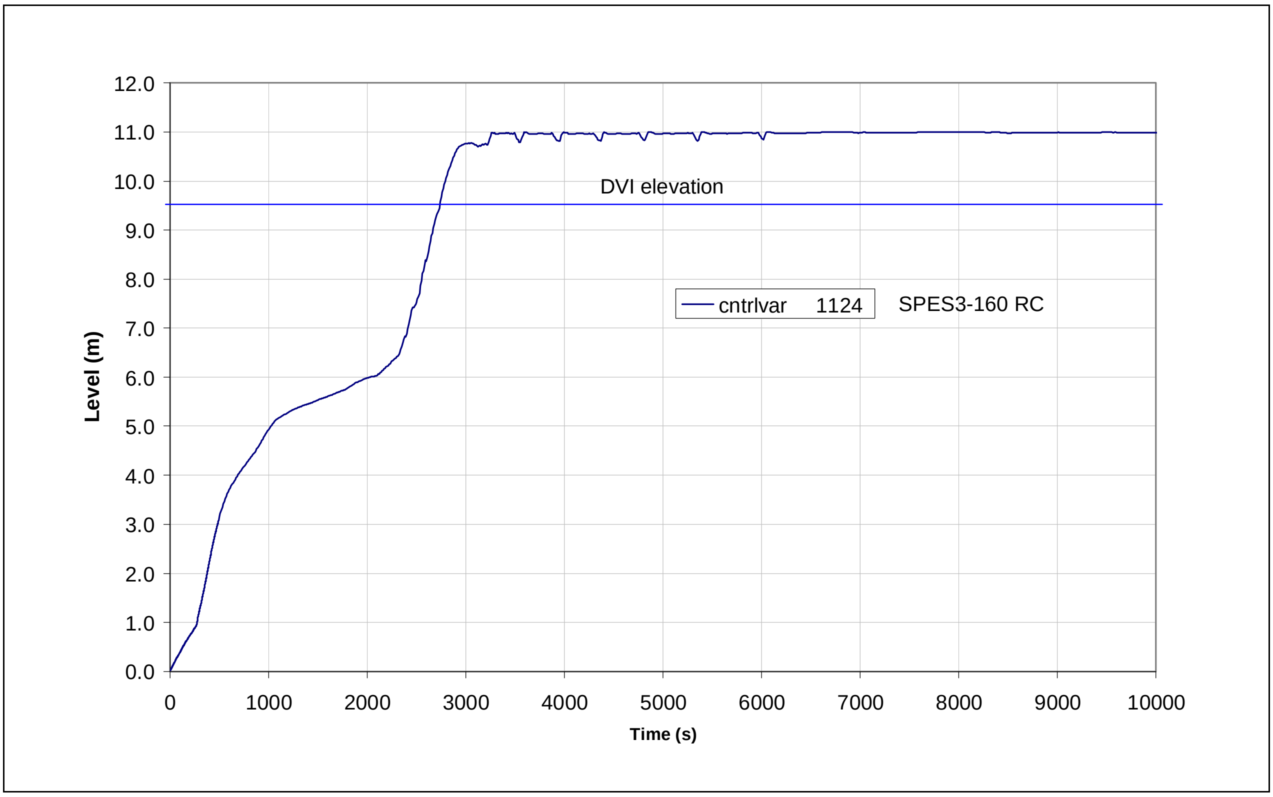


Fig.4.30 – SPES3-160 RC level

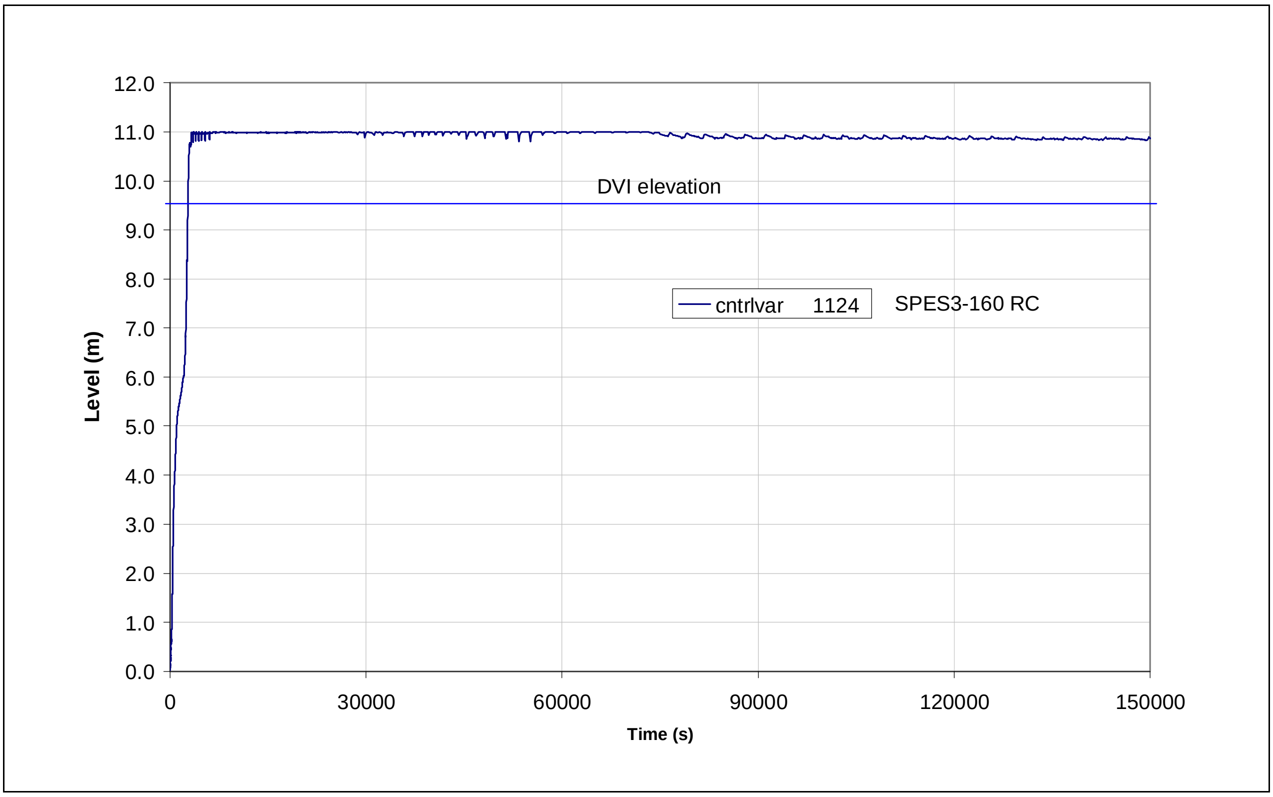


Fig.4.31 – SPES3-160 DW level

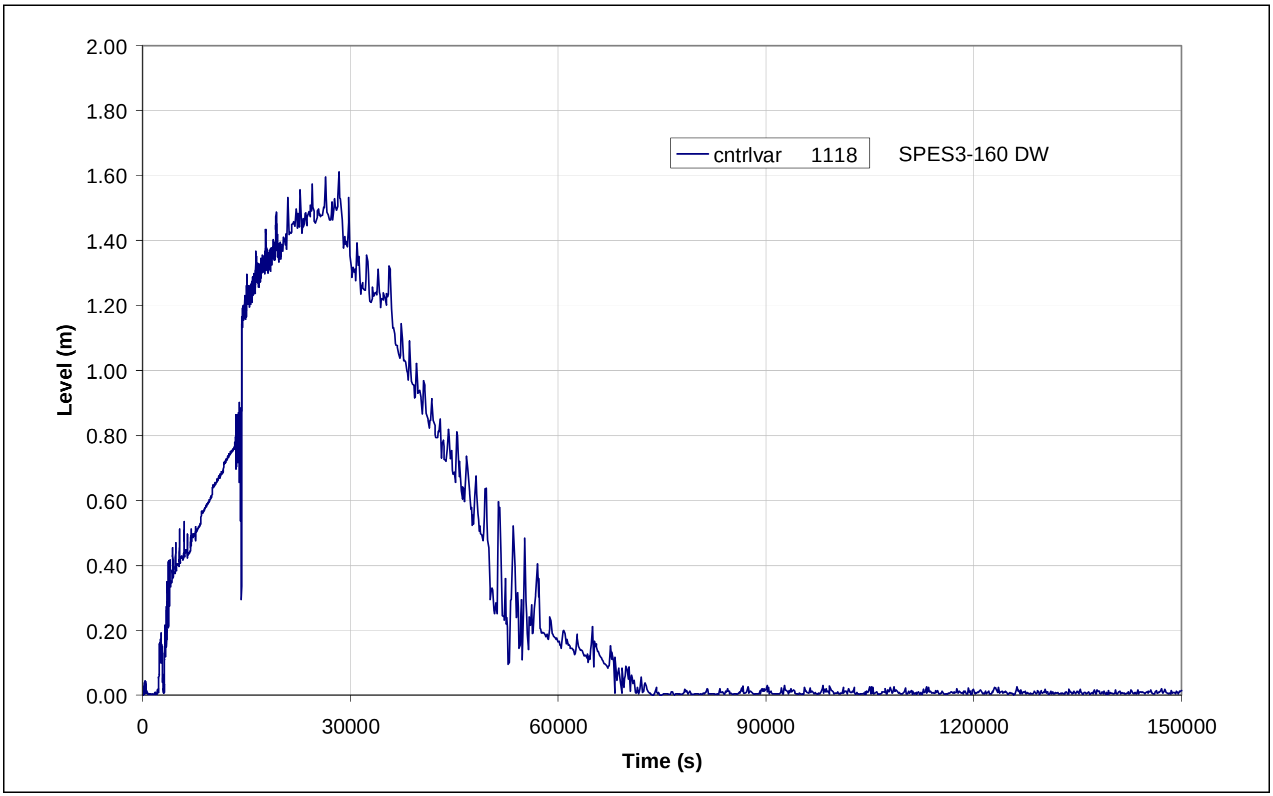


Fig.4.32 – SPES3-160 QT level

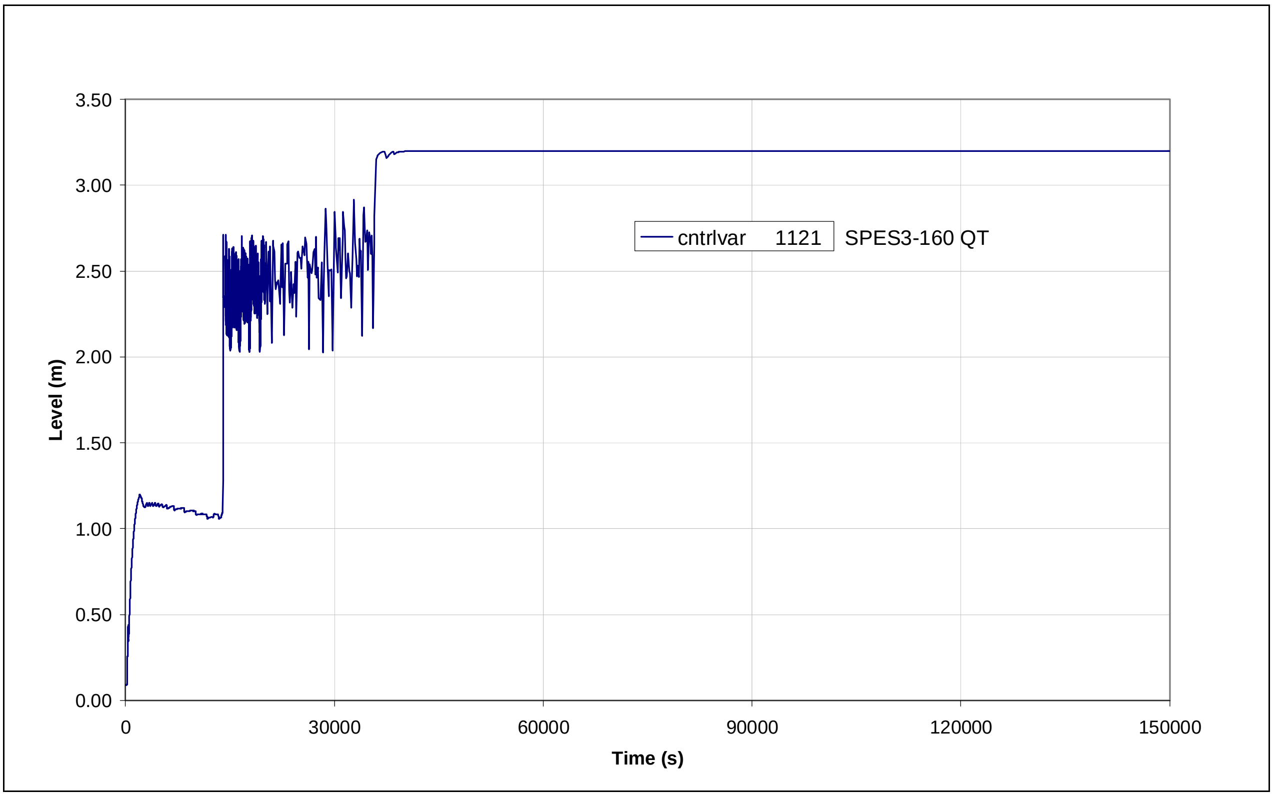


Fig.4.33 – SPES3-160 LGMS level

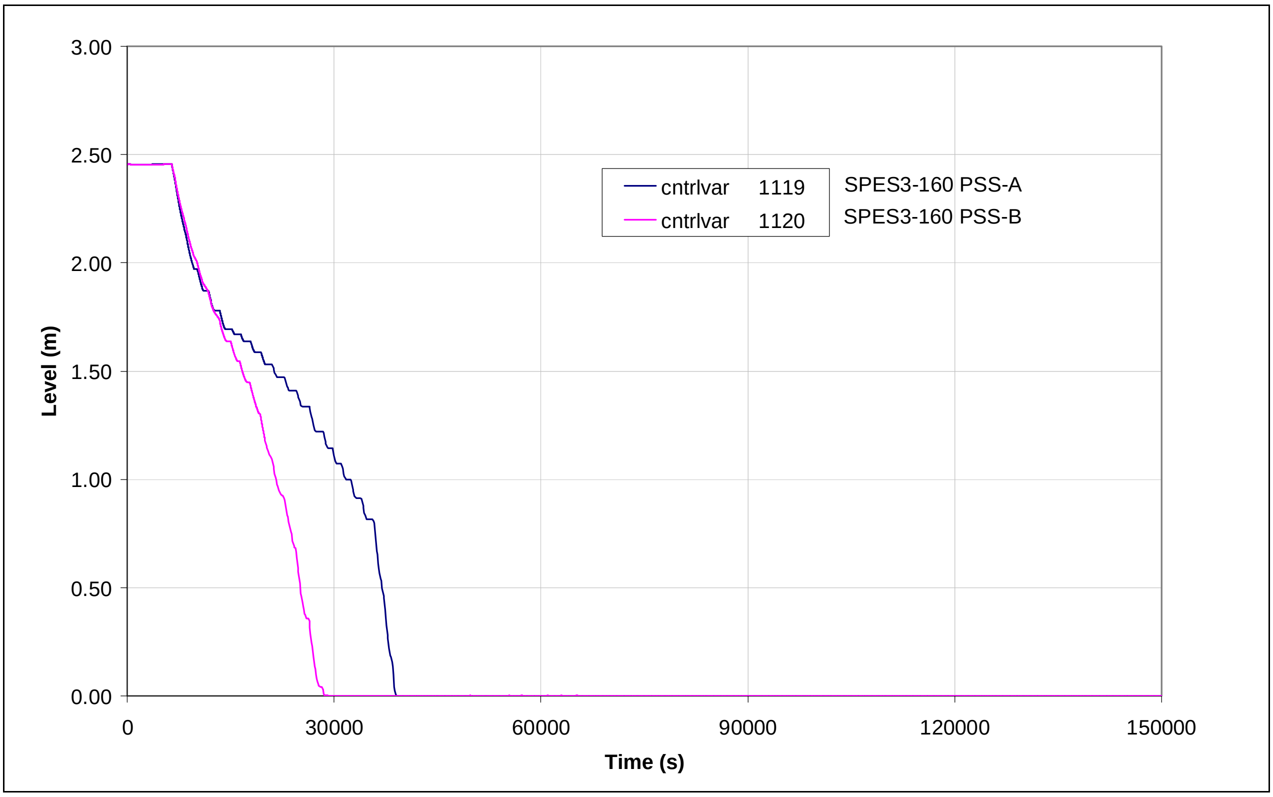


Fig.4.34 – SPES3-160 PSS mass

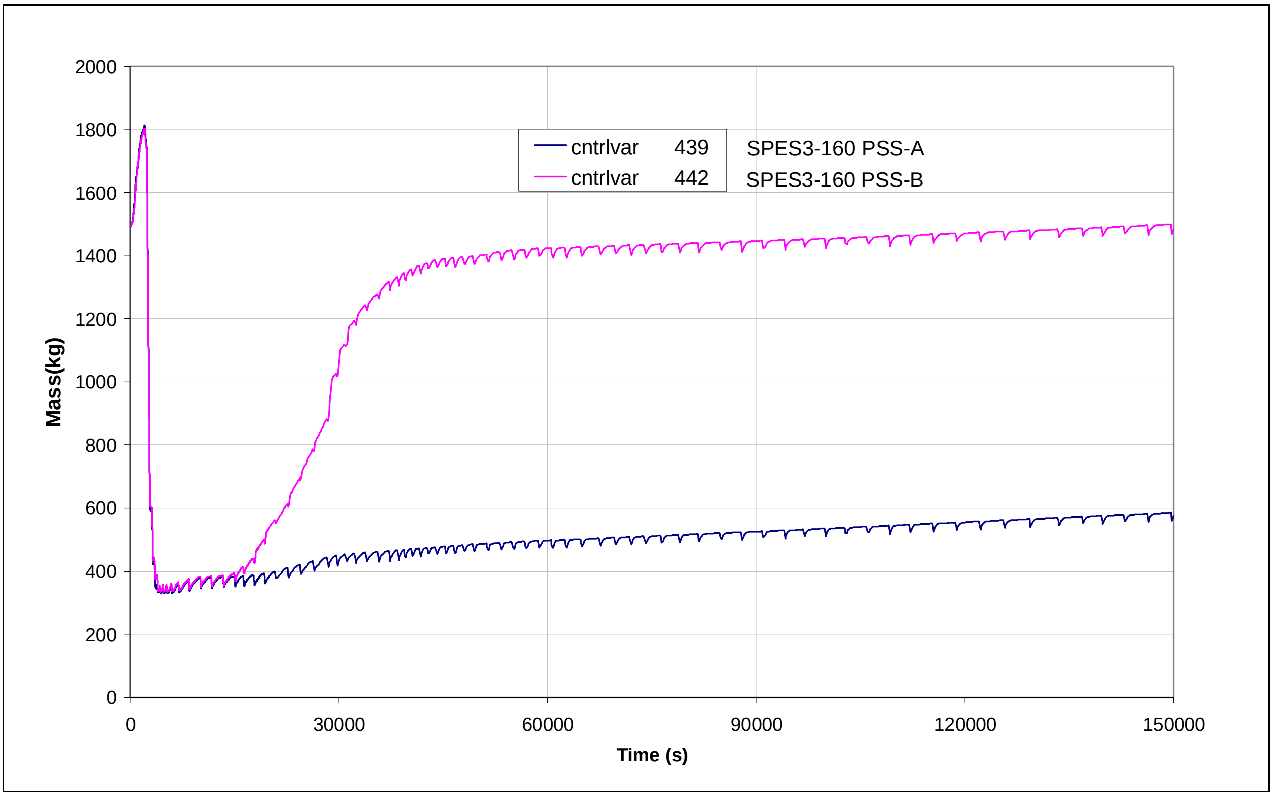


Fig.4.35 – SPES3-160 PSS temperature (window)

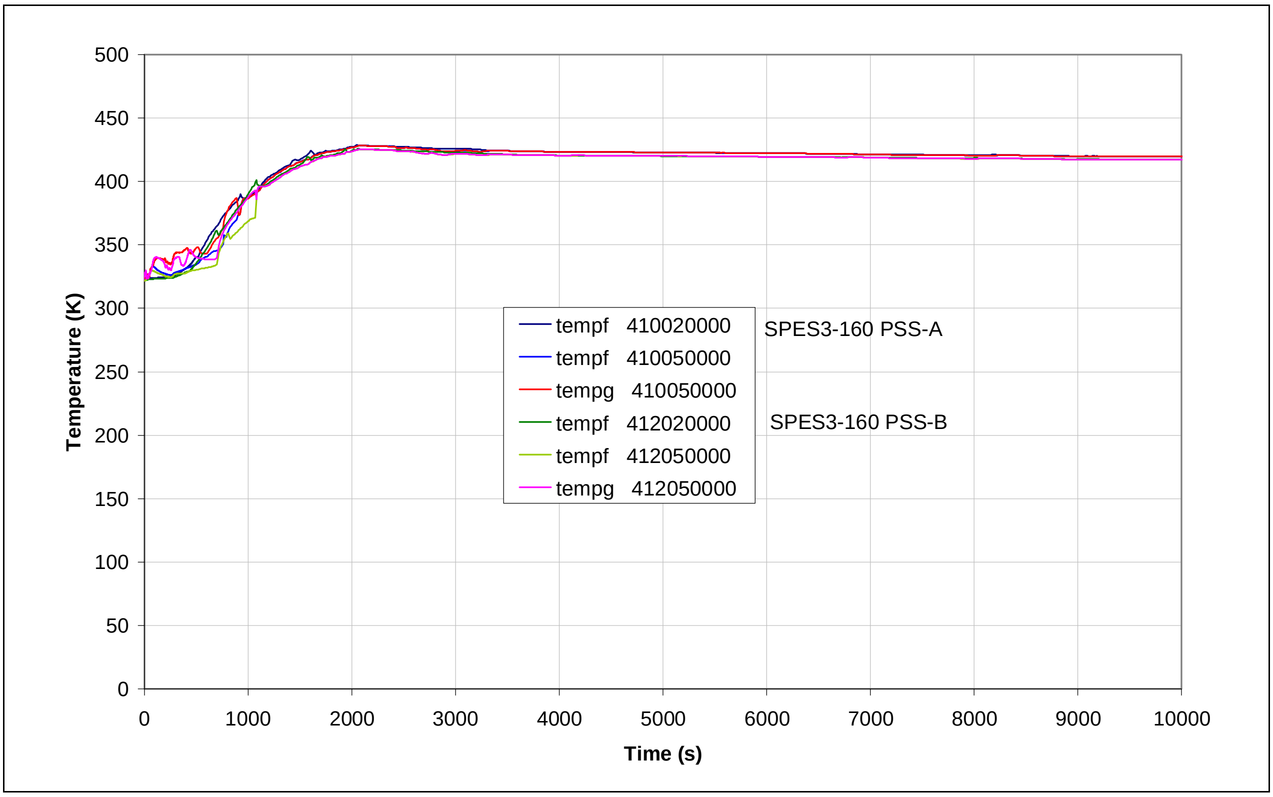


Fig.4.36 – SPES3-160 PSS temperature

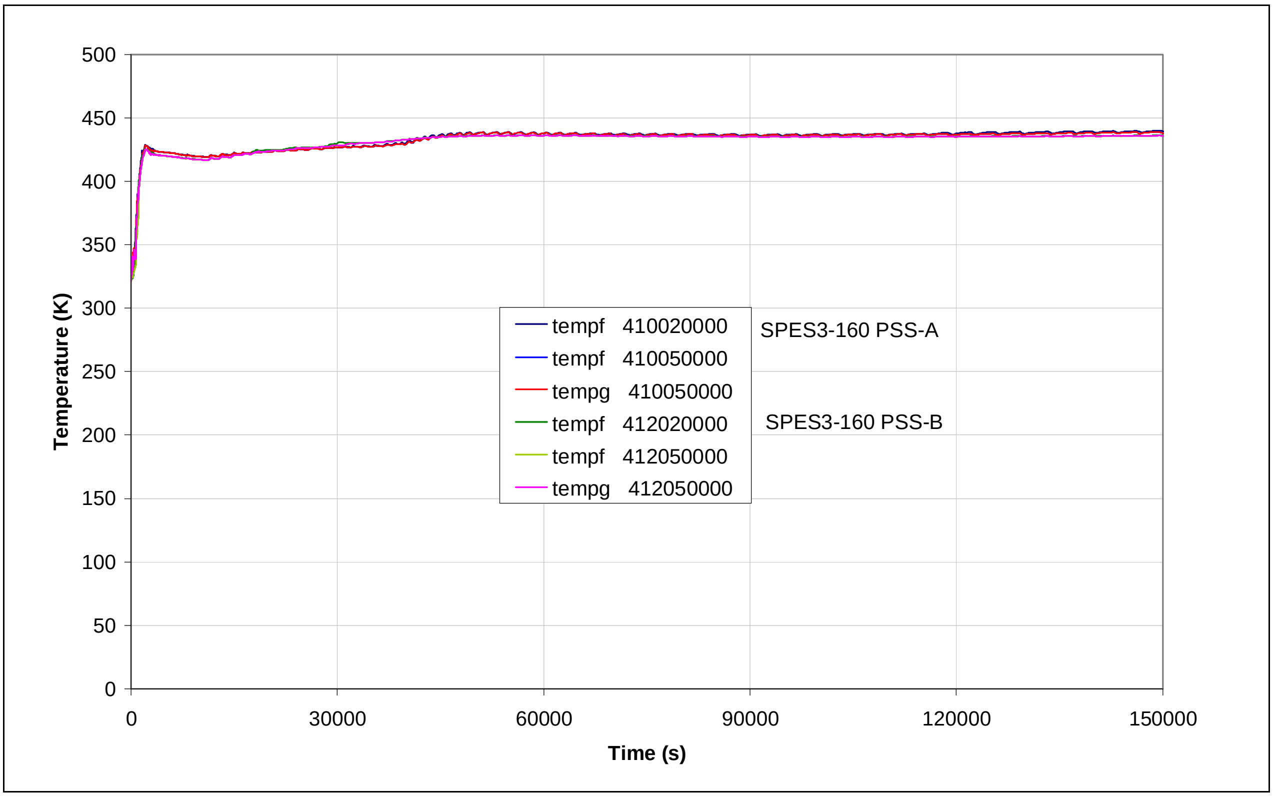


Fig.4.37 – SPES3-160 core power (window)

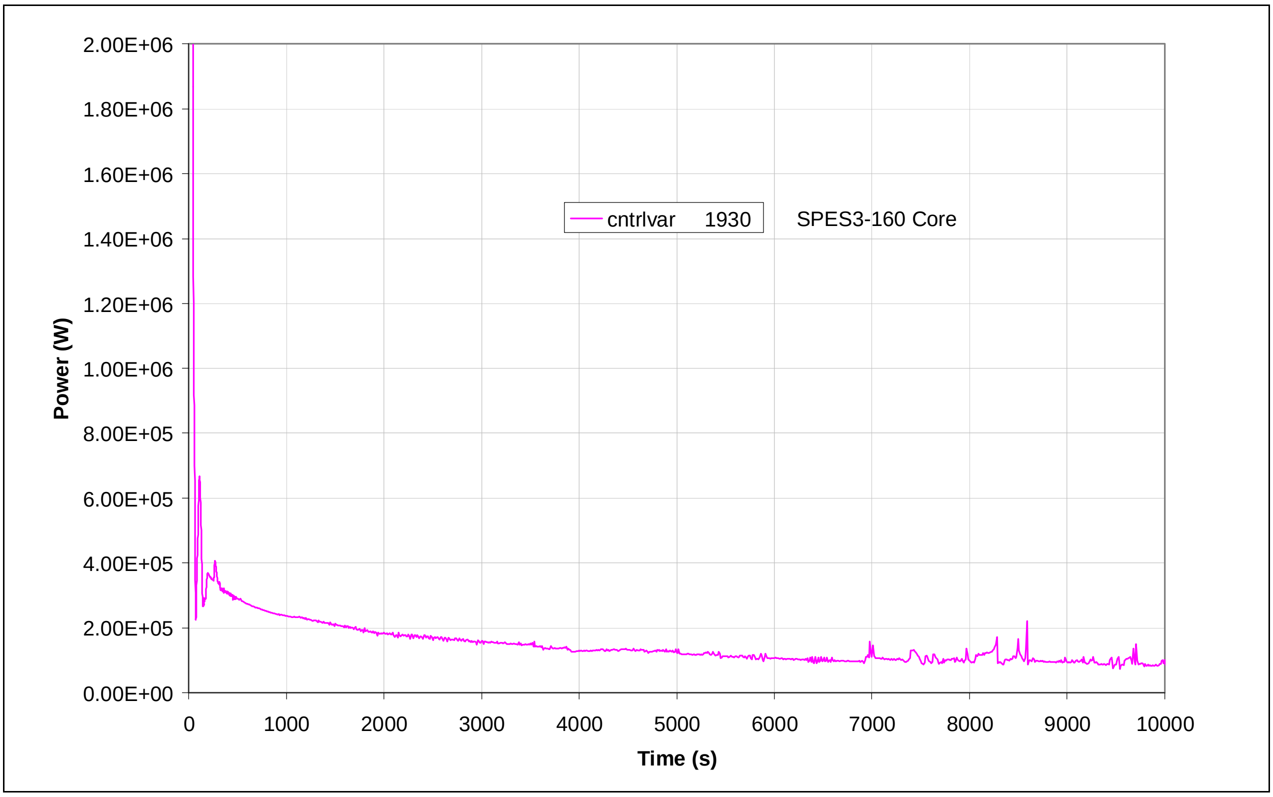


Fig.4.38 – SPES3-160 core power

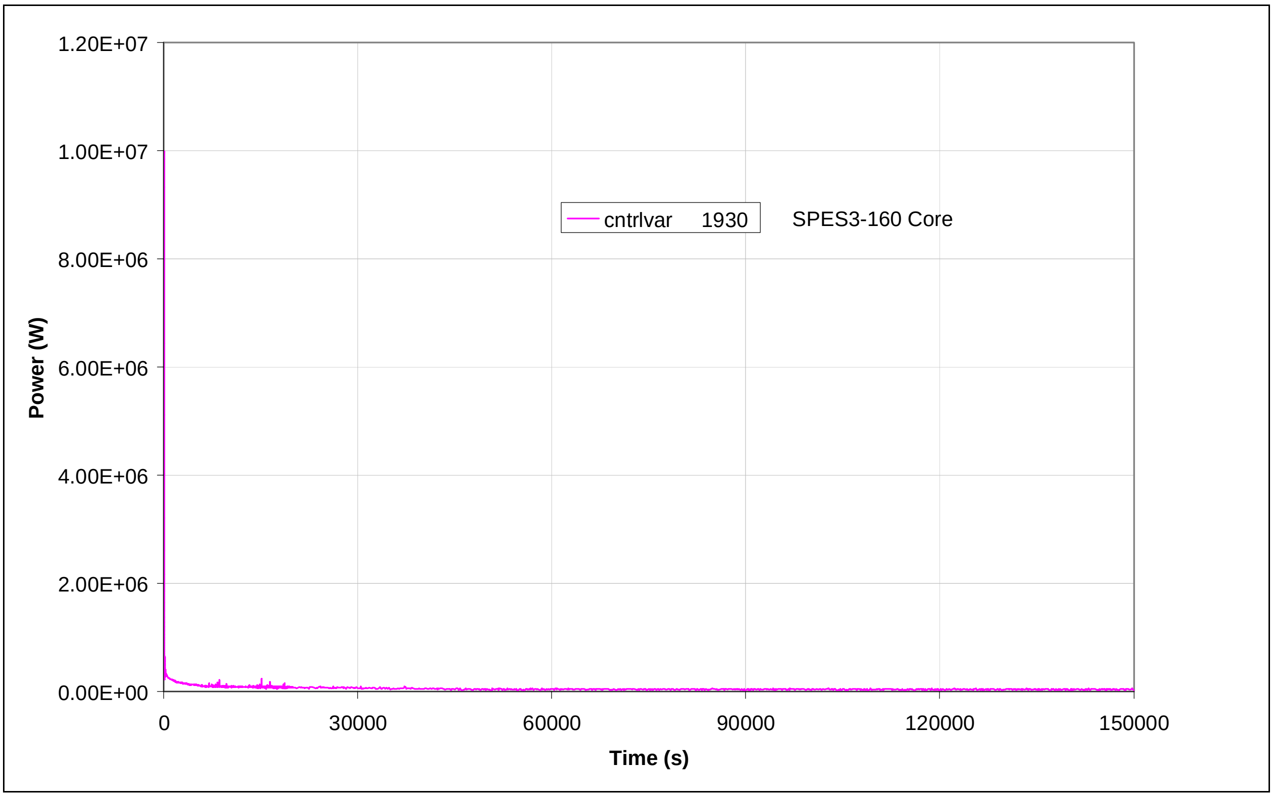


Fig.4.39 – SPES3-160 SG power (window)

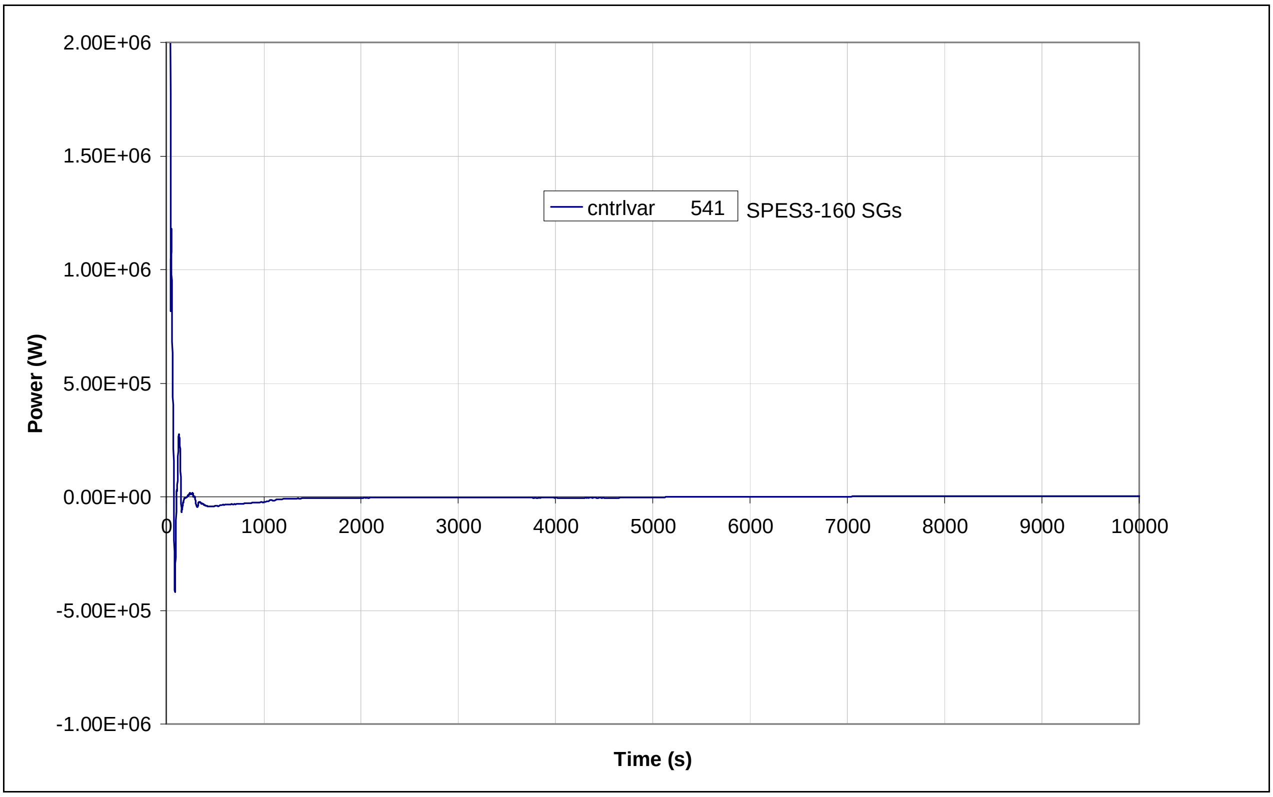


Fig.4.40 – SPES3-160 SG ss mass flow (window)

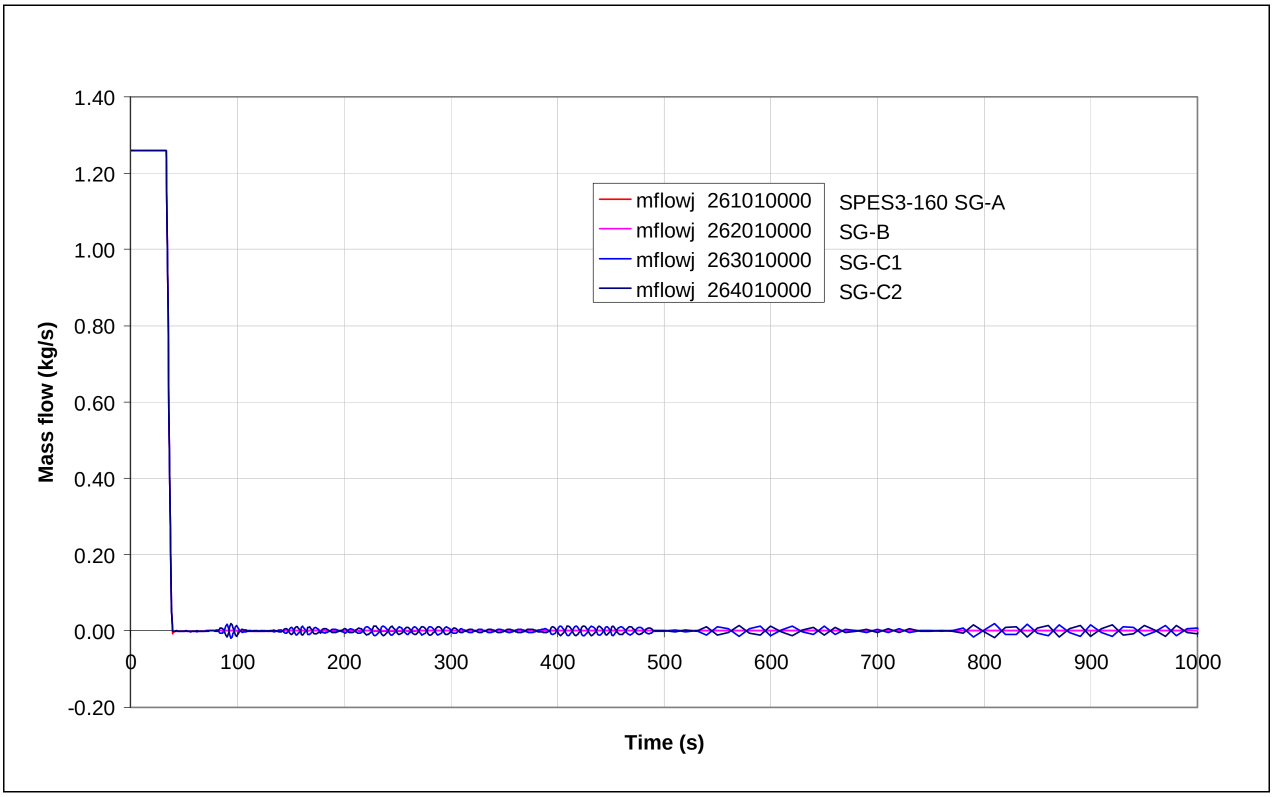


Fig.4.41 – SPES3-160 SG ss outlet pressure (window)

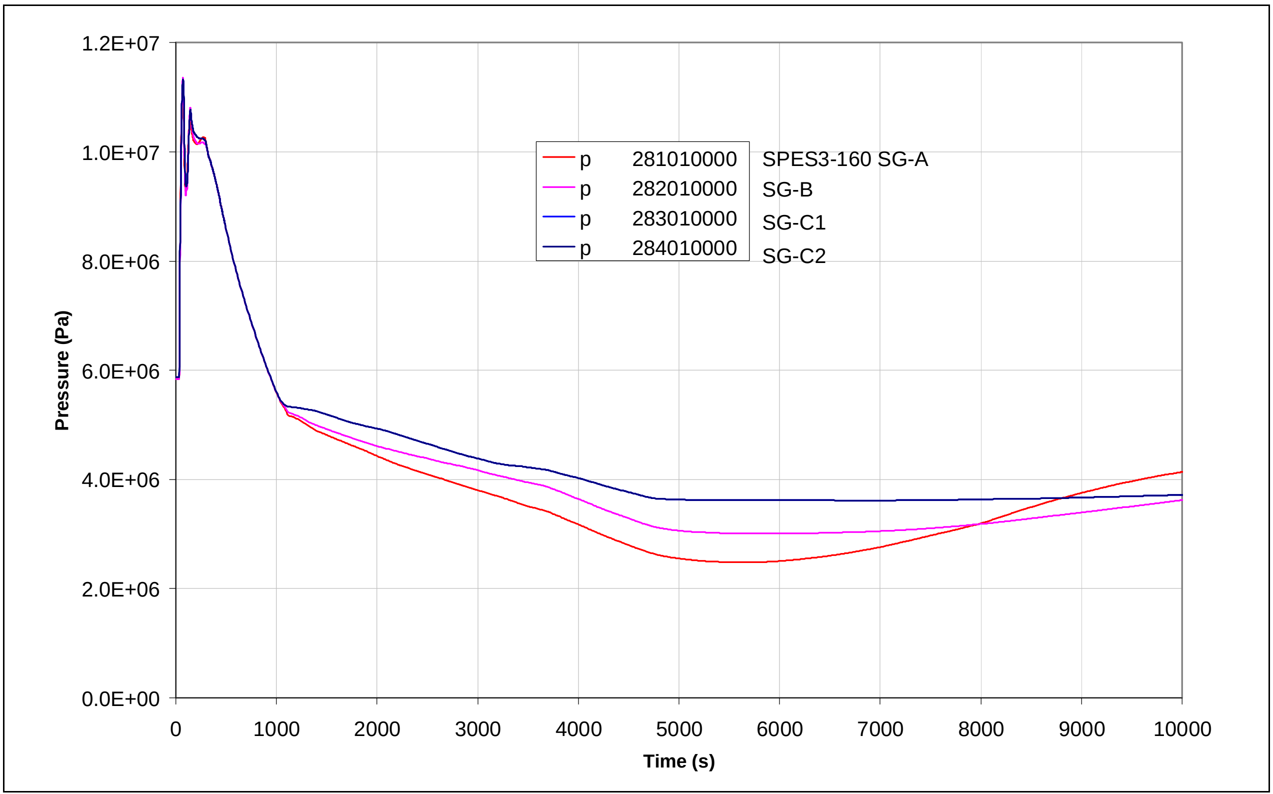


Fig.4.42 – SPES3-160 SG ss outlet pressure and RPV mass

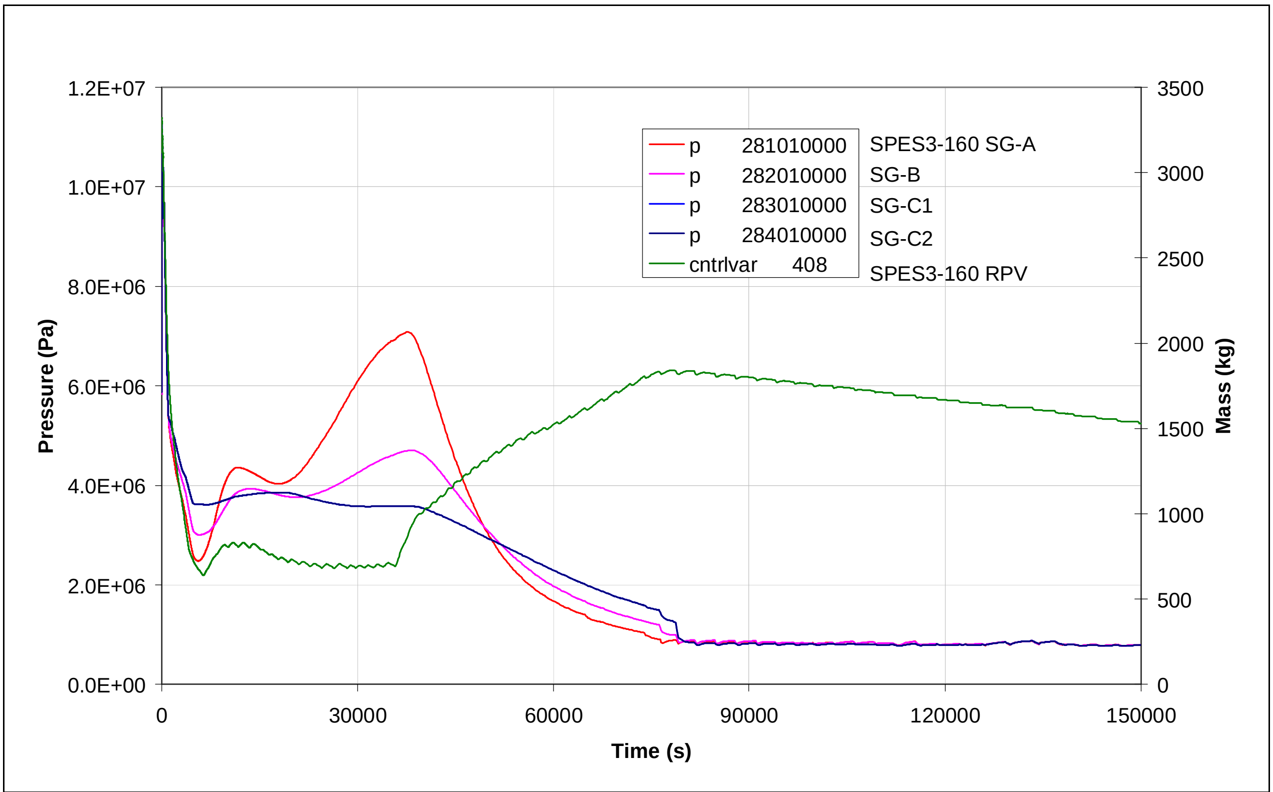


Fig.4.43 – SPES3-160 SG-A ss level (window)

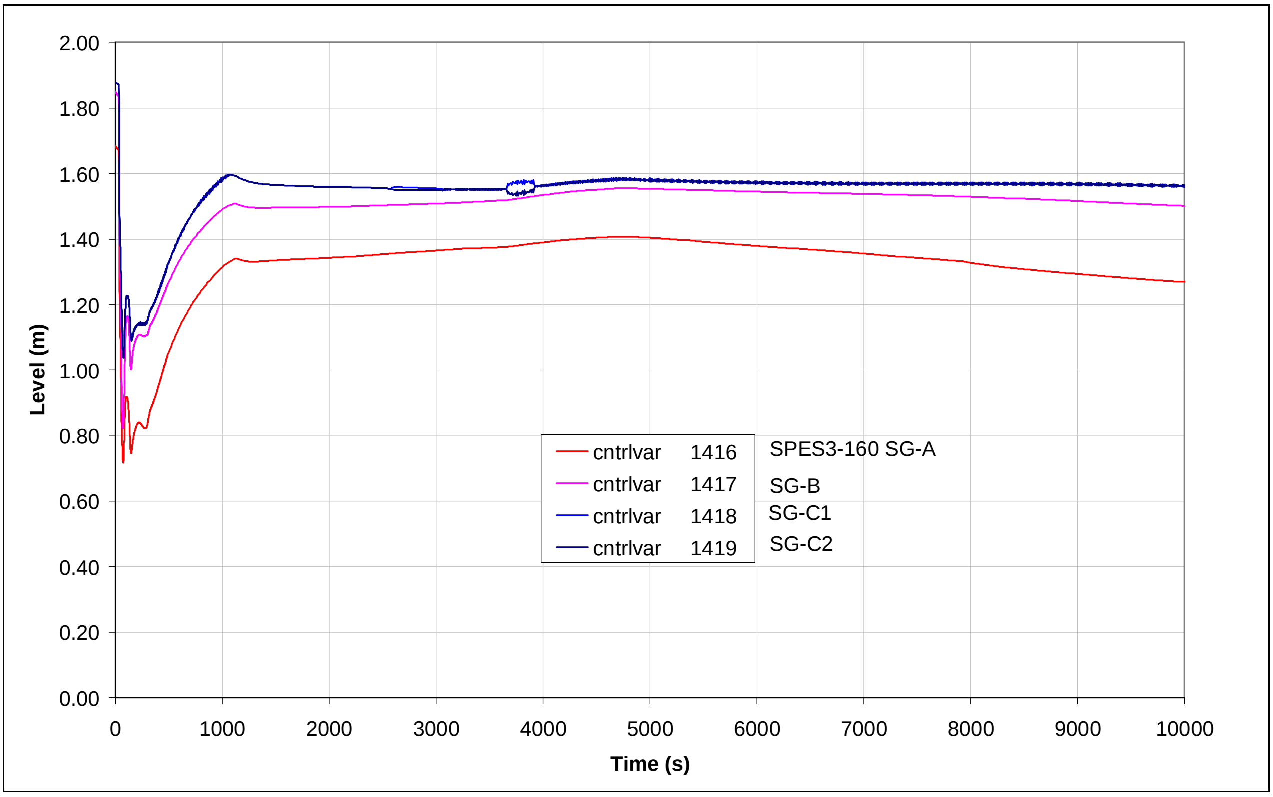


Fig.4.44 – SPES3-160 SG-A ss level

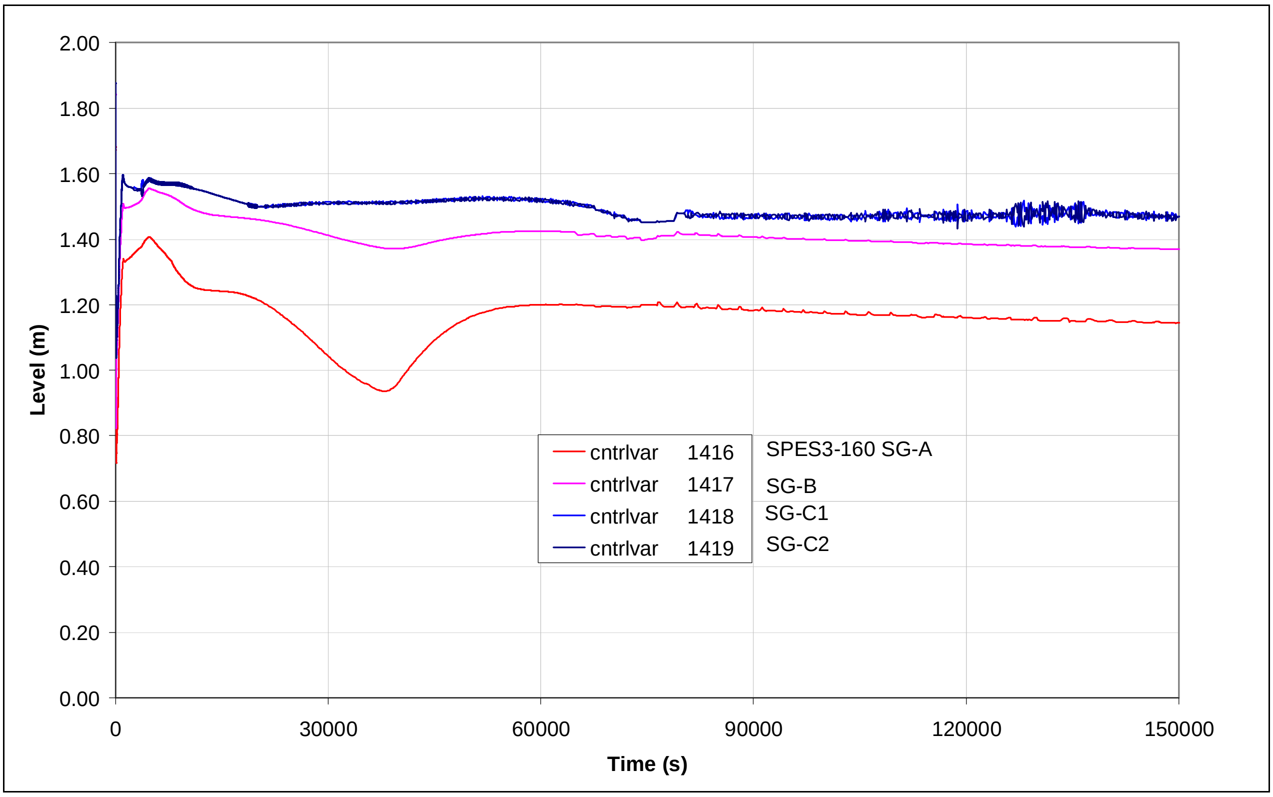


Fig.4.45 – SPES3-160 PRZ level

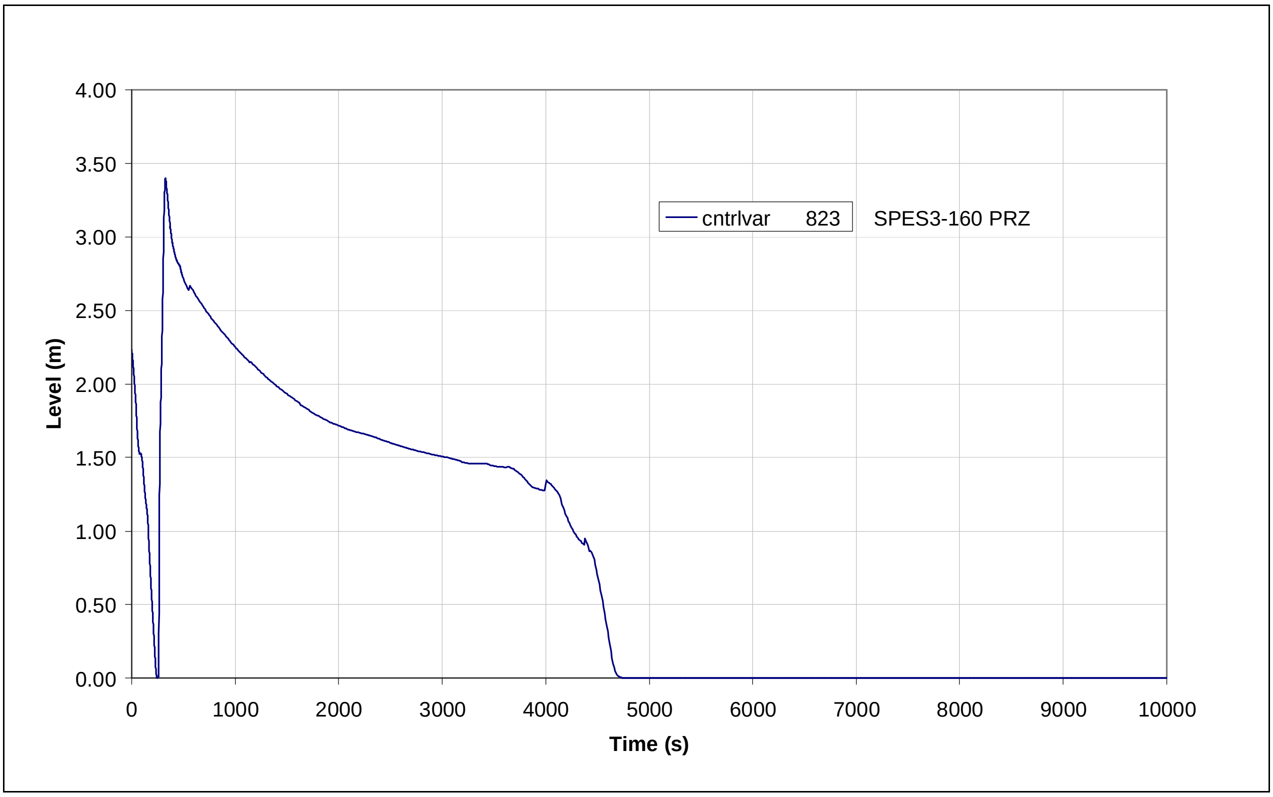


Fig.4.46 – SPES3-160 pump inlet liquid fraction

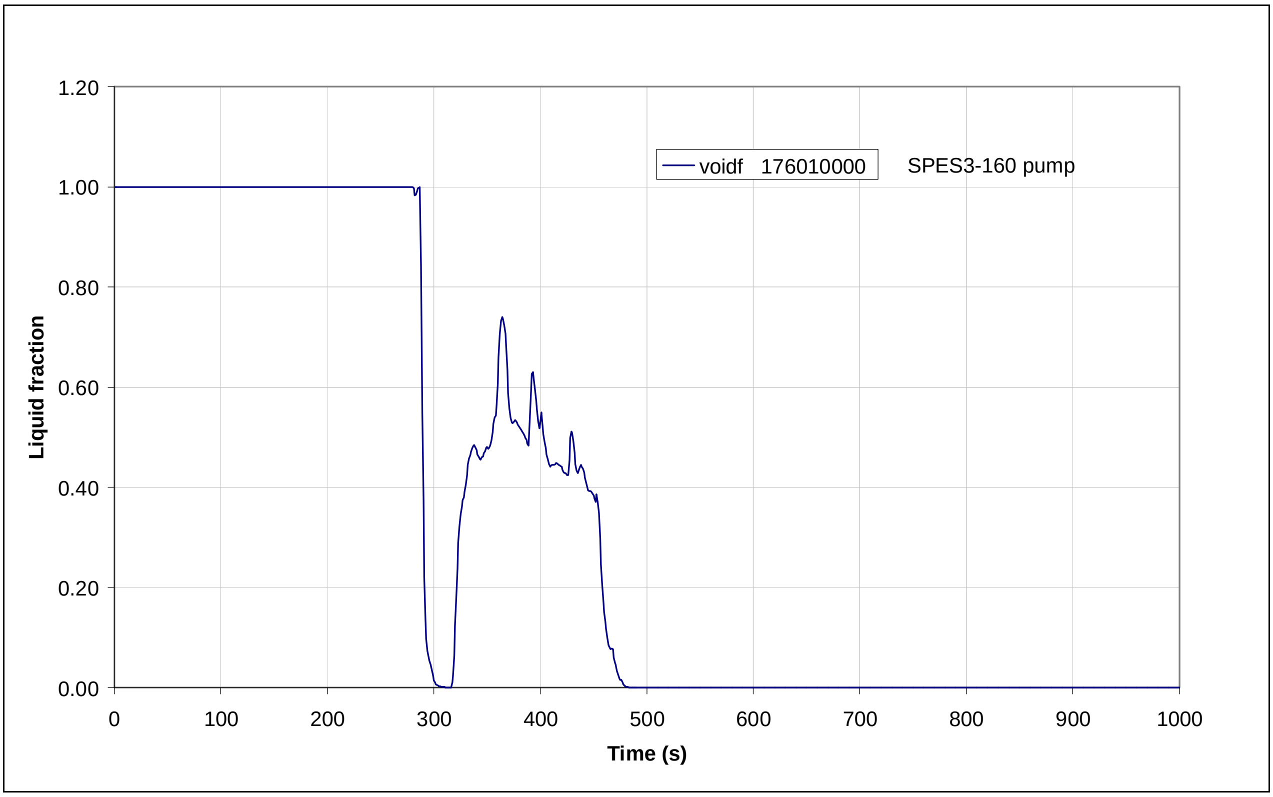


Fig.4.47 – SPES3-160 core inlet flow (window)

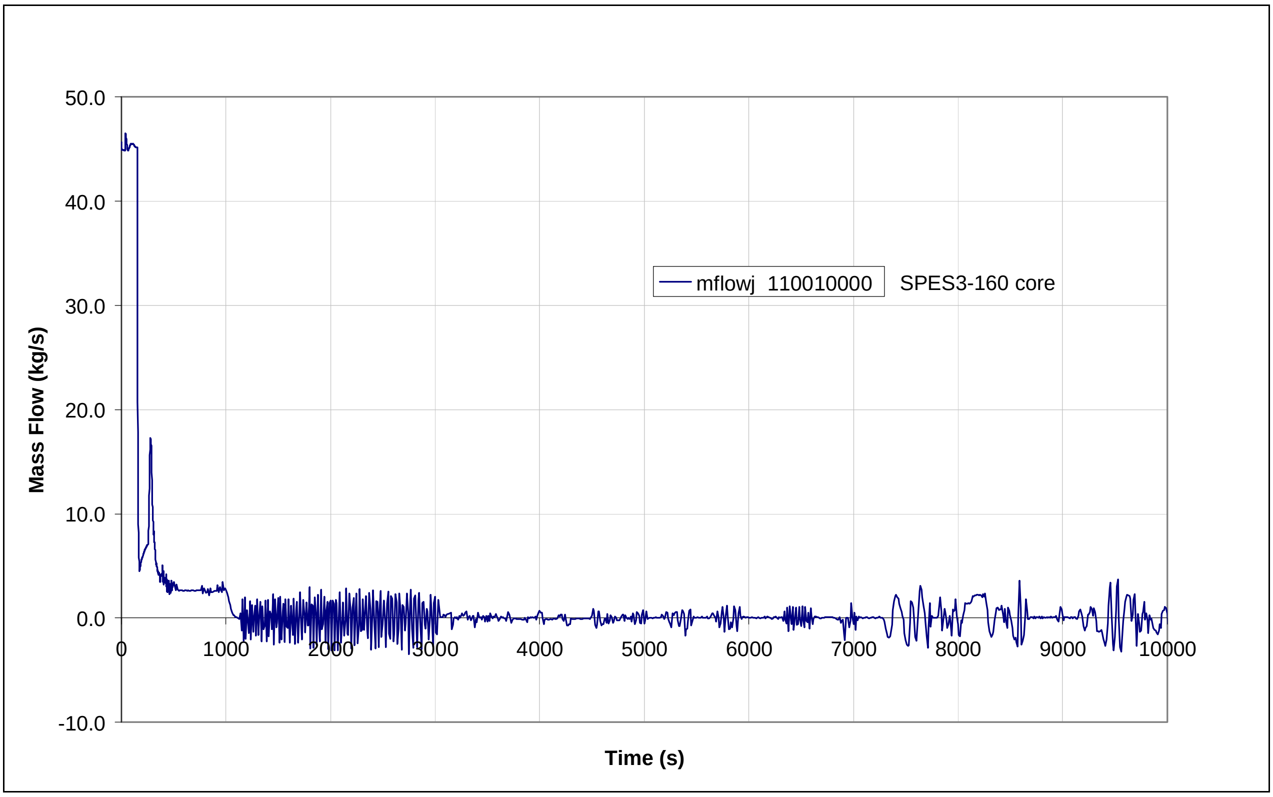


Fig.4.48 – SPES3-160 core inlet flow

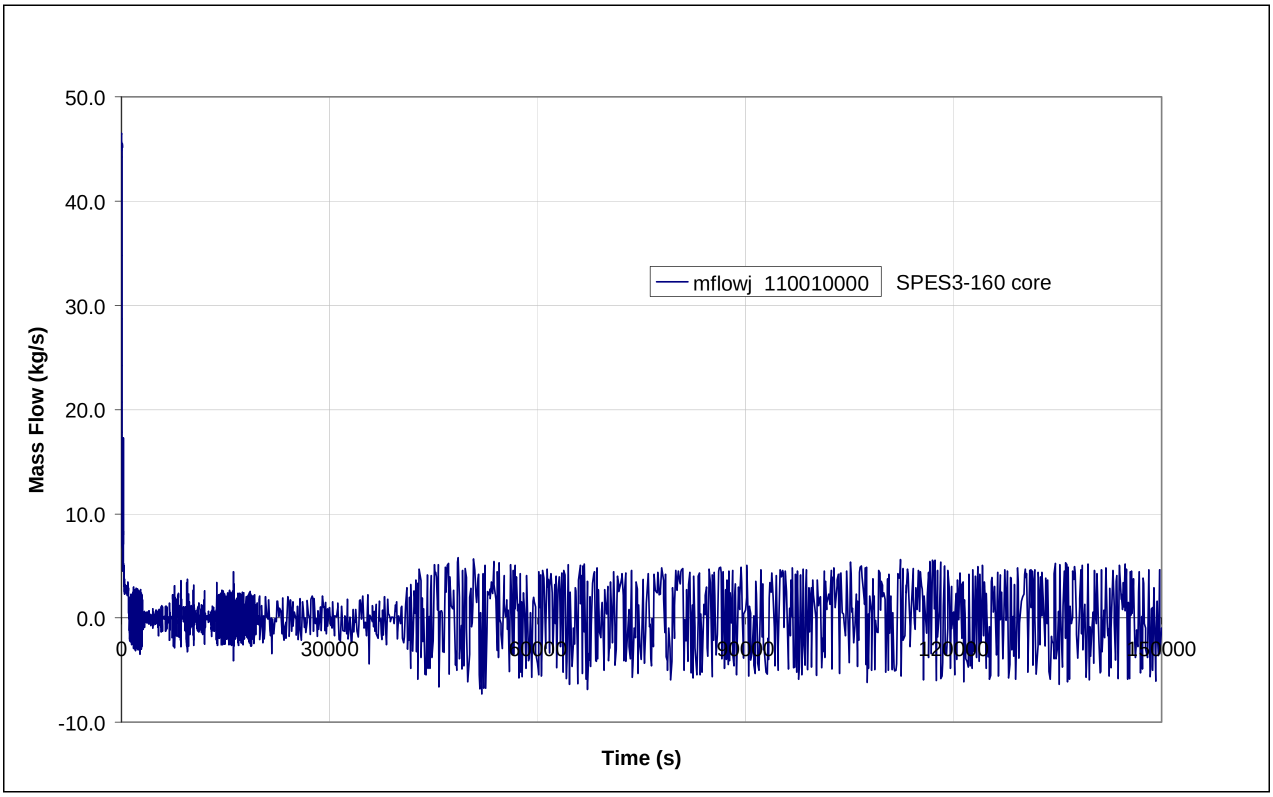


Fig.4.49 – SPES3-160 RI-DC check valve mass flow (window)

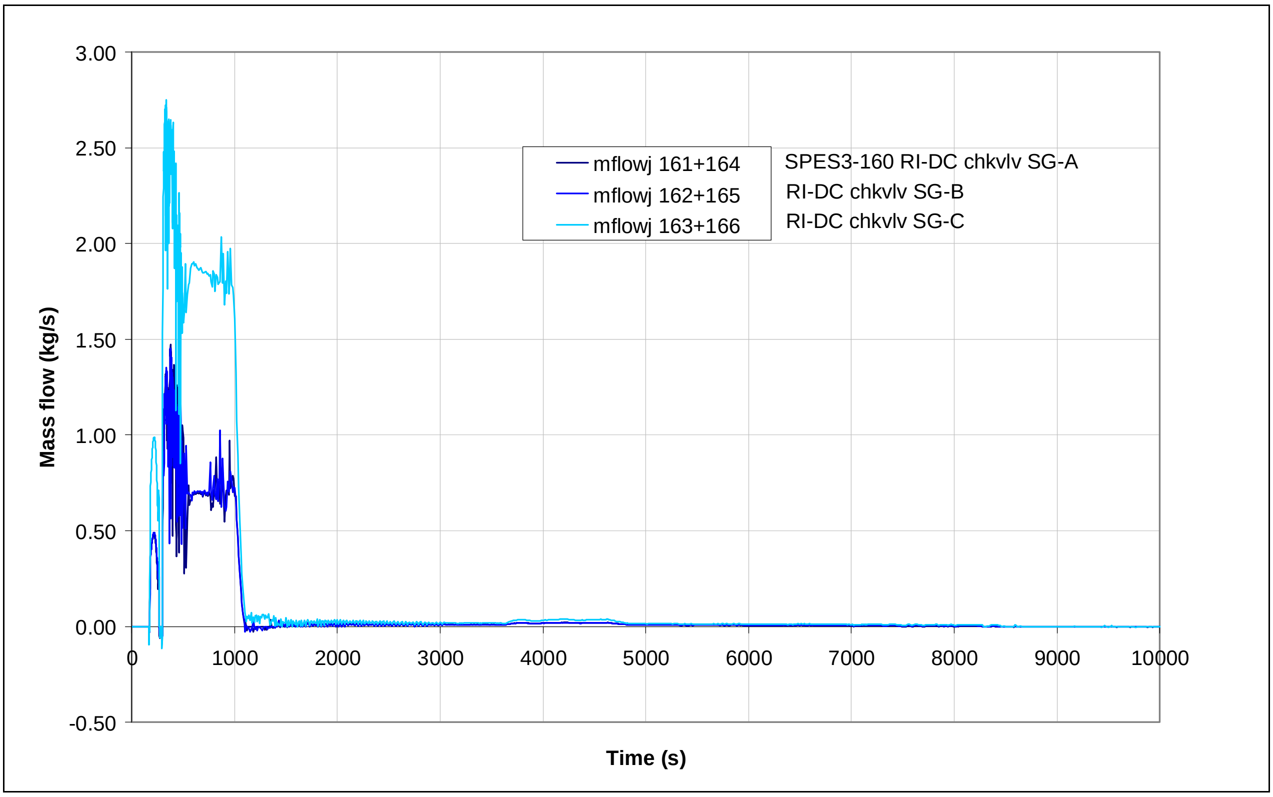


Fig.4.50 – SPES3-160 RI-DC check valve mass flow

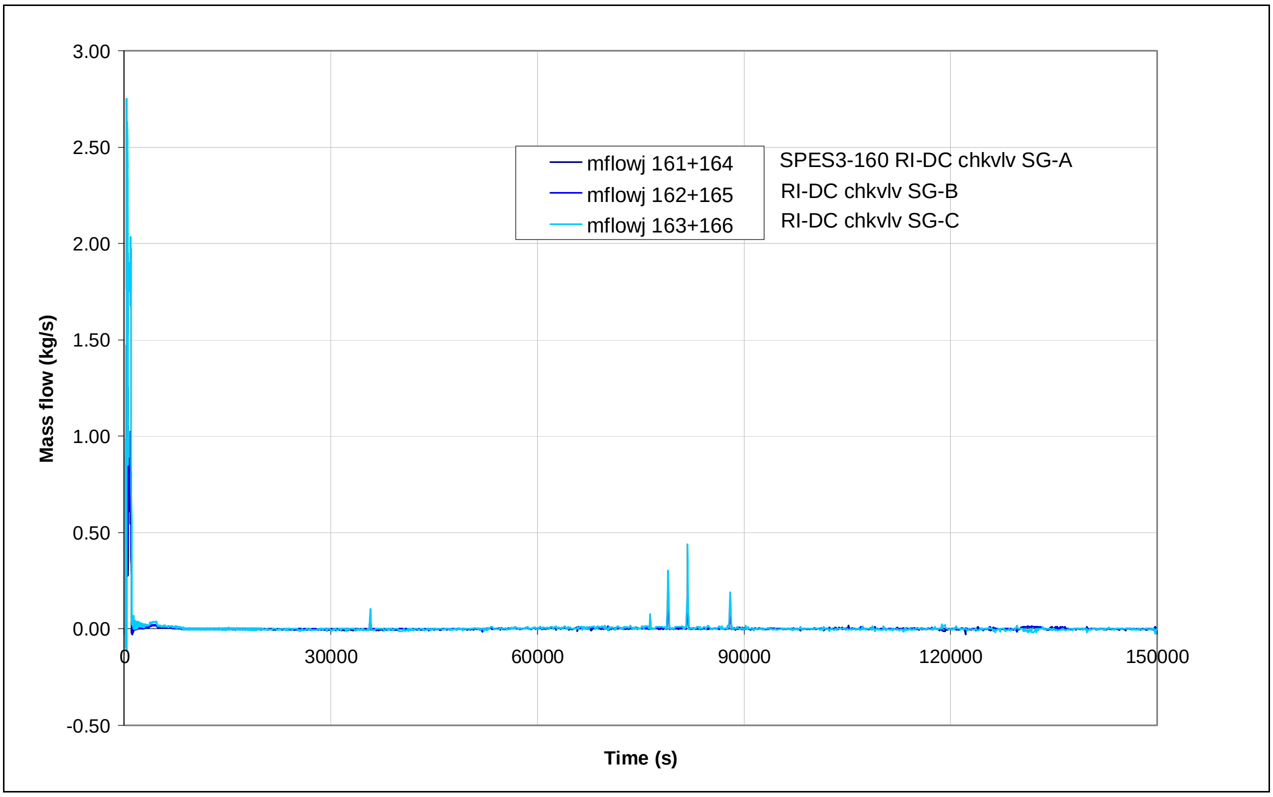


Fig.4.51 – SPES3-160 EBT mass

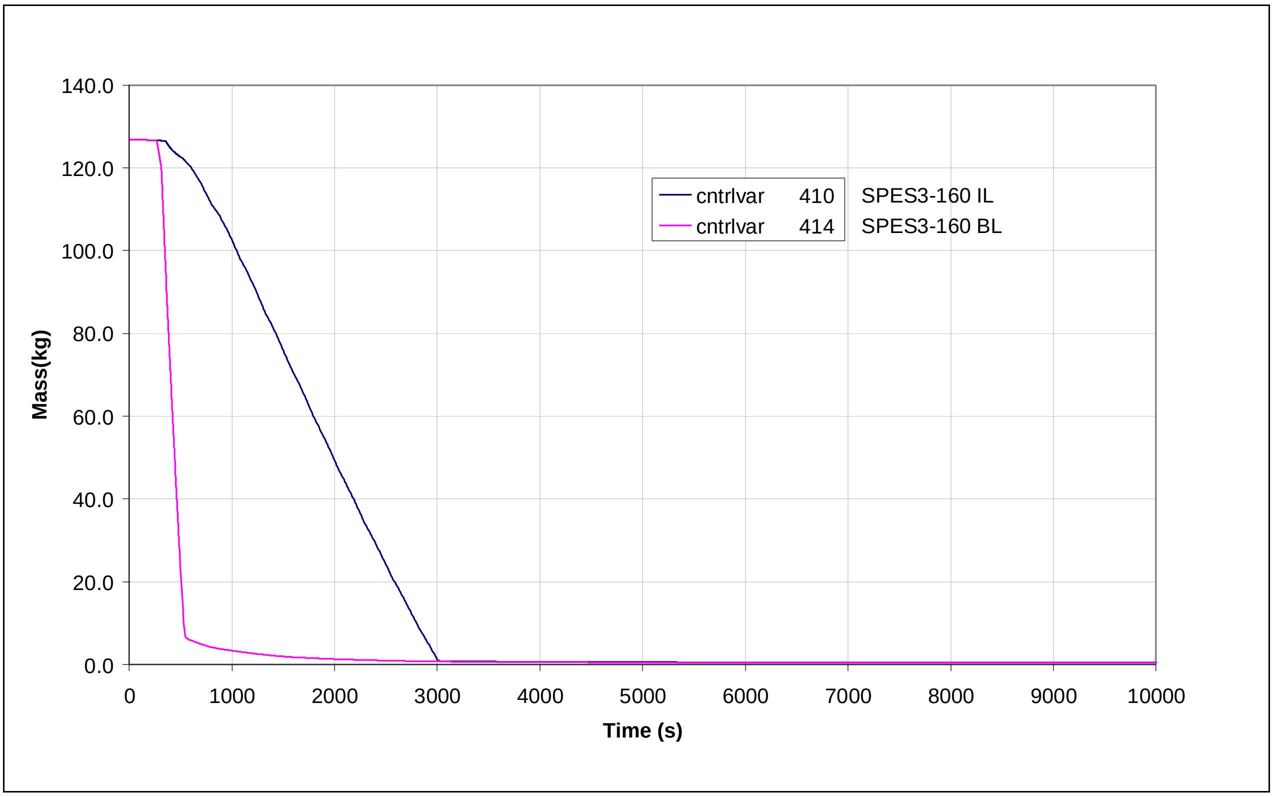


Fig.4.52 – SPES3-160 EBT level

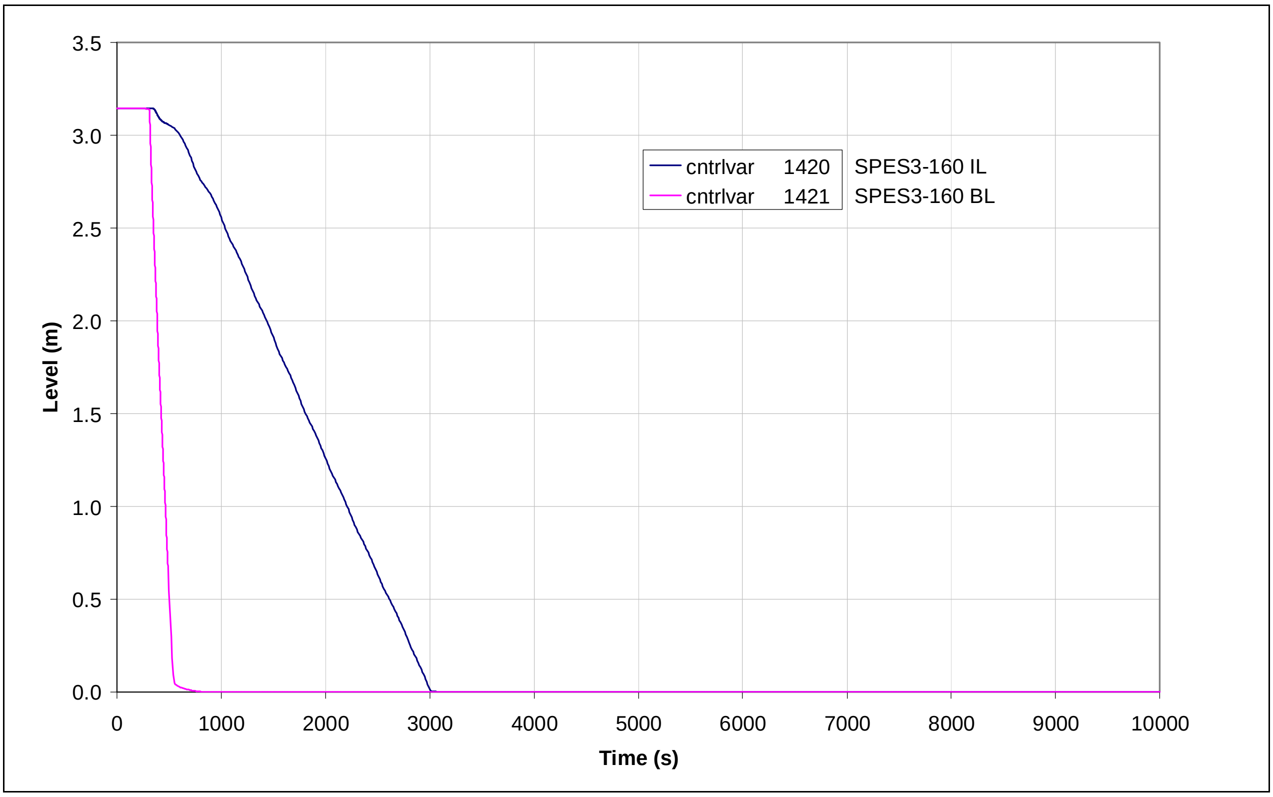


Fig.4.53 – SPES3-160 EBT balance line mass flow (mass flow)

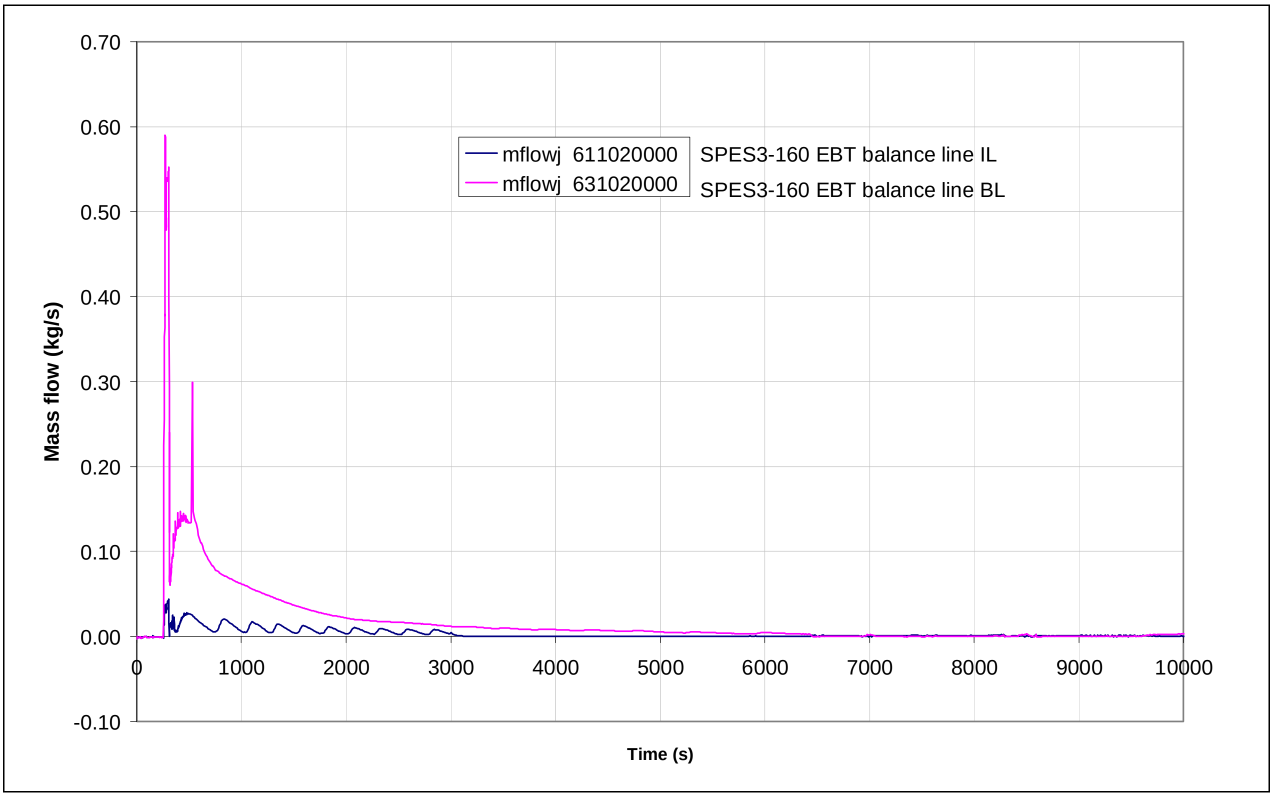


Fig.4.54 – SPES3-160 EBT balance line mass flow

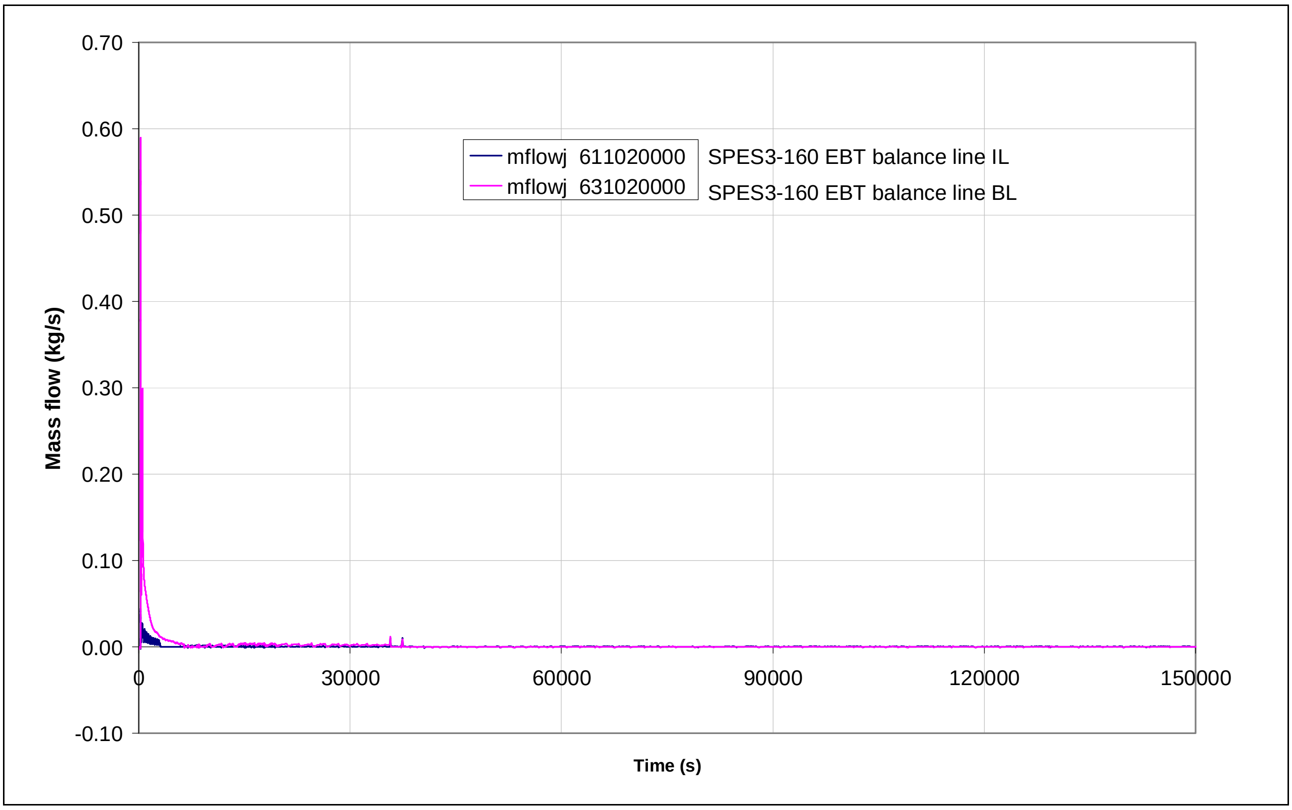


Fig.4.55 – SPES3-160 Core liquid fraction (window)

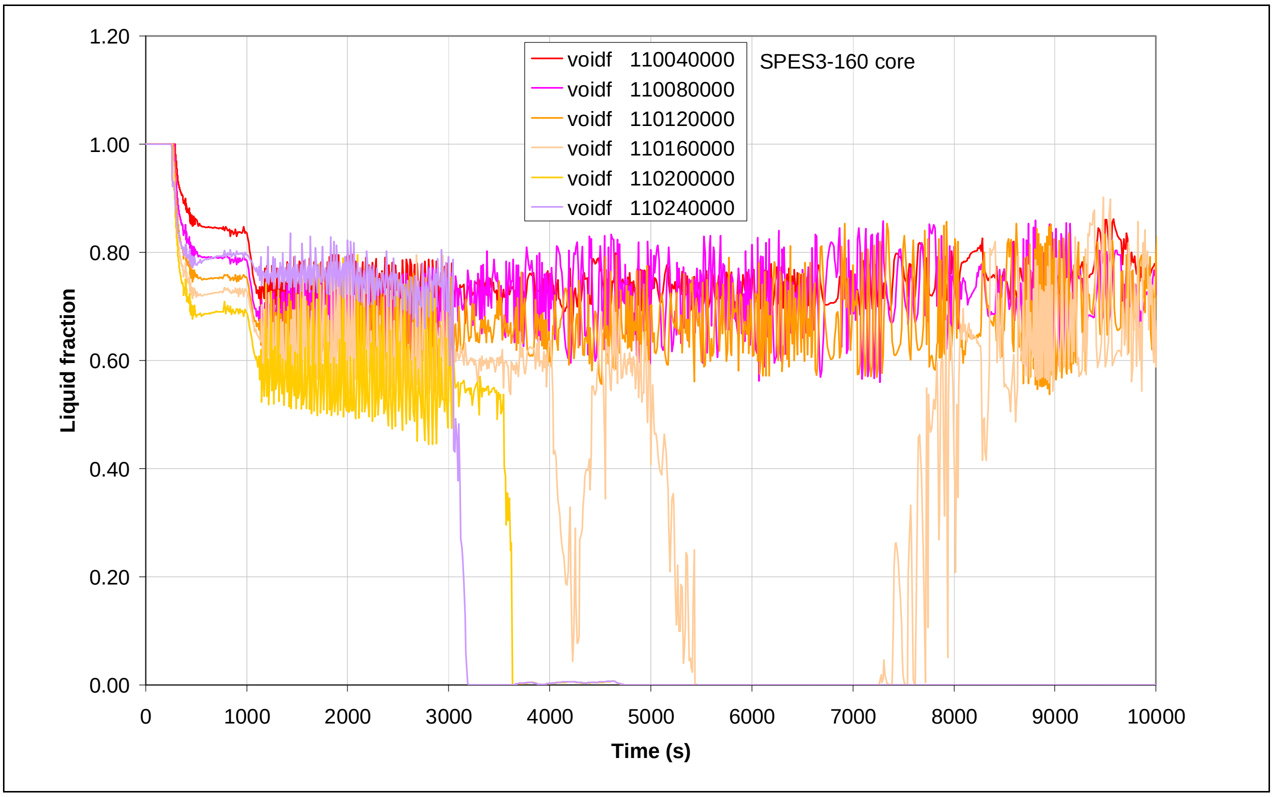


Fig.4.56 – SPES3-160 Core liquid fraction

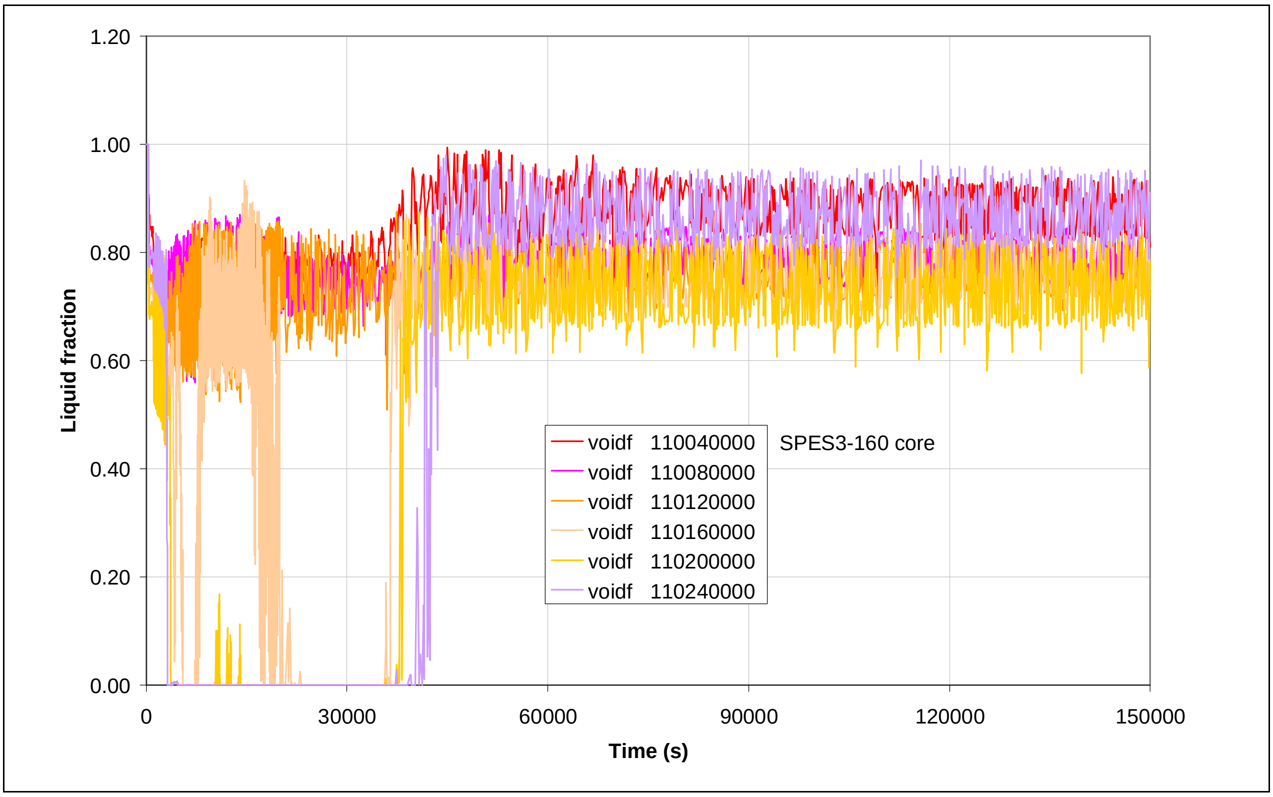


Fig.4.57 – SPES3-160 Core inlet and outlet temperatures (window)

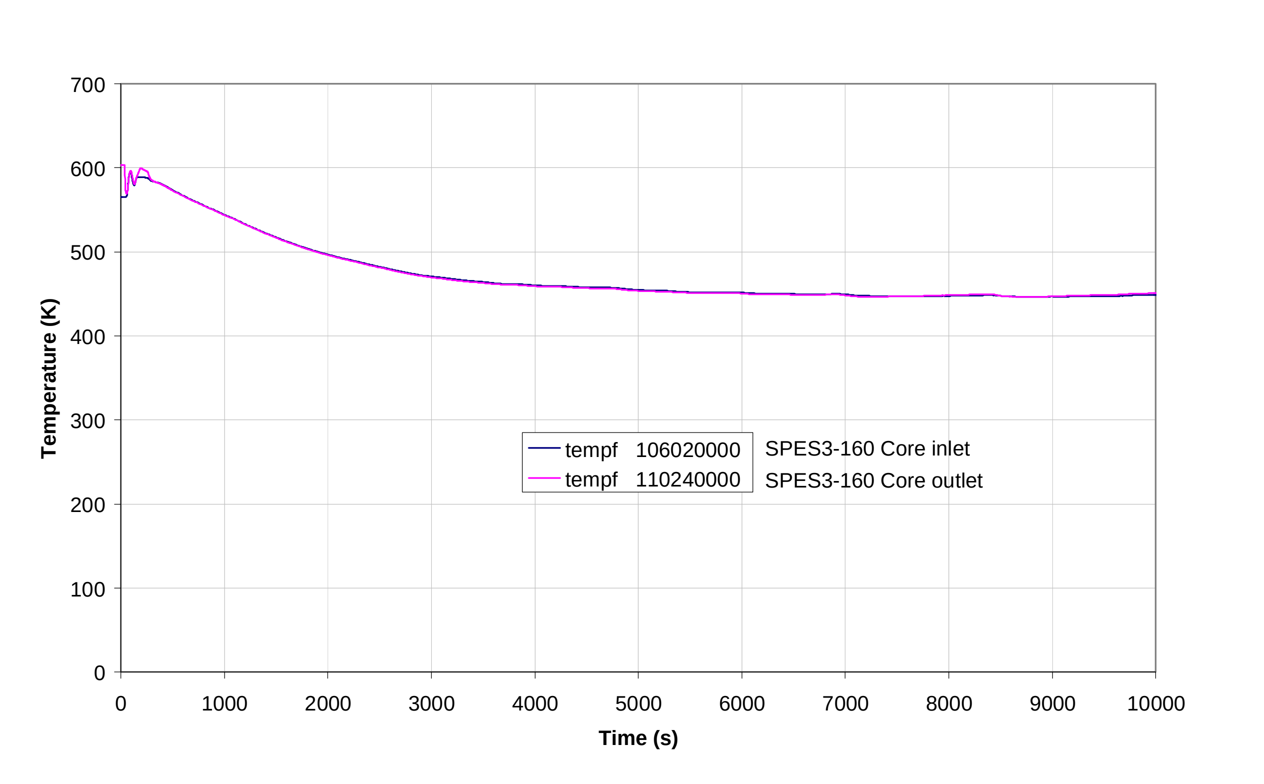


Fig.4.58 – SPES3-160 Core inlet and outlet temperatures

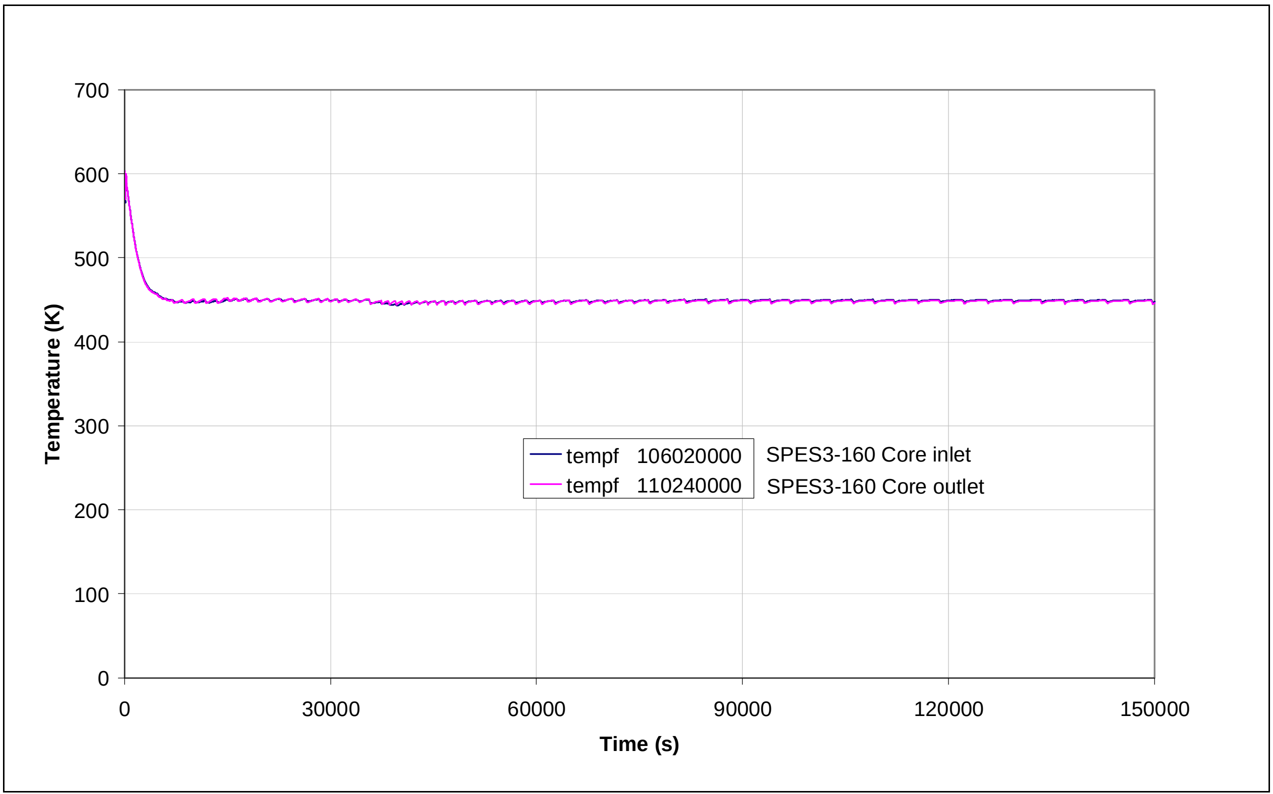


Fig.4.59 – SPES3-160 Core heater rod clad surface temperatures (normal rods)

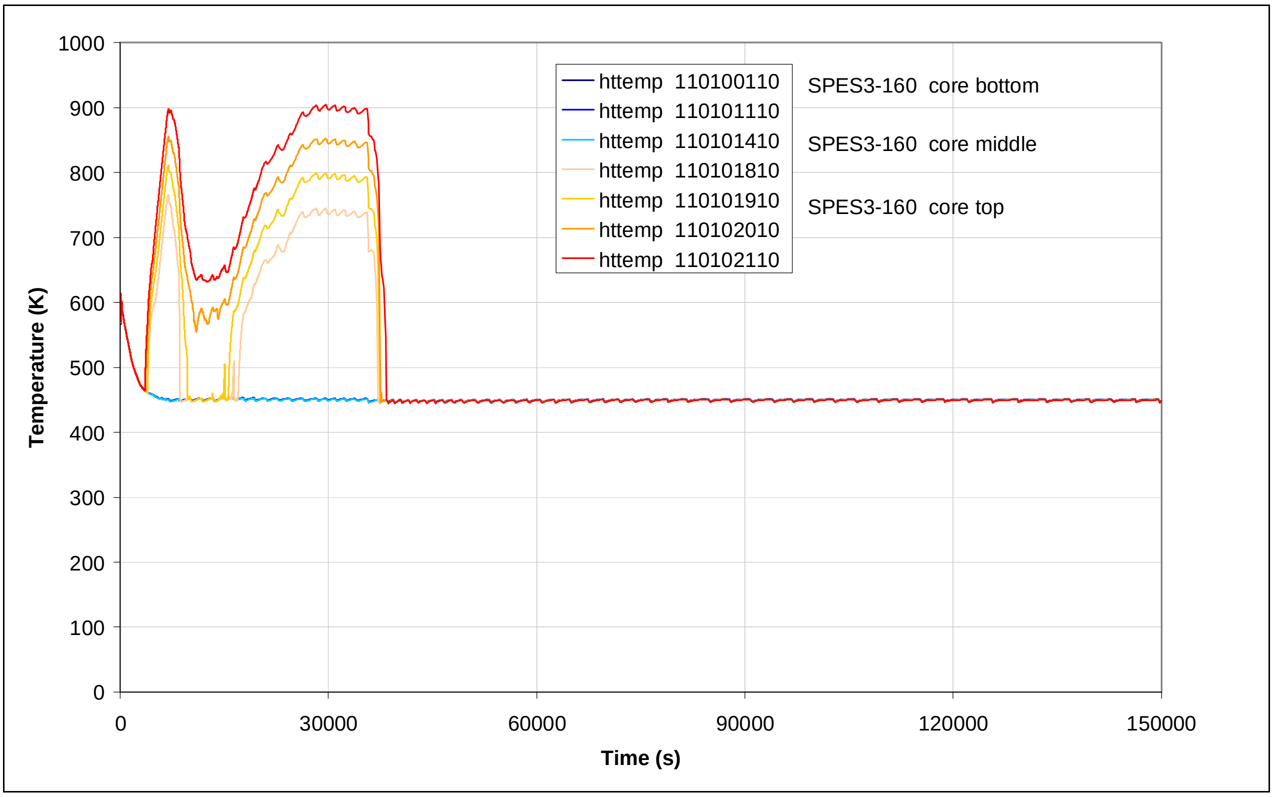


Fig.4.60 – SPES3-160 Core heater rod clad surface temperatures (hot rods)

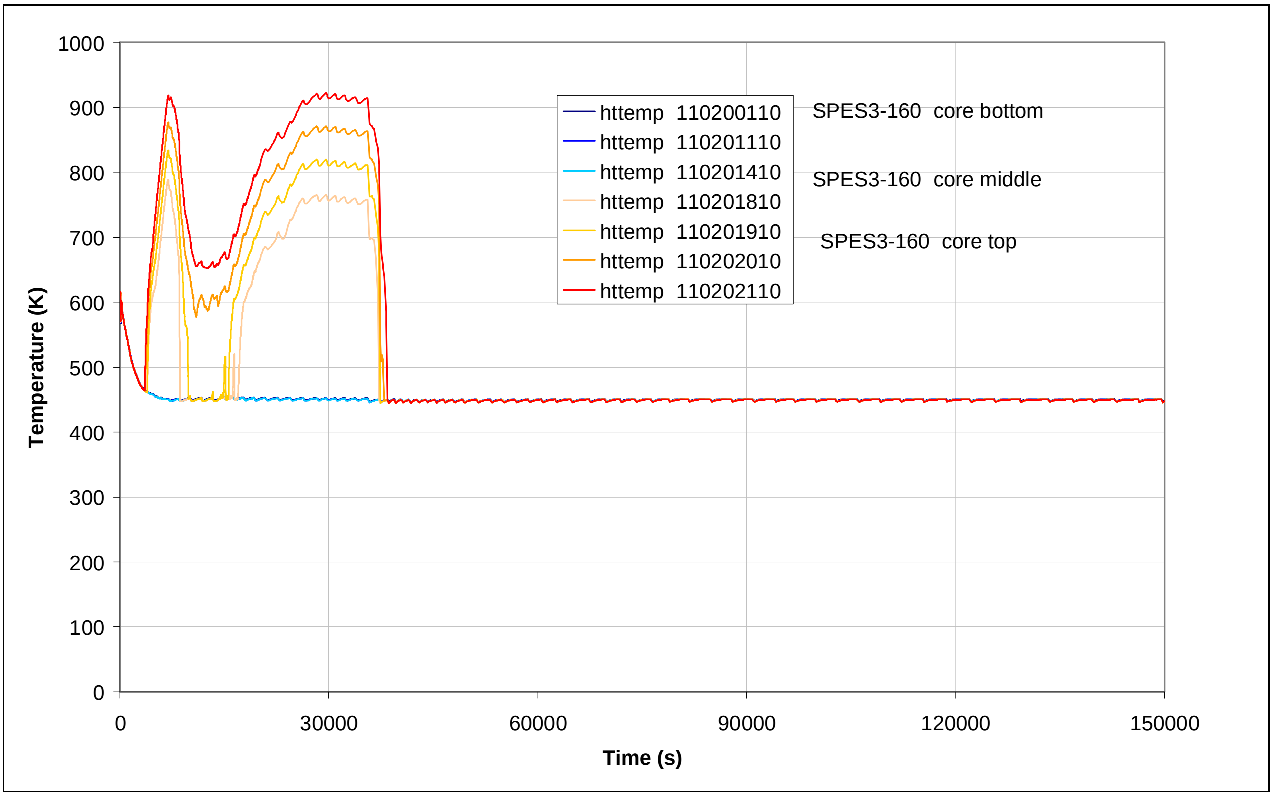


Fig.4.61 – SPES3-160 RPV mass

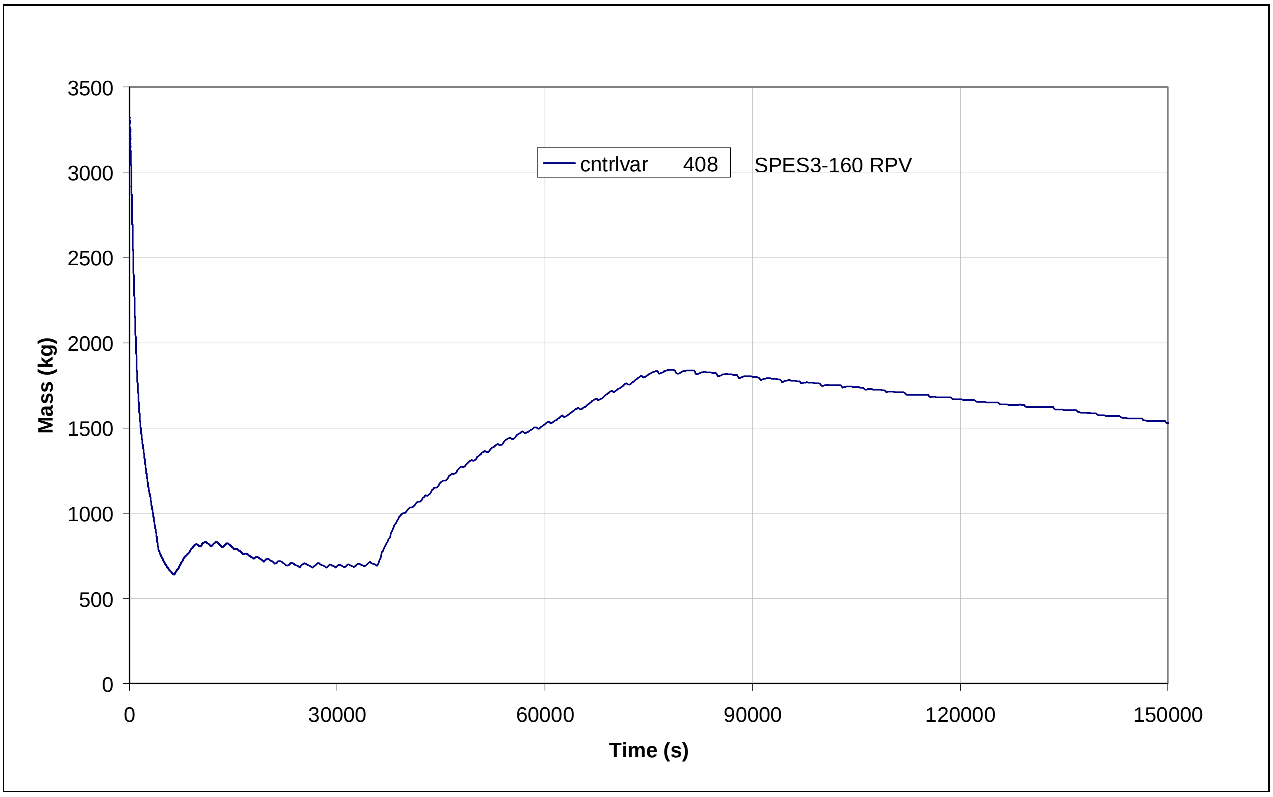


Fig.4.62 – SPES3-160 RC to DVI line mass flow

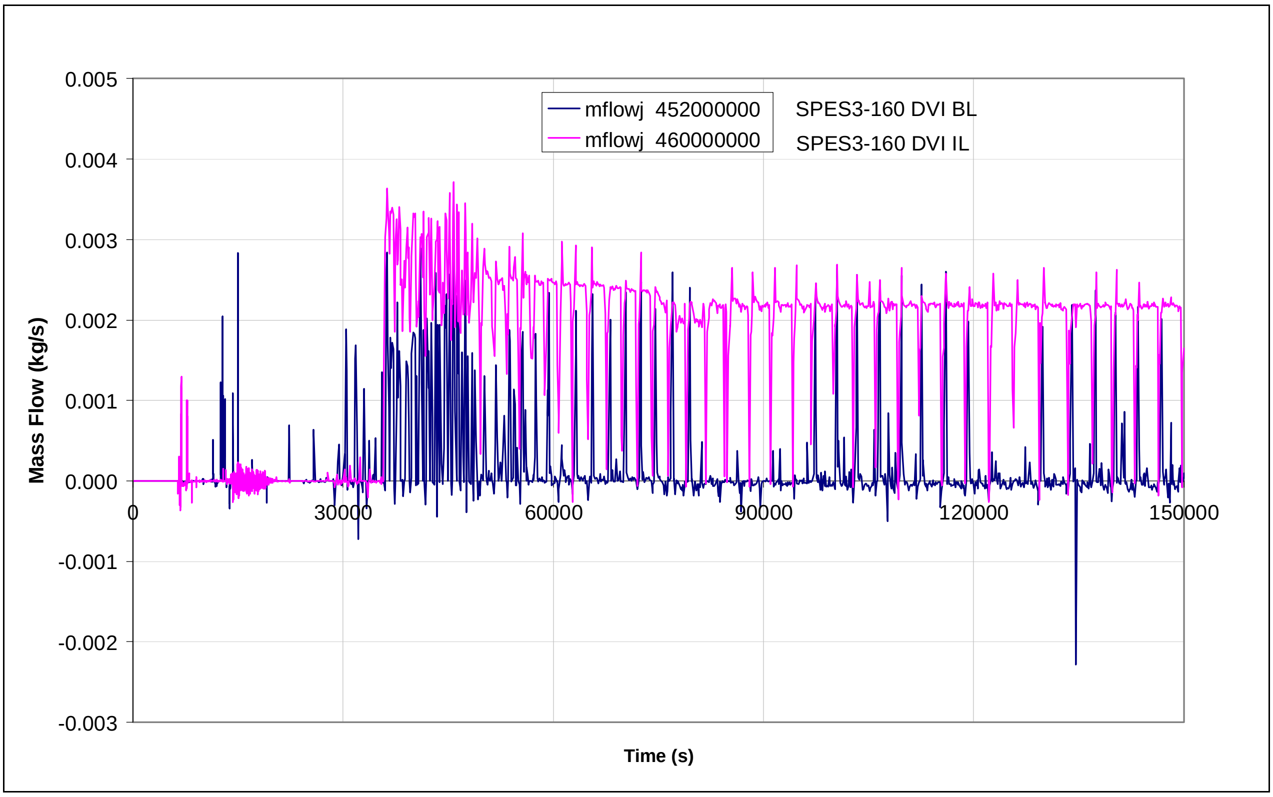


Fig.4.63 – SPES3-160 DVI line mass flow (window)

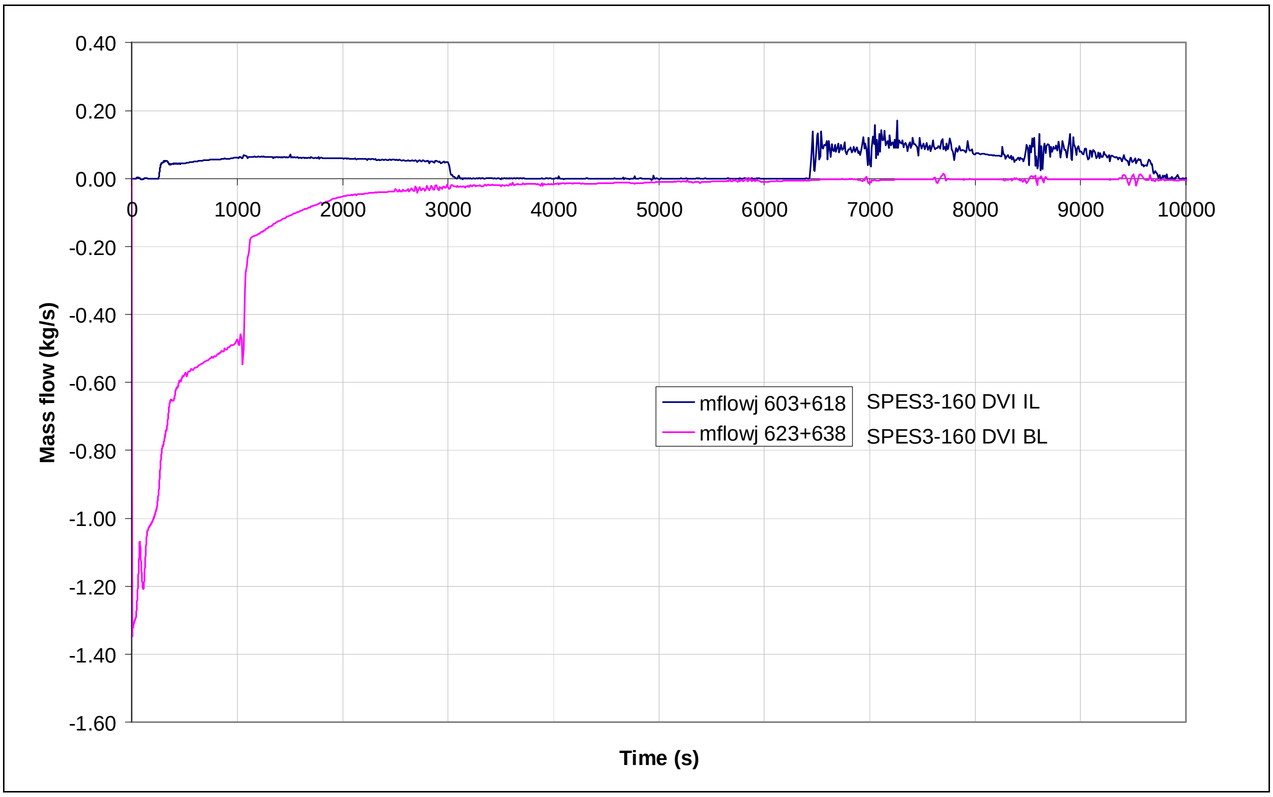


Fig.4.64 – SPES3-160 DVI line mass flow

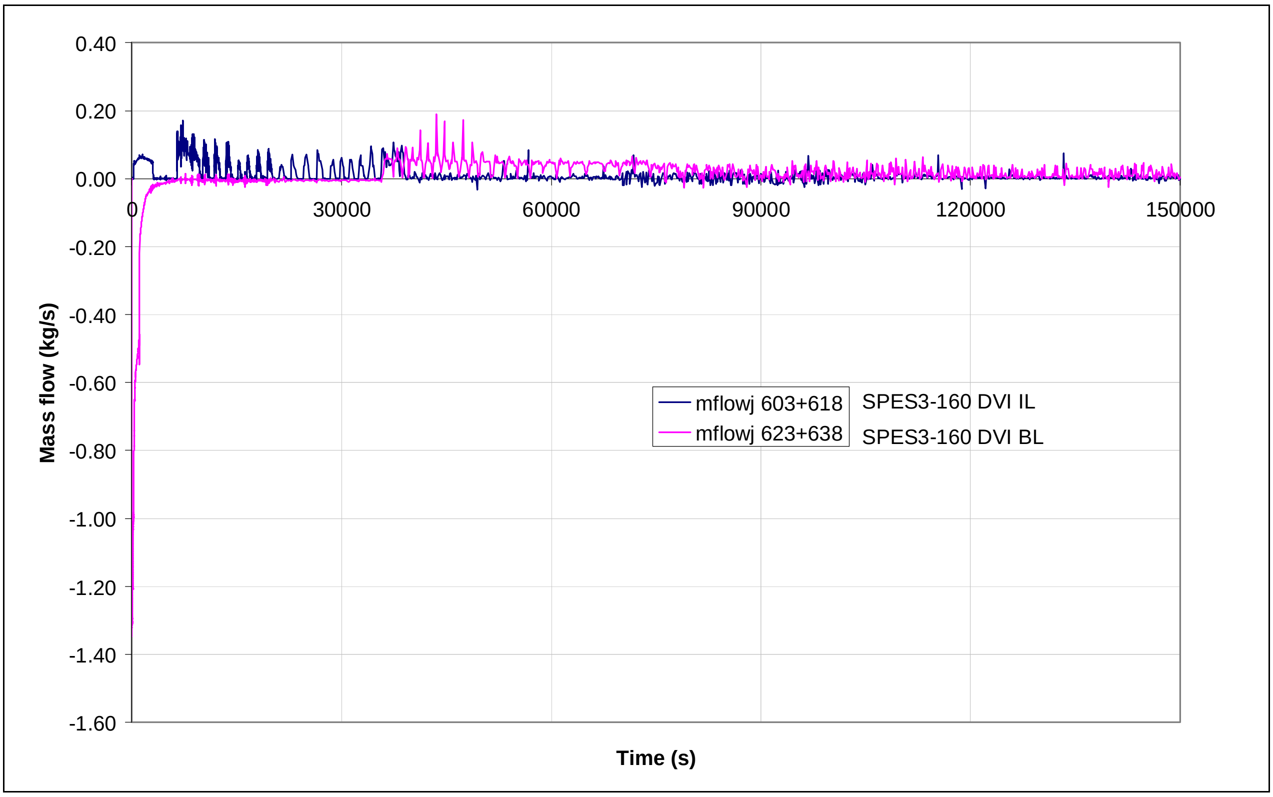


Fig.4.65 – SPES3-160 PCC mass flow

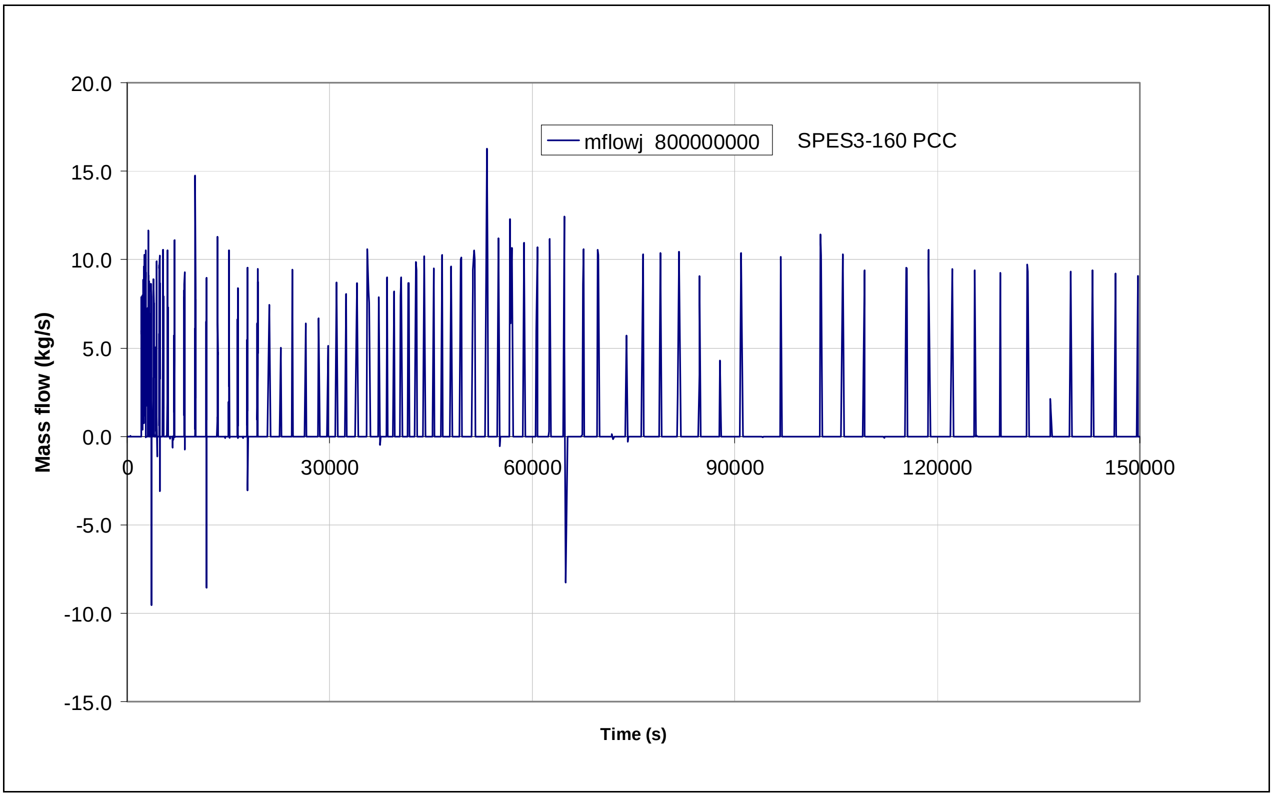


Fig.4.66 – SPES3-160 PCC tank level

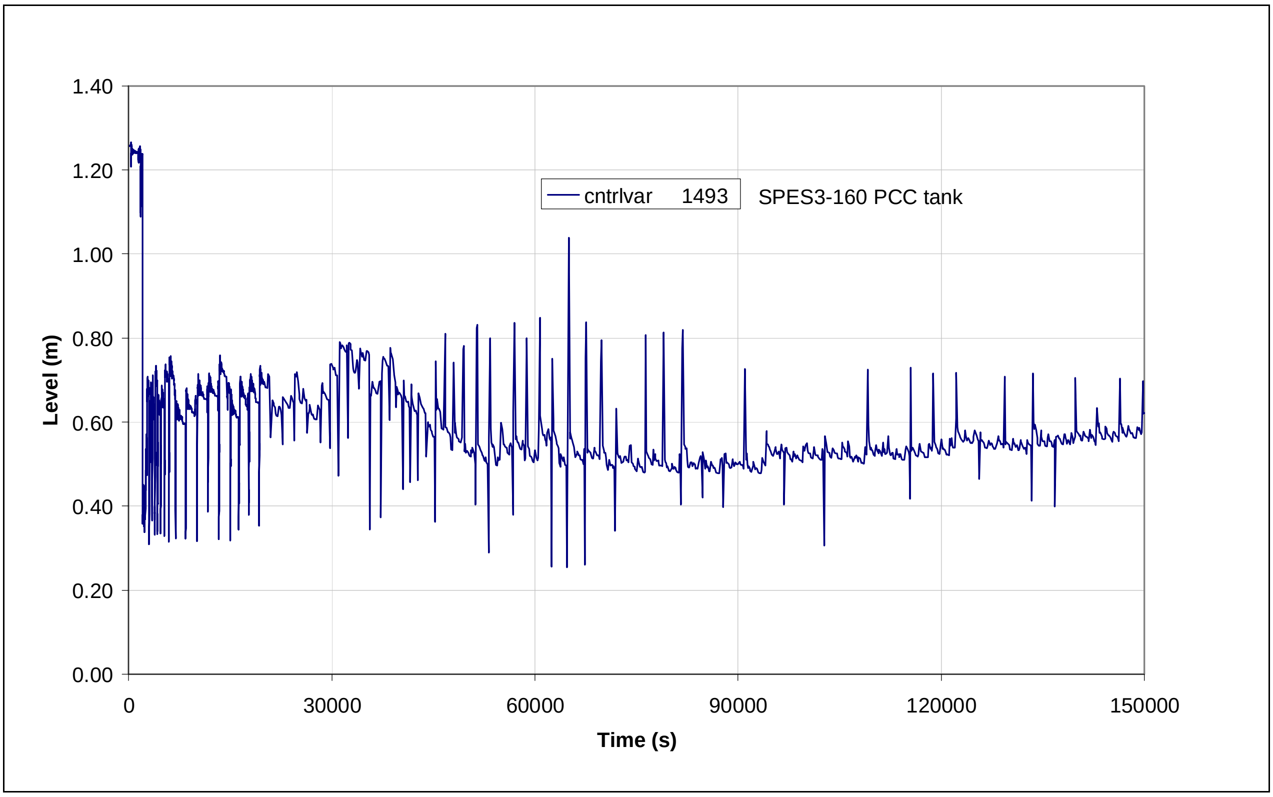


Fig.4.67 – SPES3-160 PCC inlet and outlet temperature

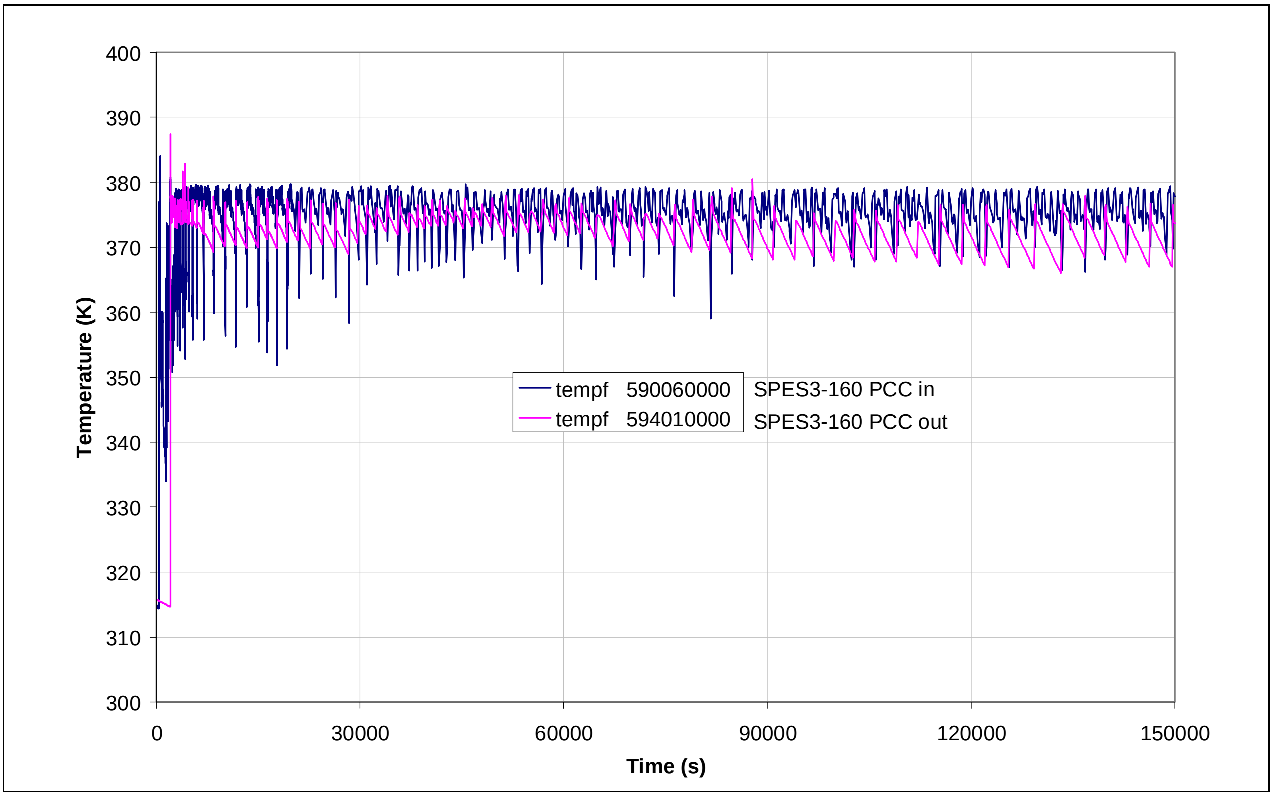


Fig.4.68 – SPES3-160 PCC liquid void fraction (window)

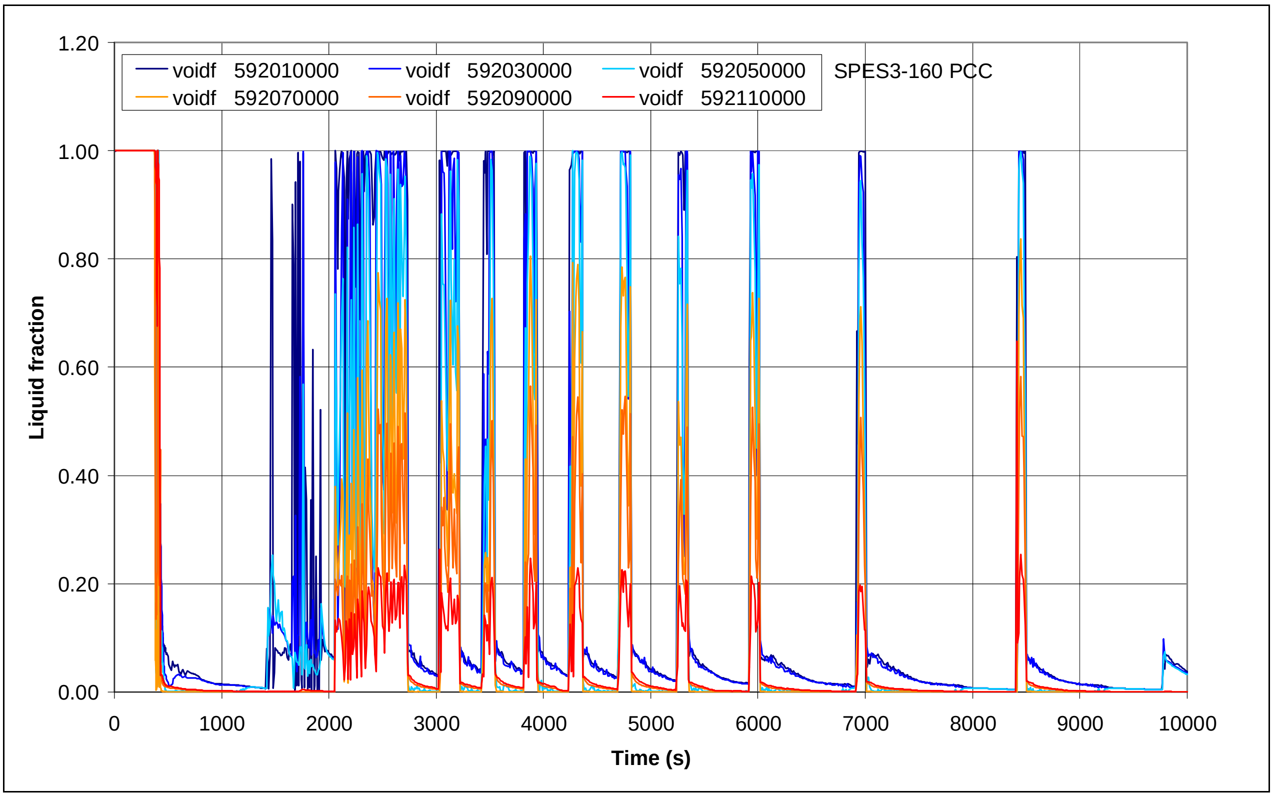


Fig.4.69 – SPES3-160 PCC liquid void fraction

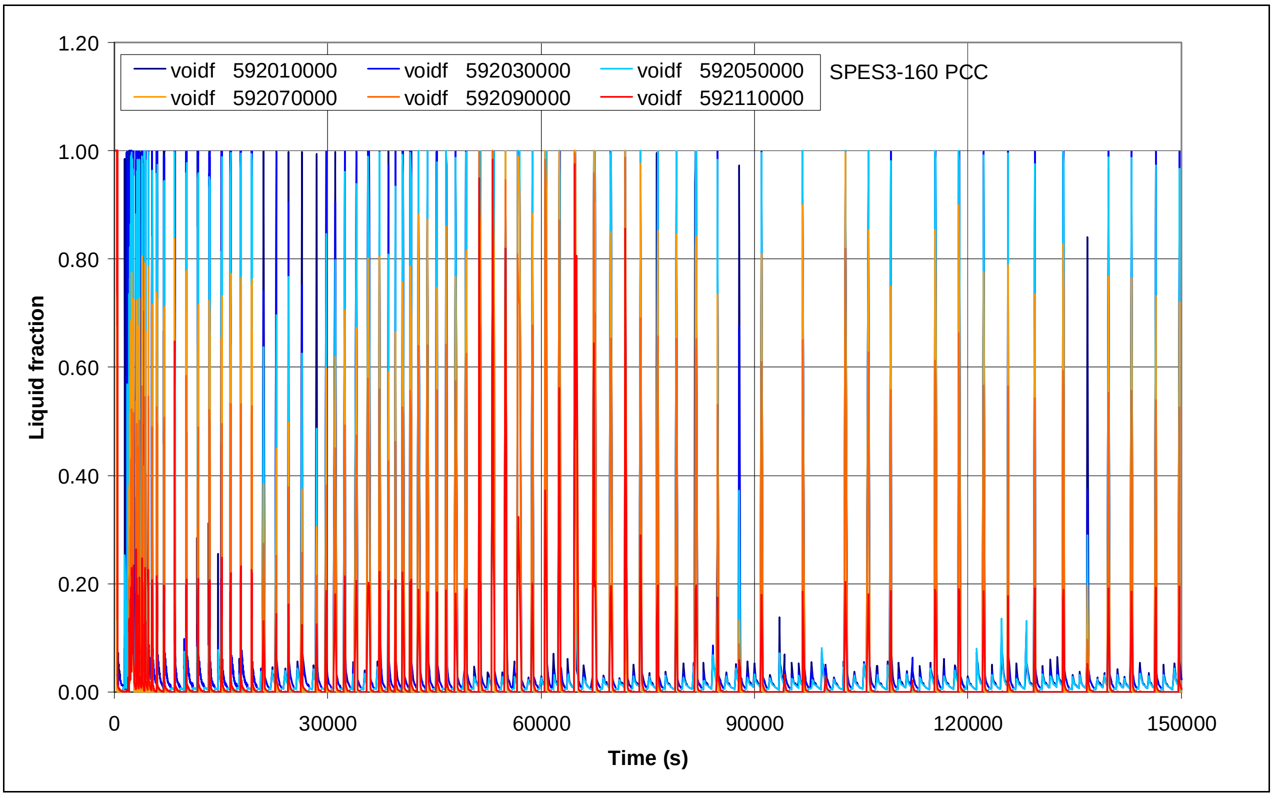


Fig.4.70 – SPES3-160 LGMS mass

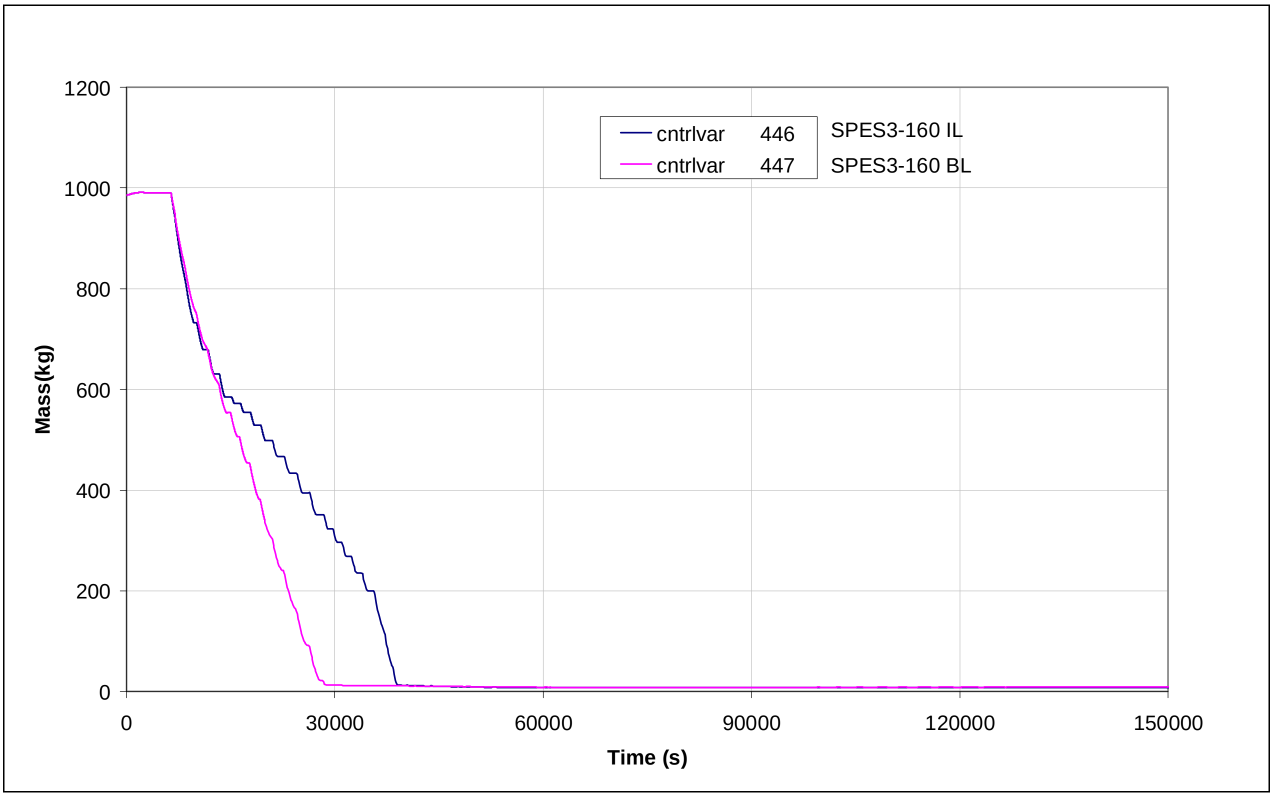


Fig.4.71 – SPES3-160 LGMS and DVI pressure (window)

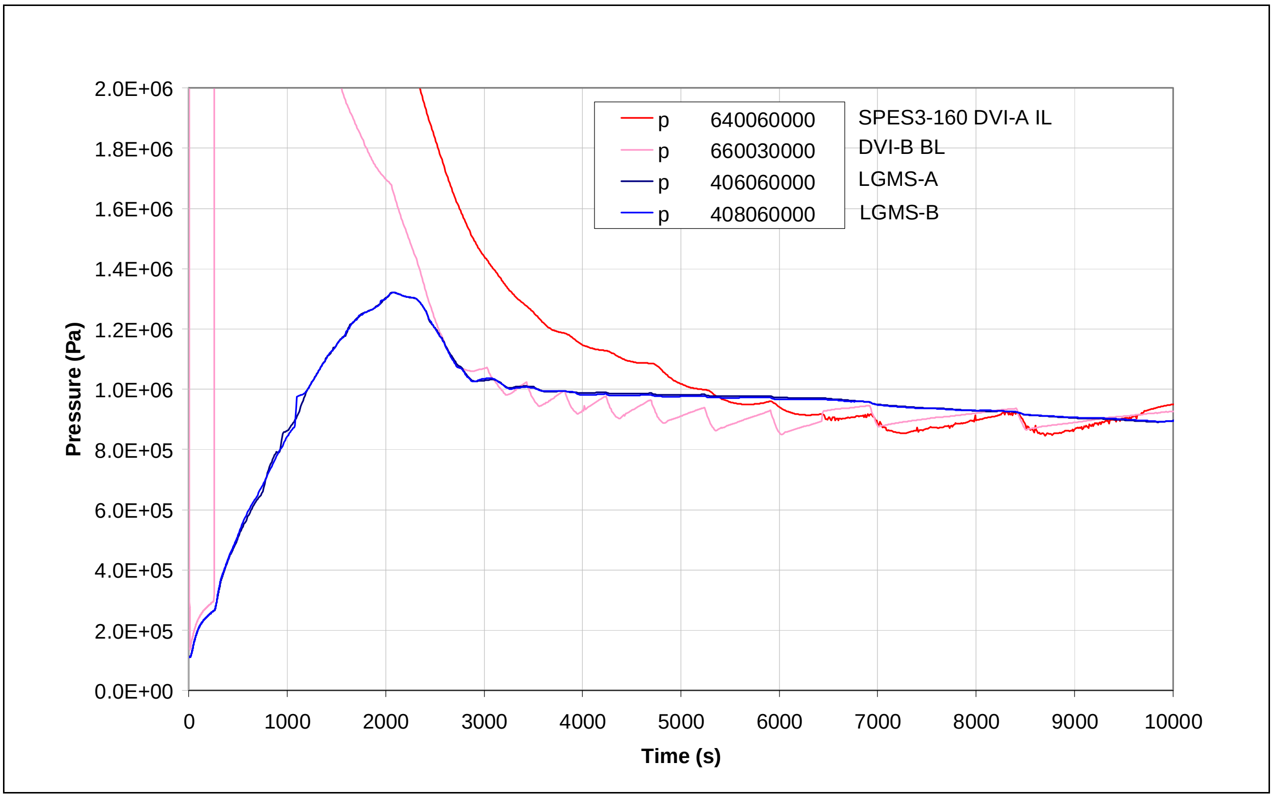
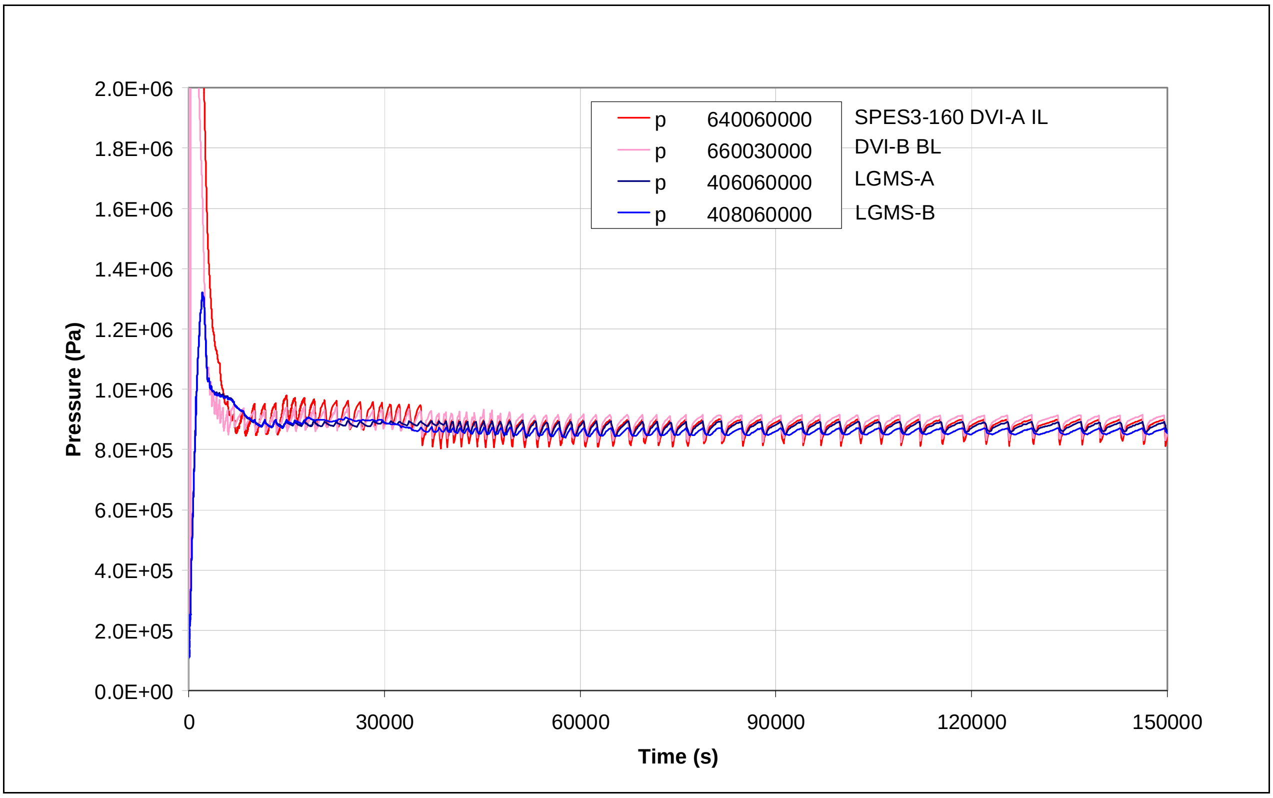


Fig.4.72 – SPES3-160 LGMS and DVI pressure (window)



5. BDBE DVI LINE DEG BREAK SENSITIVITY ANALYSES: SPES3-159, 162, 158 AND SPES3-163, 164, 165, 166.

On the basis of outcomes of the detailed analyses of SPES3-160 case (Chapter 4.), it was necessary to conduct further investigations on system behaviour under the BDBE DVI line DEG break postulated conditions, to study how the PCC and ADS Stage-II actuation time affect the system response.

PCC actuation time affects the containment pressure peak and ADS Stage-II affects primary and containment system pressure equalization and water back-flow from RC to RPV.

Sensitivity cases SPES3-159, 162 and 158 were run with the characteristics reported in Tab.5. 1. SPES3-160 is included for comparison. Two cases were studied by anticipating PCC actuation time (0 s and 1000 s delay on LM-signal) and a case was investigated with ADS Stage-II intervention anticipated to the low LGMS mass signal moved to 80% initial mass.

Analyses of these cases put in evidence the limitation of RC to DVI line back-flow due to the presence of an orifice, 1 mm diameter, on the pipe. Further four cases, SPES3-163, 164, 165 and 166 were run, with analogous conditions to SPES3-160, 159, 162 and 158, and with the orifice diameter on the RC to DVI line increased to 6 mm, Tab.5. 2.

5.1 Sensitivity cases: SPES3-159, SPES3-162 and 158

Initial steady conditions for the sensitivity cases are the same as for SPES3-160, Tab.4. 1.

The lists of the transient main events are reported in Tab.5. 2, Tab.5. 3, Tab.5. 4, respectively for cases SPES3-159, SPES3-162 and SPES3-158.

Pictures are reported only for the most important variables. SPES3-160 case is included for comparison.

DW pressure is shown in Fig.5. 1 and Fig.5. 2. Cases SPES3-160 and 162 show the same high pressure peak and cycling PCC operation. Cases SPES3-159 and 158 show more limited pressure peaks and same cycling PCC operation. Reduction of containment pressurization limits PSS pressurization with the negative consequence of lack or insufficient water back-flow from PSS to DW and the negative effect on RPV mass recovery. PSS pressure is shown in Fig.5. 3 and Fig.5. 4.

Fig.5. 5 and Fig.5. 6 show total (two vent pipes) DW to PSS mass flow: in the first phase, steam-air mixture flows from DW to PSS and in the second phase water flows from PSS to DW. Due to anticipated PCC intervention, in cases SPES3-159 and 158, mixture transfer is lower than in cases SPES3-160 and 162 and PSS pressurization is not sufficient to overcome the PSS vent line gravity head. That prevents water back-flow from PSS to DW in case SPES3-159 and limits it in SPES3-158, Fig.5. 5.

PSS mass is shown in Fig.5. 7 where it is possible to observe PSS emptying in cases SPES3-160 and 162. SPES3-162 case does not show non-symmetric behaviour observed in case SPES3-160 (described in Chapter 4.) where PSS-B fills-up again, after emptying.

Water transfer from containment to primary system occurs by LGMS and RC, through the RC to DVI line and the break line (RPV side), when containment pressure overcomes RPV pressure. Fig.5. 8 shows intact loop LGMS mass and Fig.5. 9 LGMS to DVI mass flow. Fig.5. 10 and Fig.5. 11 show mass flow from RC to RPV, respectively through the RC to DVI line (intact loop) and through the DVI break line (RPV side). It is important to note that RPV inlet mass flow through the break line, in the long term, is about ten times greater than that through the RC to DVI line. This shows the orifice on the RC to DVI line is under dimensioned.

Anticipation of ADS Stage-II opening, based on the low LGMS mass signal, allows earlier pressure balance between the primary and containment systems, enhancing RPV water inlet both from LGMS and RC with consequent mass inventory recovery, Fig.5. 12.

Fig.5. 13 and Fig.5. 14 report the heater rod clad surface temperatures at high elevation in the core. All the cases show high temperature excursions and only in SPES3-162 the core is definitively rewetted in about 6000 s, thanks to injection of water from RC.

5.2 Sensitivity cases: SPES3-163, 164, 165 and 166

SPES3 core decay power in the long term is around 50 kW. Mass flow of about 0.02 kg/s is required to remove such power by evaporation and mass flow must be guaranteed through the RC to DVI line, neglecting water inlet through the DVI break line, RPV side. Fig.5. 10 shows that, in cases SPES3-160, 159, 162 and 158, water entering the RPV, through the RC to DVI line, is about one tenth of the required 0.02 kg/s.

The solution of increasing the RC to DVI line orifice diameter was adopted, passing from 1 mm to 6 mm, to guarantee required mass flow under estimated differential pressure of about 200 Pa, suitable to overcome local and distributed pressure drops between RC and DVI line.

Further four sensitivity cases, SPES3-163, 164, 165 and 166, were run, as reported in Tab.5. 1, with the same characteristics as SPES3-160, 159, 162 and 158, but different RC to DVI line orifice diameter, in order to investigate the influence of the orifice size on the transient trend.

Initial steady conditions for the sensitivity cases are the same as for SPES3-160, Tab.4. 1.

The lists of the transient main events are reported in Tab.5. 5, Tab.5. 6, Tab.5. 7, Tab.5. 8, respectively for cases SPES3-163, SPES3-164, SPES3-165 and SPES3-166.

Pictures are reported only for the most important variables.

DW pressure is shown in Fig.5. 15 and Fig.5. 16. Cases SPES3-163 and 165 show the same high pressure peak and cycling PCC operation. Cases SPES3-164 and 166 show more limited pressure peak and same PCC cycling operation. As for cases SPES3-159 and 158, lower containment pressurization limits PSS pressurization with the negative consequence of insufficient back-flow from PSS to DW and lower RPV mass make-up. PSS pressure is shown in Fig.5. 17 and Fig.5. 18.

Fig.5. 19 and Fig.5. 20 show total (two vent pipes) DW to PSS mass flow: In the first phase steam-air mixture flows from the DW to the PSS and in the second phase water flows from PSS to DW. Due to anticipated PCC intervention, in SPES3-164 and 166, such mixture transfer is lower than in cases SPES3-163 and 165 and PSS pressurization is not sufficient to overcome the PSS vent line gravity head. Similarly to cases SPES3-159 and 158, this almost prevents back-flow from PSS to DW in case SPES3-164 and limits it in SPES3-166.

PSS mass is shown in Fig.5. 21, where it is possible to observe the emptying in cases SPES3-163 and SPES3-165.

Water transfer from containment to primary system occurs by LGMS and RC, through the RC to DVI line and the break line (RPV side), when containment pressure overcomes RPV pressure. Fig.5. 22 shows intact loop LGMS mass and Fig.5. 23 LGMS to DVI mass flow. Fig.5. 24 and Fig.5. 25 show mass flow from RC to RPV, respectively through the RC to DVI line (intact loop) and through the DVI break line (RPV side). Fig.5. 24 clearly put in evidence the positive effect of the orifice size increase on the RC to DVI line that allows to have required RPV inlet mass flow of at least 0.02 kg/s, suitable to remove decay power.

Anticipation of ADS Stage-II opening, based on the low LGMS mass signal, allows earlier pressure balance between primary and containment systems, enhancing RPV water inlet both from LGMS and RC with consequent mass inventory recovery, Fig.5. 26.

Fig.5. 27 and Fig.5. 28 report the heater rod clad temperatures at high elevation in the core. All the cases show high temperature excursions and in case SPES3-165, as in case SPES3-162, core is rewetted in about 6000 s. Thanks to enhanced injection of water from RC, also the other cases are definitively rewetted after

longer times, up to 50000 s, anyway undergoing very high clad temperatures, up to 1200 K in case SPES3-164.

The improvement in accident mitigation is clearly reached by enhancing water transfer from RC to RPV through the RC to DVI line.

5.3 IRIS plant sensitivity cases on the ADS Stage-II actuation time

Some sensitivity cases were run in the past, on the IRIS nodalization, by FER at Zagreb University. The nodalization used for the analyses is not the last one, as come out of optimization process described in [18], anyway the results provide important information on influence of ADS Stage-II actuation delay on LM-signal.

Four cases were analysed: no delay, half an hour delay, one hour delay and two hours delay. The results are overlapped and showed in the figures.

Fig.5. 29 and Fig.5. 30 report RPV mass and core mass, respectively. All the delayed cases undergo long period of low mass and only in case where ADS Stage-II is actuated at LM-signal, mass recovery is anticipated.

Heater rod clad surface temperatures at top elevation in the core are shown in Fig.5. 31 and, accordingly to low RPV mass, show high peaks of temperature. The 0.5 hour delay case shows high temperature even after core rewetting. Such behaviour is not explained here due to lack of further data and information.

DW pressure is shown in Fig.5. 32. It shows PCC actuation is at reaching of the 0.9 MPa containment pressure set point and maintained between 0.8 and 0.9 MPa. No delay on PCC actuation is imposed, conditioned to containment refuelling cavity fill-up. ADS Stage-II actuation anticipation decreases the slope of pressure increase during the blowdown phase.

LGMS mass is shown in Fig.5. 33.

Fig.5. 34 and Fig.5. 35 report RC to DVI line mass flow and break mass flow (RPV side), respectively. They show that water back-flow from containment to RPV occurs both through the RC to DVI line and through the break line (RPV side).

5.4 Cases conclusions

The sensitivity runs on PCC, ADS Stage-II actuation delay and RC to DVI line orifice size, performed on SPES3 nodalization, showed the importance of such system intervention on the BDBE DVI line DEG break accident recovery.

PCC actuation delay affects DW and PSS pressurization, conditioning later PSS to DW water injection. Limiting the DW pressure peak, with anticipated PCC intervention, affects the transient negatively.

Anticipation of ADS Stage-II intervention to 80% LGMS initial mass (compared to the original 20% LGMS mass signal, foreseen in the DBE), is fundamental to cope with the BDBE. It equalises RPV and DW pressure and enhances water back-flow from containment to RPV with mass inventory recovery and core quenching.

The RC to DVI line orifice diameter increase (from 1 mm original size to 6 mm) is required to allow sufficient back-flow from RC, suitable to remove decay power by evaporation.

Tab.5. 1 – BDBE DVI line DEG break sensitivity cases

Case	PCC actuation delay on LM-signal	ADS Stage-II actuation on low LGMS mass signal	RC to DVI line orifice diameter
SPES3-160	1800 s	20%	1 mm
SPES3-159	0 s	20%	1 mm
SPES3-162	1800 s	80%	1 mm
SPES3-158	1000 s	20%	1 mm
SPES3-163	1800 s	20%	6 mm
SPES3-164	0 s	20%	6 mm
SPES3-165	1800 s	80%	6 mm
SPES3-166	1000 s	20%	6 mm

Tab.5. 2 – SPES3-159 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	SPES3-159		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.36	16.96e6 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.36		
7	MFIV-A,B,C closure start	33.36		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.36		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.36		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.86	9e6 Pa	
11	SG-A high pressure reached	46.86		
12	SG-B high pressure reached	48.30		
13	SG-C high pressure reached	47.86		
14	Secondary loop pressure peak	69 70 72	111e5 Pa A 114e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP costdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.65	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.65		
21	ADS Stage-I opening start (3 trains)	253.65		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	265	1.364 kg/s	ST 0.470 kg/s; DT 0.894 kg/s
23	ADS Stage-I second peak flow (3 trains)	329	2.003 kg/s	ST 0.663 kg/s; DT 1.340 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.65		EBT valve stroke 15 s
25	Break flow peak (Containment side)	273		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	482		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	308		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	1036.54	0.9 MPa	
31	PCC actuation	1036.54		LM-signal + 0 s + P cont > 0.9 MPa
Low DP RPV-Containment signal,PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	1590	9.85e5 Pa	
33	DW pressure lower than PSS pressure	NO		
34	Water starts to flow from PSS to DW	NO		
35	RC level at DVI elevation	21490		
36	EBT-A empty (intact loop)	3030		
37	RC full of water	NO		max. water level 10.5 m at 45790 s
38	**Low DP RV-Containment**	6076.99	50e3 Pa	
39	LGMSA/B valve opening start	6076.99		LM + low DP RV-cont. LGMS valve stroke 2 s.
40	RC to DVI line valve opening	6076.99		RC to DVI valve stroke 2 s.
41	LGMS-B starts to inject into RC through DVI broken loop	6077		
42	LGMS-A starts to inject into RV through DVI intact loop	6077		
43	QT fill-up starts from DW connection	NO		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
44	**Low LGMS mass**	27027.19	20% mass (198 kg)	LGMS B (broken loop)
45		34789.0	20% mass (198 kg)	LGMS A (intact loop)
46	ADS Stage-II start opening	34789.0		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
47	Water starts to flow from RC to DVI-A	34790		
48	Containment and RV pressure equalization	34990		
49	LGMS-B empty (broken loop)	40490		
50	LGMS-A empty (intact loop)	46590		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		44.67 kW	Average between 100000 s and 150000 s
53	PCC removed power		14.34 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Tab.5. 3 – SPES3-162 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	SPES3-162		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.36	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.36		
7	MFIV-A,B,C closure start	33.36		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.36		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.36		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.86	9e6 Pa	
11	SG-A high pressure reached	46.86		
12	SG-B high pressure reached	48.30		
13	SG-C high pressure reached	47.86		
14	Secondary loop pressure peak	71 71 72	111e5 Pa A 114e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.65	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.65		
21	ADS Stage-I opening start (3 trains)	253.65		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	264	1.364 kg/s	ST 0.470 kg/s; DT 0.894 kg/s
23	ADS Stage-I second peak flow (3 trains)	328	2.003 kg/s	ST 0.663 kg/s; DT 1.340 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.65		EBT valve stroke 15 s
25	Break flow peak (Containment side)	274		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	482		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	293		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	1001.89	0.9 MPa	
31	PCC actuation	2053.66		LM-signal + 1800 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	2070	13.4e5 Pa	
33	DW pressure lower than PSS pressure	2100		
34	Water starts to flow from PSS to DW	2290		
35	RC level at DVI elevation	2740		
36	EBT-A empty (intact loop)	3030		
37	RC full of water	3300		
38	**Low DP RV-Containment**	6439.05	50e3 Pa	
39	LGMSA/B valve opening start	6439.05		LM + low DP RV-cont. LGMS valve stroke 2 s.
40	RC to DVI line valve opening	6439.05		RC to DVI valve stroke 2 s.
41	LGMS-B starts to inject into RC through DVI broken loop	6440		
42	LGMS-A starts to inject into RV through DVI intact loop	6440		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
43	**Low LGMS mass**	8822.73	80% mass (788 kg)	LGMS B (broken loop)
44		9203.59	80% mass (788 kg)	LGMS A (intact loop)
45	ADS Stage-II start opening	9203.59		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
46	Water starts to flow from RC to DVI-A	9210		
47	Containment and RV pressure equalization	9310		
48	QT fill-up starts from DW connection	25490		
49	LGMS-B empty (broken loop)	28590		
50	LGMS-A empty (intact loop)	29590		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		46.20 kW	Average between 100000 s and 150000 s
53	PCC removed power		25.53 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Tab.5. 4 – SPES3-158 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	**SPES3-158**		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.36	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.36		
7	MFIV-A,B,C closure start	33.36		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.36		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.36		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.86	9e6 Pa	
11	SG-A high pressure reached	46.86		
12	SG-B high pressure reached	48.30		
13	SG-C high pressure reached	47.86		
14	Secondary loop pressure peak	69 71 72	111e5 Pa A 114e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.65	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.65		
21	ADS Stage-I opening start (3 trains)	253.65		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	265	1.364 kg/s	ST 0.470 kg/s; DT 0.894 kg/s
23	ADS Stage-I second peak flow (3 trains)	328	2.003 kg/s	ST 0.663 kg/s; DT 1.340 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.65		EBT valve stroke 15 s
25	Break flow peak (Containment side)	274		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	311		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	308		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	1001.89	0.9 MPa	
31	PCC actuation	1253.65		LM-signal + 1000 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	1410	10.7e5 Pa	
33	DW pressure lower than PSS pressure	1810		
34	Water starts to flow from PSS to DW	2560		cyclic injection until 5710 s
35	EBT-A empty (intact loop)	3030		
36	**Low DP RV-Containment**	6152.24	50e3 Pa	
37	LGMSA/B valve opening start	6152.24		LM + low DP RV-cont. LGMS valve stroke 2 s.
38	RC to DVI line valve opening	6152.24		RC to DVI valve stroke 2 s.
39	LGMS-B starts to inject into RC through DVI broken loop	6140		
40	LGMS-A starts to inject into RV through DVI intact loop	6140		
41	RC level at DVI elevation	12980		
42	RC full of water	34490		
43	QT fill-up starts from DW connection	NO		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
44	**Low LGMS mass**	32439.27	20% mass (198 kg)	LGMS B (broken loop)
45		36007.66	20% mass (198 kg)	LGMS A (intact loop)
46	ADS Stage-II start opening	36007.66		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
47	Water starts to flow from RC to DVI-A	35790		
48	Containment and RV pressure equalization	36190		
49	LGMS-B empty (broken loop)	41790		
50	LGMS-A empty (intact loop)	44790		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		45.29 kW	Average between 100000 s and 150000 s
53	PCC removed power		27.23 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Tab.5. 5 – SPES3-163 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	SPES3-163		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.40	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.40		
7	MFIV-A,B,C closure start	33.40		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.40		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.40		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.90	9e6 Pa	
11	SG-A high pressure reached	46.90		
12	SG-B high pressure reached	48.34		
13	SG-C high pressure reached	47.90		
14	Secondary loop pressure peak	70 70 71	111e5 Pa A 113e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.69	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.69		
21	ADS Stage-I opening start (3 trains)	253.69		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	264	1.365 kg/s	ST 0.470 kg/s; DT 0.895 kg/s
23	ADS Stage-I second peak flow (3 trains)	329	2.013 kg/s	ST 0.663 kg/s; DT 1.350 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.69		EBT valve stroke 15 s
25	Break flow peak (Containment side)	273		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	312		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	307		
29	EBT-B empty (broken loop)	550		550 s almost empty (760 s completely empty)
30	High containment pressure signal	966.48	0.9 MPa	
31	PCC actuation	2053.69		LM-signal + 1800 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	2060	13.4e5 Pa	
33	DW pressure lower than PSS pressure	2120		
34	Water starts to flow from PSS to DW	2270		cyclic injection until 4320 s
35	RC level at DVI elevation	2730		
36	EBT-A empty (intact loop)	3030		
37	RC full of water	3310		
38	**Low DP RV-Containment**	6328.76	50e3 Pa	
39	LGMSA/B valve opening start	6328.76		LM + low DP RV-cont. LGMS valve stroke 2 s.
40	RC to DVI line valve opening	6328.76		RC to DVI valve stroke 2 s.
41	LGMS-B starts to inject into RC through DVI broken loop	6329		
42	LGMS-A starts to inject into RV through DVI intact loop	6329		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
43	**Low LGMS mass**	23924.56	20% mass (198 kg)	LGMS B (broken loop)
44		29206.56	20% mass (198 kg)	LGMS A (intact loop)
45	ADS Stage-II start opening	29206.56		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
46	Water starts to flow from RC to DVI-A	28990		
47	Containment and RV pressure equalization	29240		
48	QT fill-up starts from DW connection	29240		
49	LGMS-B empty (broken loop)	32390		
50	LGMS-A empty (intact loop)	34240		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		46.27 kW	Average between 100000 s and 150000 s
53	PCC removed power		27.95 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Tab.5. 6 – SPES3-164 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	**SPES3-164**		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.40	16.96e6 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.40		
7	MFIV-A,B,C closure start	33.40		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.40		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.40		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.90	9e6 Pa	
11	SG-A high pressure reached	46.90		
12	SG-B high pressure reached	48.34		
13	SG-C high pressure reached	47.90		
14	Secondary loop pressure peak	70 70 72	111e5 Pa A 114e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.69	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.69		
21	ADS Stage-I opening start (3 trains)	253.69		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	264	1.365 kg/s	ST 0.470 kg/s; DT 0.895 kg/s
23	ADS Stage-I second peak flow (3 trains)	329	2.013 kg/s	ST 0.663 kg/s; DT 1.350 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.69		EBT valve stroke 15 s
25	Break flow peak (Containment side)	273		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	483		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	306		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	984.20	0.9 MPa	
31	PCC actuation	1158.19		LM-signal + 0 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	1560	9.42e5 Pa	
33	DW pressure lower than PSS pressure	1320, 1850		lower than PSS-B, PSS-A
34	Water starts to flow from PSS to DW	NO		
35	RC level at DVI elevation	21490		
36	EBT-A empty (intact loop)	3030		
37	RC full of water	NO		max. water level 10.5 m at 45790 s
38	**Low DP RV-Containment**	6513.3	50e3 Pa	
39	LGMSA/B valve opening start	6513.3		LM + low DP RV-cont. LGMS valve stroke 2 s.
40	RC to DVI line valve opening	6513.3		RC to DVI valve stroke 2 s.
41	LGMS-B starts to inject into RC through DVI broken loop	6500		
42	LGMS-A starts to inject into RV through DVI intact loop	6500		
43	QT fill-up starts from DW connection	NO		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
44	**Low LGMS mass**	30365.69	20% mass (198 kg)	LGMS B (broken loop)
45		47731.28	20% mass (198 kg)	LGMS A (intact loop)
46	ADS Stage-II start opening	47731.28		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
47	Water starts to flow from RC to DVI-A	46990		
48	Containment and RV pressure equalization	47590		
49	LGMS-B empty (broken loop)	48240		
50	LGMS-A empty (intact loop)	61790		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		44.21 kW	Average between 100000 s and 150000 s
53	PCC removed power		29.84 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Tab.5. 7 – SPES3-165 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	SPES3-165		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.36	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.36		
7	MFIV-A,B,C closure start	33.36		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.36		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.36		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.86	9e6 Pa	
11	SG-A high pressure reached	46.86		
12	SG-B high pressure reached	48.30		
13	SG-C high pressure reached	47.86		
14	Secondary loop pressure peak	70 70 72	111e5 Pa A 114e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.65	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.65		
21	ADS Stage-I opening start (3 trains)	253.65		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	264	1.364 kg/s	ST 0.470 kg/s; DT 0.894 kg/s
23	ADS Stage-I second peak flow (3 trains)	329	2.003 kg/s	ST 0.663 kg/s; DT 1.340 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.65		EBT valve stroke 15 s
25	Break flow peak (Containment side)	273		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	483		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	293		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	1001.89	0.9 MPa	
31	PCC actuation	2053.66		LM-signal + 1800 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	2060	13.5e5 Pa	
33	DW pressure lower than PSS pressure	2100		
34	Water starts to flow from PSS to DW	2290		
35	RC level at DVI elevation	2740		
36	EBT-A empty (intact loop)	3030		
37	RC full of water	3310		
38	**Low DP RV-Containment**	6439.34	50e3 Pa	
39	LGMSA/B valve opening start	6439.34		LM + low DP RV-cont. LGMS valve stroke 2 s.
40	RC to DVI line valve opening	6439.34		RC to DVI valve stroke 2 s.
41	LGMS-B starts to inject into RC through DVI broken loop	6440		
42	LGMS-A starts to inject into RV through DVI intact loop	6440		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
43	**Low LGMS mass**	9194.73	80% mass (788 kg)	LGMS B (broken loop)
44		8819.97	80% mass (788 kg)	LGMS A (intact loop)
45	ADS Stage-II start opening	9194.73		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
46	Water starts to flow from RC to DVI-A	9200		
47	Containment and RV pressure equalization	9310		
48	LGMS-A empty (intact loop)	23790		
49	LGMS-B empty (broken loop)	30590		
50	QT fill-up starts from DW connection	82990		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		46.26 kW	Average between 100000 s and 150000 s
53	PCC removed power		24.73 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Tab.5. 8 – SPES3-166 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	**SPES3-166**		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Notes**
Break				
1	Break initiation	0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS				
4	Steam-air mixture begins to flow from DW to PSS	15		
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure				
5	**High Containment pressure signal**	33.36	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	33.36		
7	MFIV-A,B,C closure start	33.36		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.36		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	33.36		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.86	9e6 Pa	
11	SG-A high pressure reached	46.86		
12	SG-B high pressure reached	48.30		
13	SG-C high pressure reached	47.86		
14	Secondary loop pressure peak	70 70 71	111e5 Pa A 114e5 Pa B 113e5 Pa C	
Pump coastdown and primary circulation through RI-DC check valves				
15	**Low PRZ water level signal**	136.78	1.189 m	
16	RCP coastdown starts	151.78		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173		
18	Flashing begins at core outlet	257		voidf 110 (core) < 1
LM-Signal: ADS Stage-I and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation				
19	**Low PRZ pressure signal**	253.65	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.65		
21	ADS Stage-I opening start (3 trains)	253.65		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	264	1.364 kg/s	ST 0.470 kg/s; DT 0.894 kg/s
23	ADS Stage-I second peak flow (3 trains)	329	2.003 kg/s	ST 0.663 kg/s; DT 1.340 kg/s. Due to liquid fraction.
24	EBT-A and B valve opening start	253.65		EBT valve stroke 15 s
25	Break flow peak (Containment side)	274		Due to EBT intervention
26	EBT-RV connections uncovered	308, 333		EBT-B, EBT-A
27	Natural circulation interrupted at SGs top	311		Pump inlet uncovered (voidf 176-01 ~0)
28	Core in saturation conditions	307		
29	EBT-B empty (broken loop)	550		550 s almost empty (750 s completely empty)
30	High containment pressure signal	1001.89	0.9 MPa	
31	PCC actuation	1253.65		LM-signal + 1000 s + P cont > 0.9 MPa
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation				
32	Containment pressure peak	1380	10.7e5 Pa	
33	DW pressure lower than PSS pressure	1820		
34	Water starts to flow from PSS to DW	2560		cyclic injection until 5600 s
35	EBT-A empty (intact loop)	3030		
36	**Low DP RV-Containment**	6152.40	50e3 Pa	
37	LGMSA/B valve opening start	6152.40		LM + low DP RV-cont. LGMS valve stroke 2 s.
38	RC to DVI line valve opening	6152.40		RC to DVI valve stroke 2 s.
39	LGMS-B starts to inject into RC through DVI broken loop	6140		
40	LGMS-A starts to inject into RV through DVI intact loop	6140		
41	RC level at DVI elevation	12510		
42	RC full of water	34490		
43	QT fill-up starts from DW connection	NO		
Low LGMS mass signal: ADS Stage-II actuation, reverse flow from containment to RPV				
44	**Low LGMS mass**	29237.3	20% mass (198 kg)	LGMS B (broken loop)
45		36376.17	20% mass (198 kg)	LGMS A (intact loop)
46	ADS Stage-II start opening	36376.17		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
47	Water starts to flow from RC to DVI-A	35990		
48	Containment and RV pressure equalization	36390		
49	LGMS-B empty (broken loop)	41590		
50	LGMS-A empty (intact loop)	44590		
Long Term conditions				
51	Containment and RPV pressure	100000 s to 150000 s	0.8–0.9 MPa	Controlled by PCC
52	Core power		46.32 kW	Average between 100000 s and 150000 s
53	PCC removed power		24.82 kW	Average between 100000 s and 150000 s Core and PCC power unbalance due to heat losses

Fig.5. 1 – SPES3-159, 162, 158 and 160 DW pressure (window)

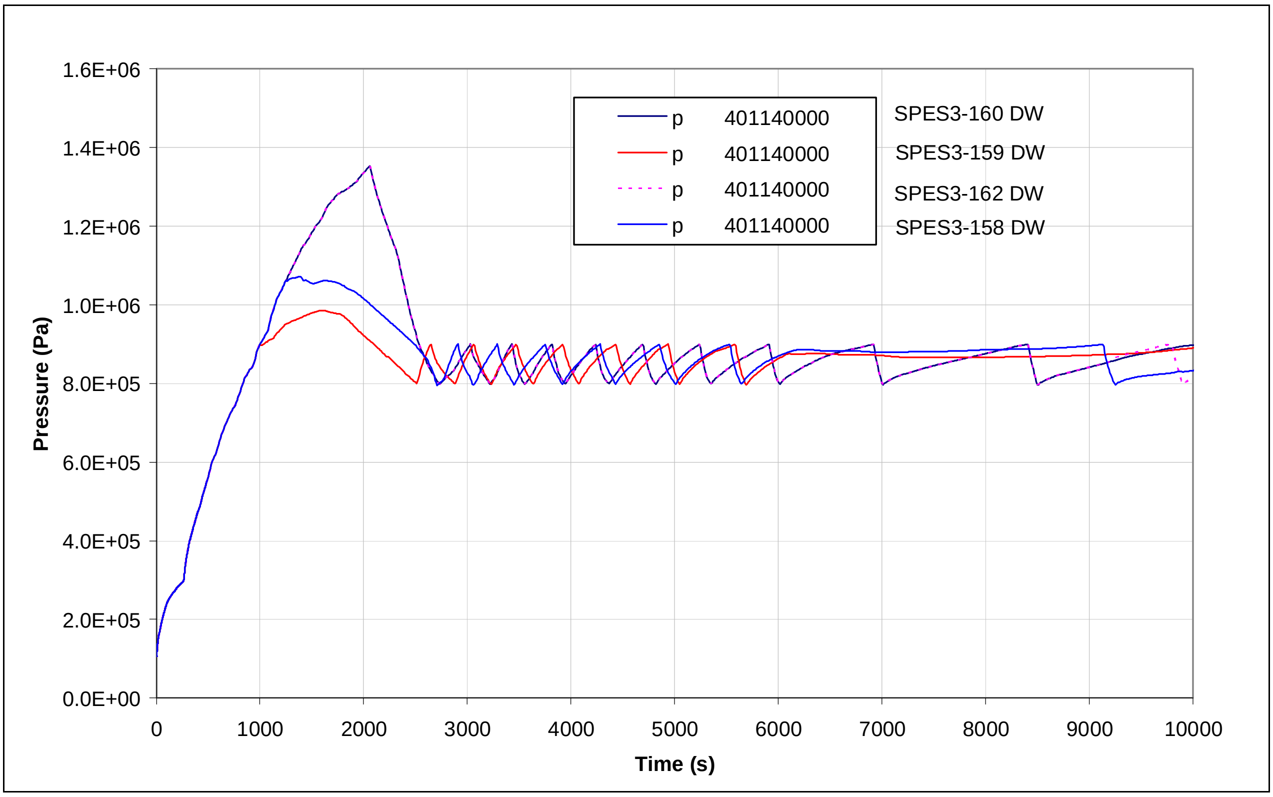


Fig.5. 2 – SPES3-159, 162, 158 and 160 DW pressure

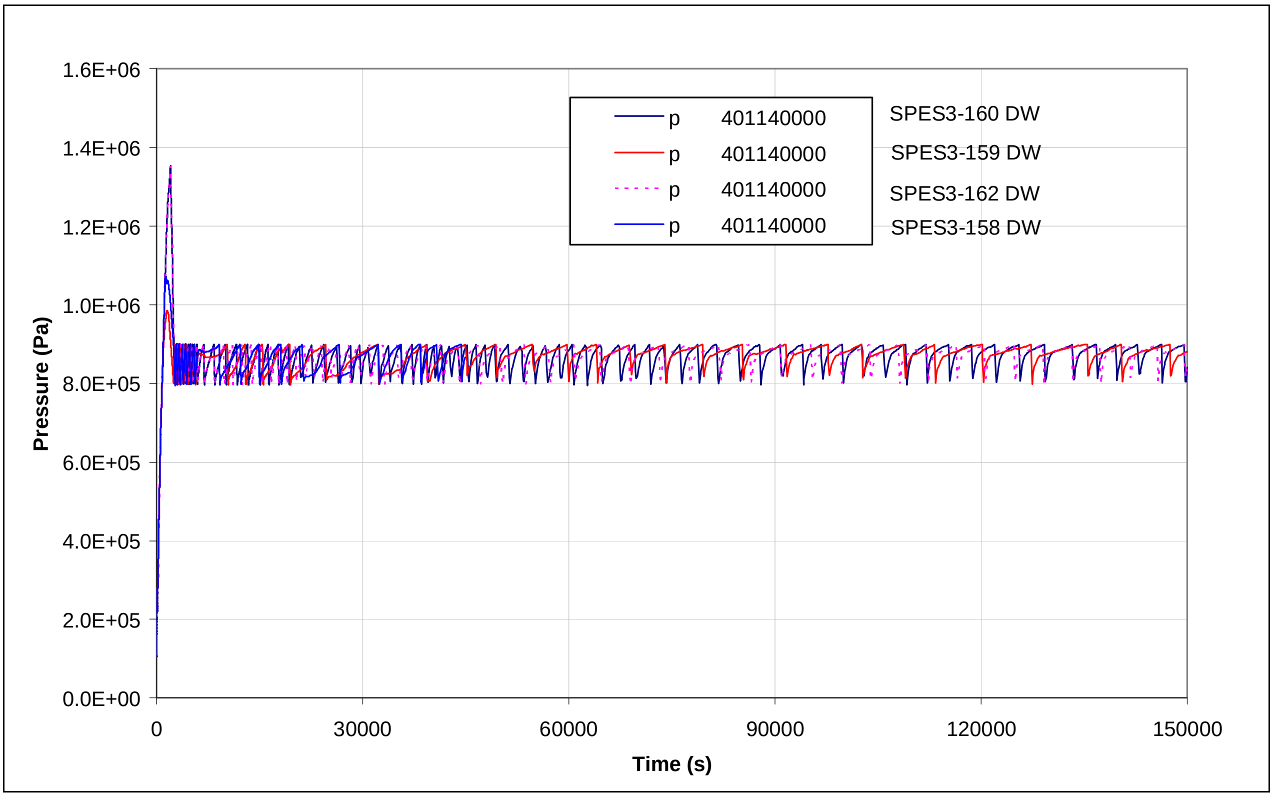


Fig.5. 3 – SPES3-159, 162, 158 and 160 PSS pressure (window)

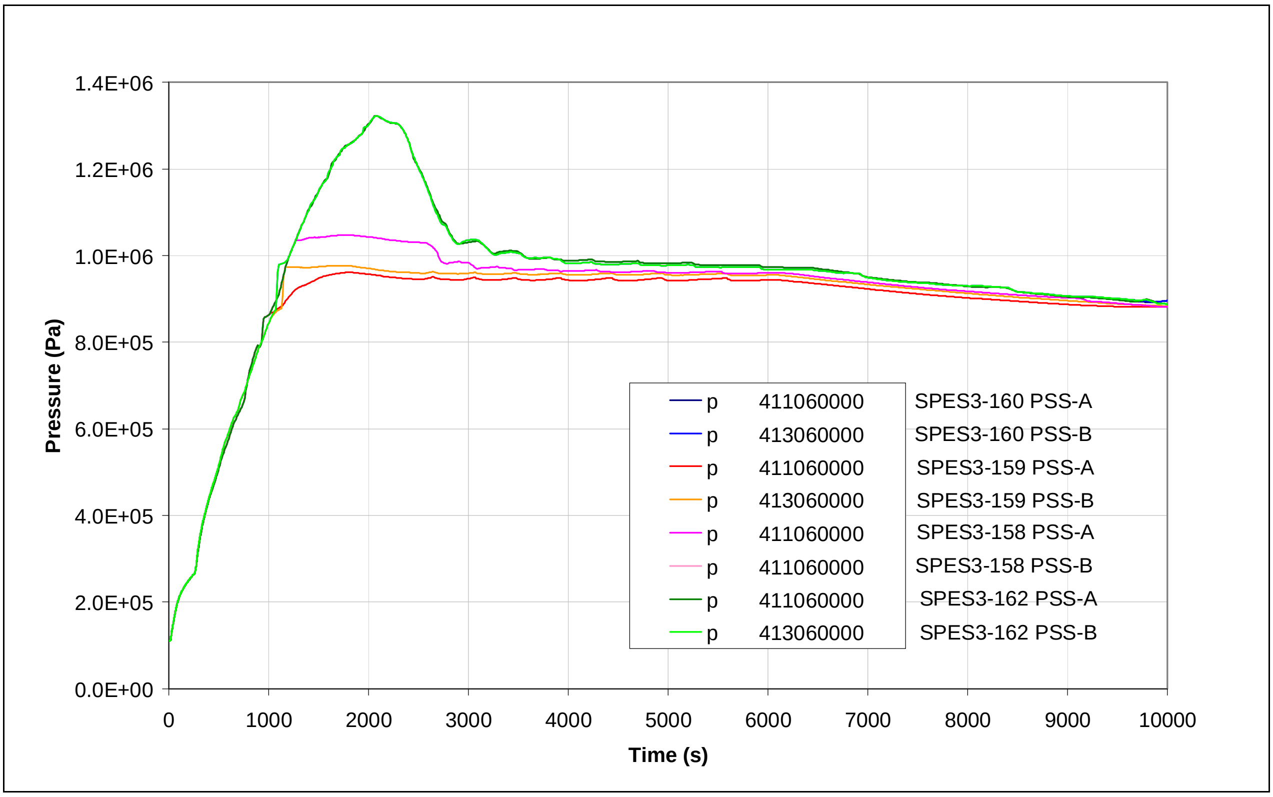


Fig.5. 4 – SPES3-159, 162, 158 and 160 PSS pressure

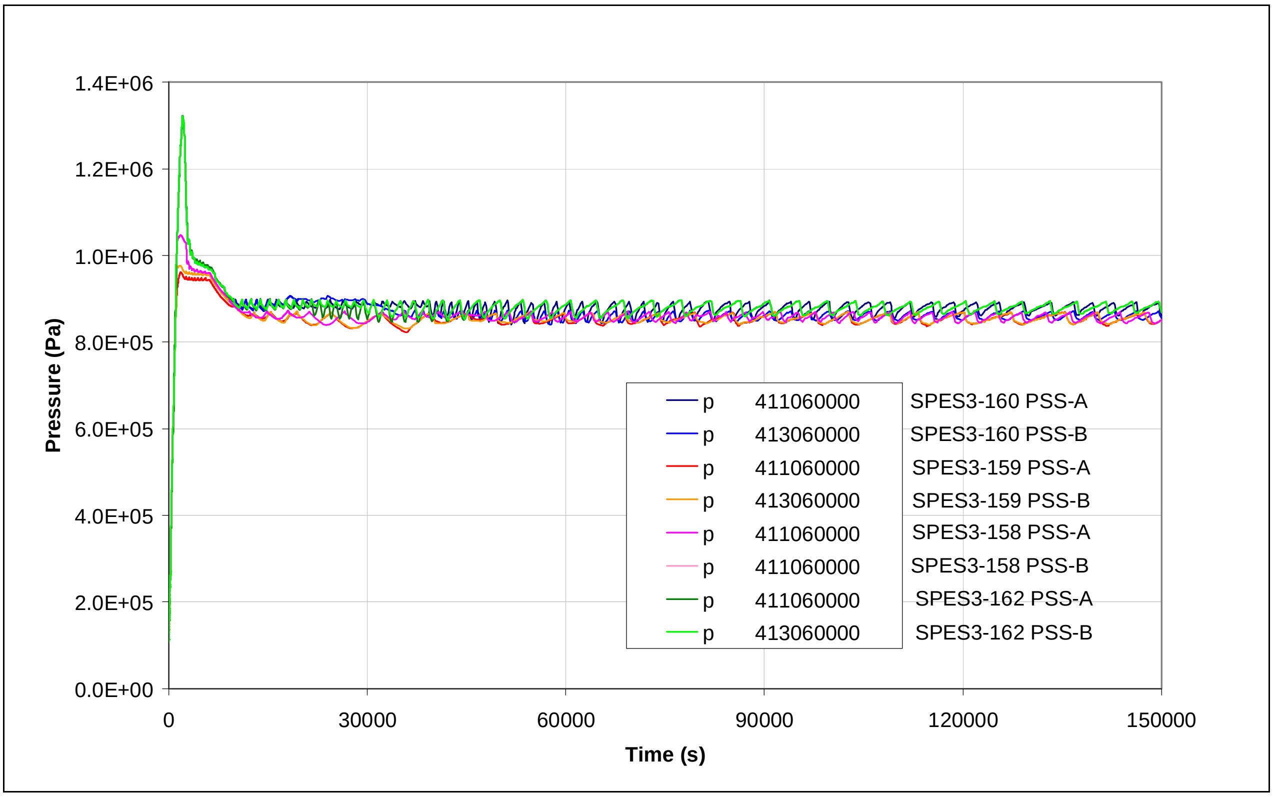


Fig.5. 5 – SPES3-159, 162, 158 and 160 PSS to DW mass flow (window)

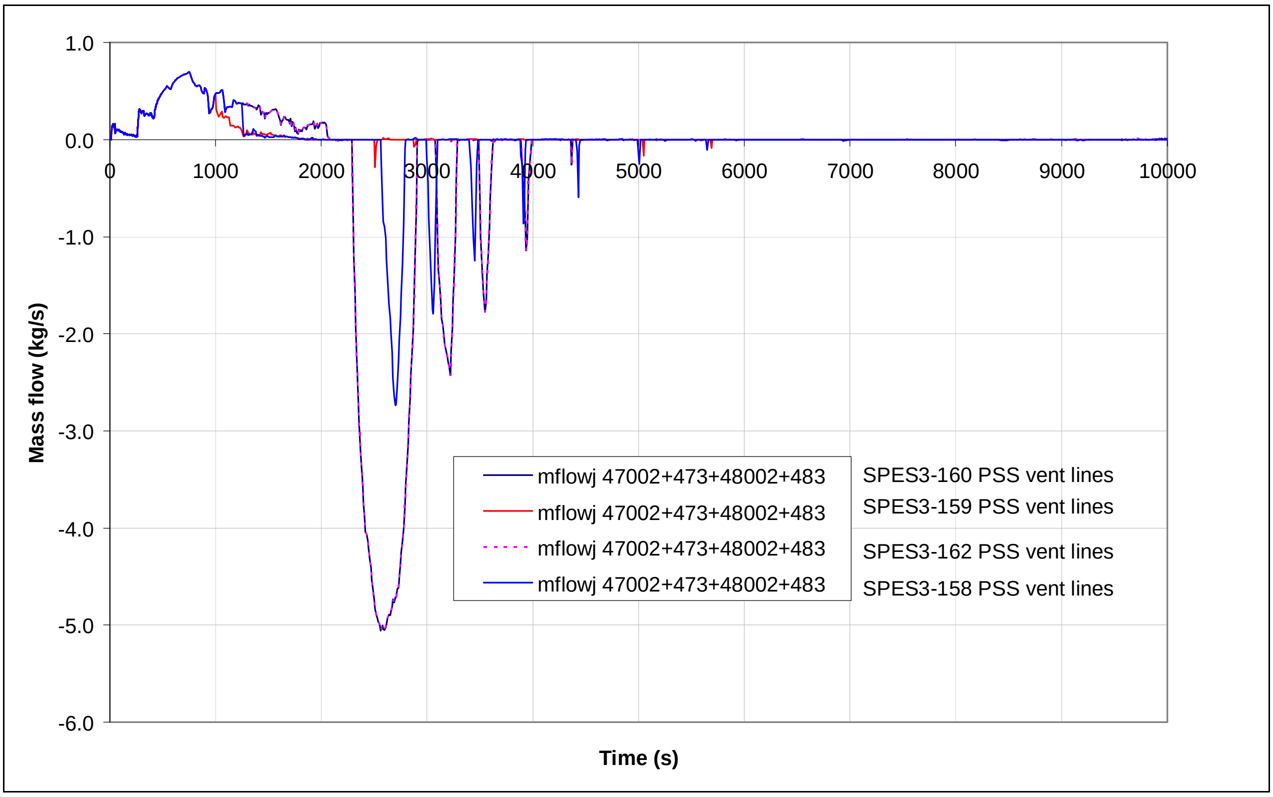


Fig.5. 6 – SPES3-159, 162, 158 and 160 PSS to DW mass flow

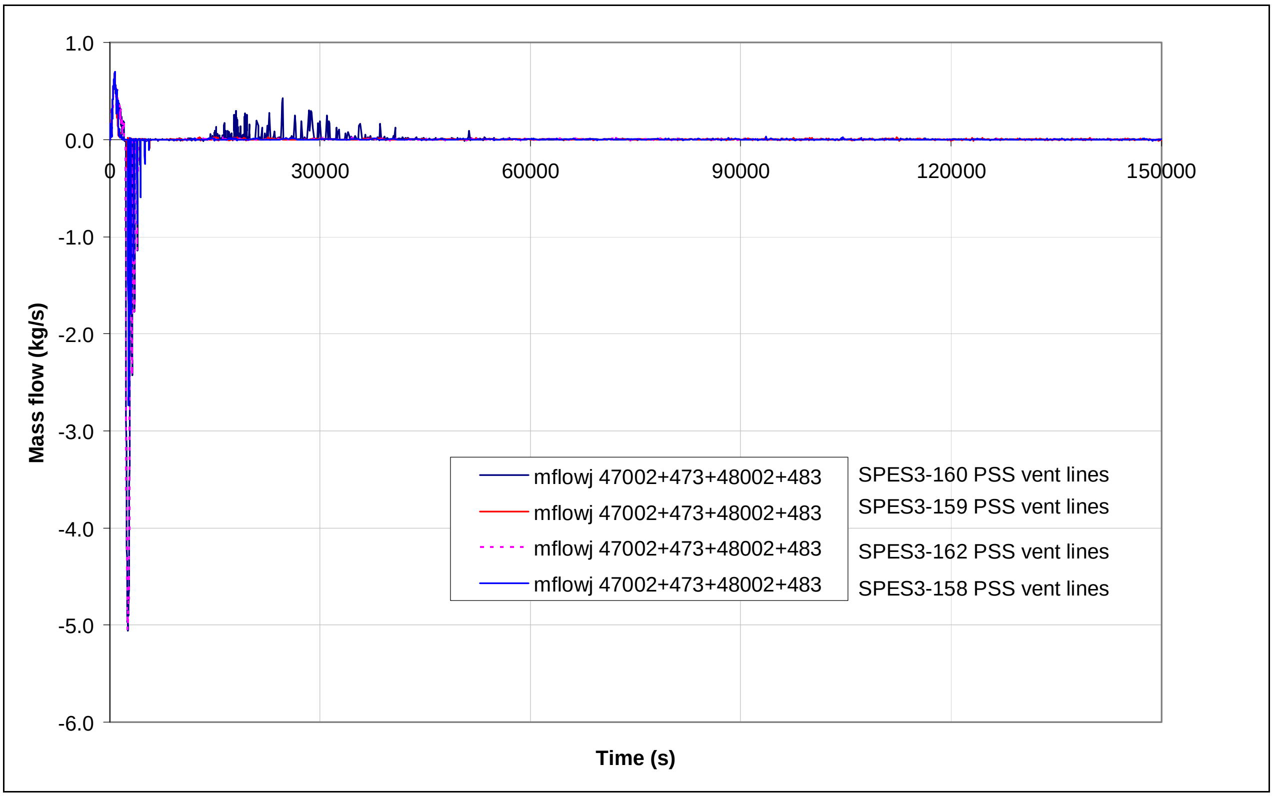


Fig.5. 7 – SPES3-159, 162, 158 and 160 PSS mass

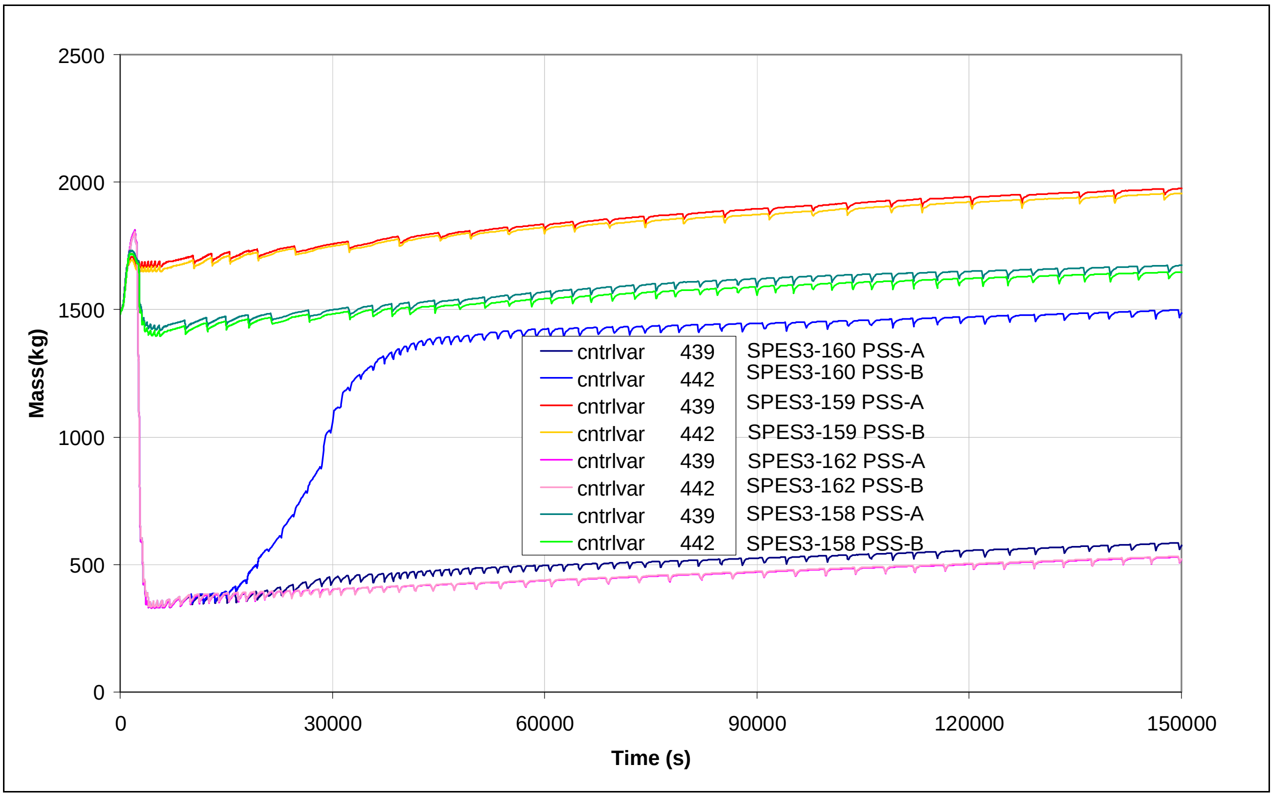


Fig.5. 8 – SPES3-159, 162, 158 and 160 LGMS-A mass (intact loop)

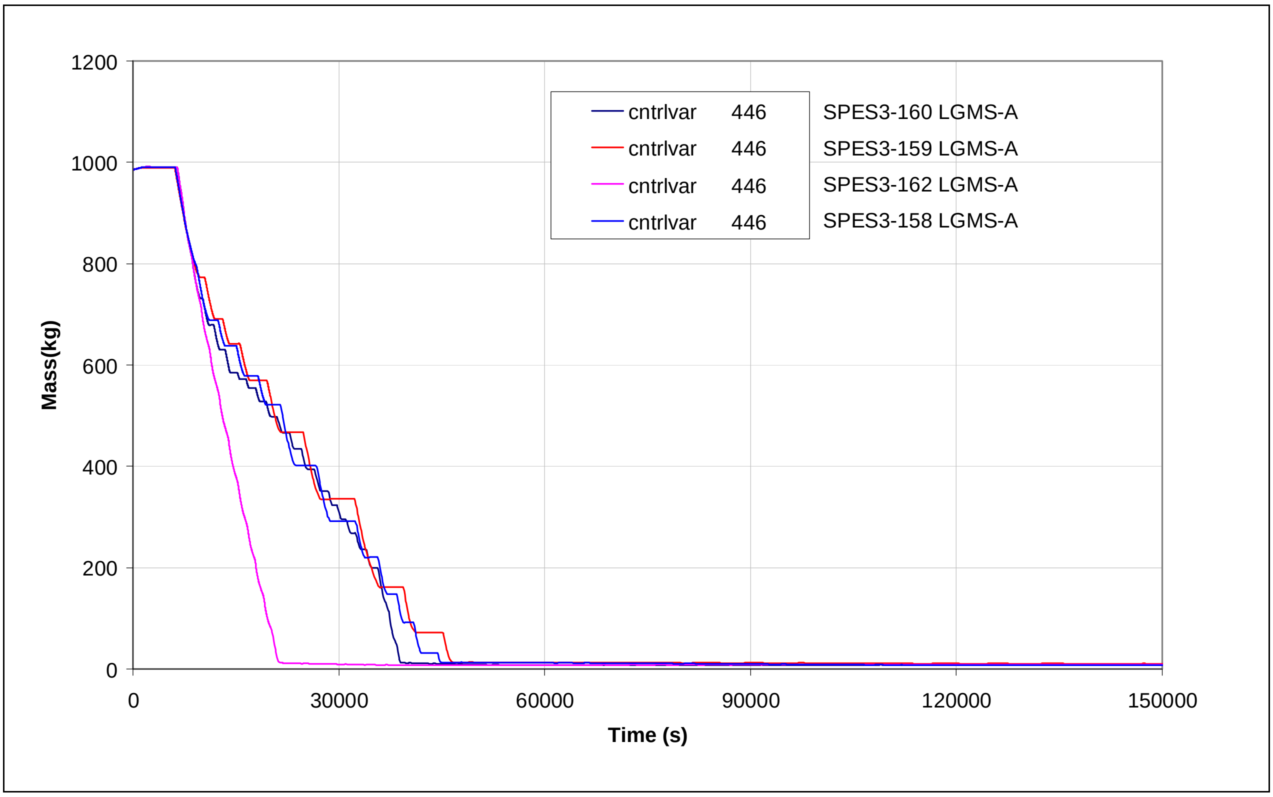


Fig.5. 9 – SPES3-159, 162, 158 and 160 LGMS to DVI line mass flow (intact loop)

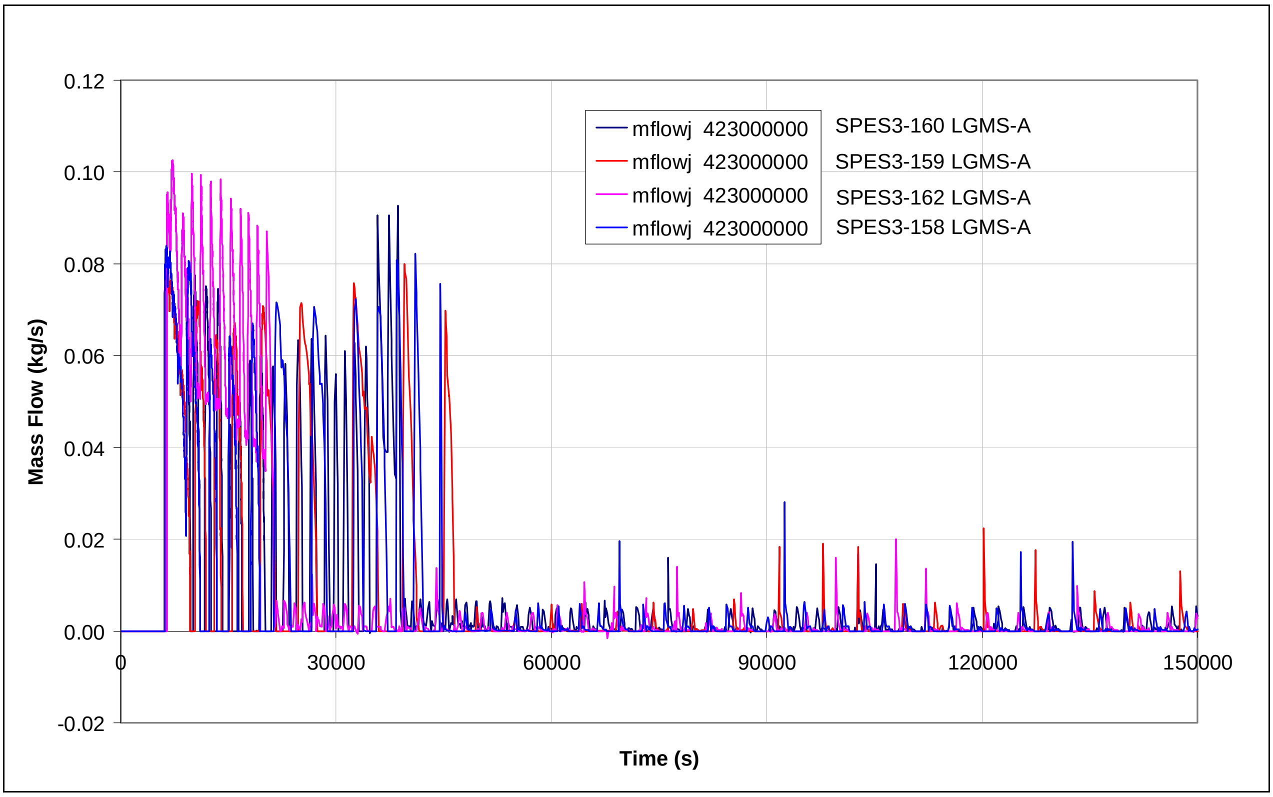


Fig.5. 10 – SPES3-159, 162, 158 and 160 RC to DVI line mass flow (intact loop)

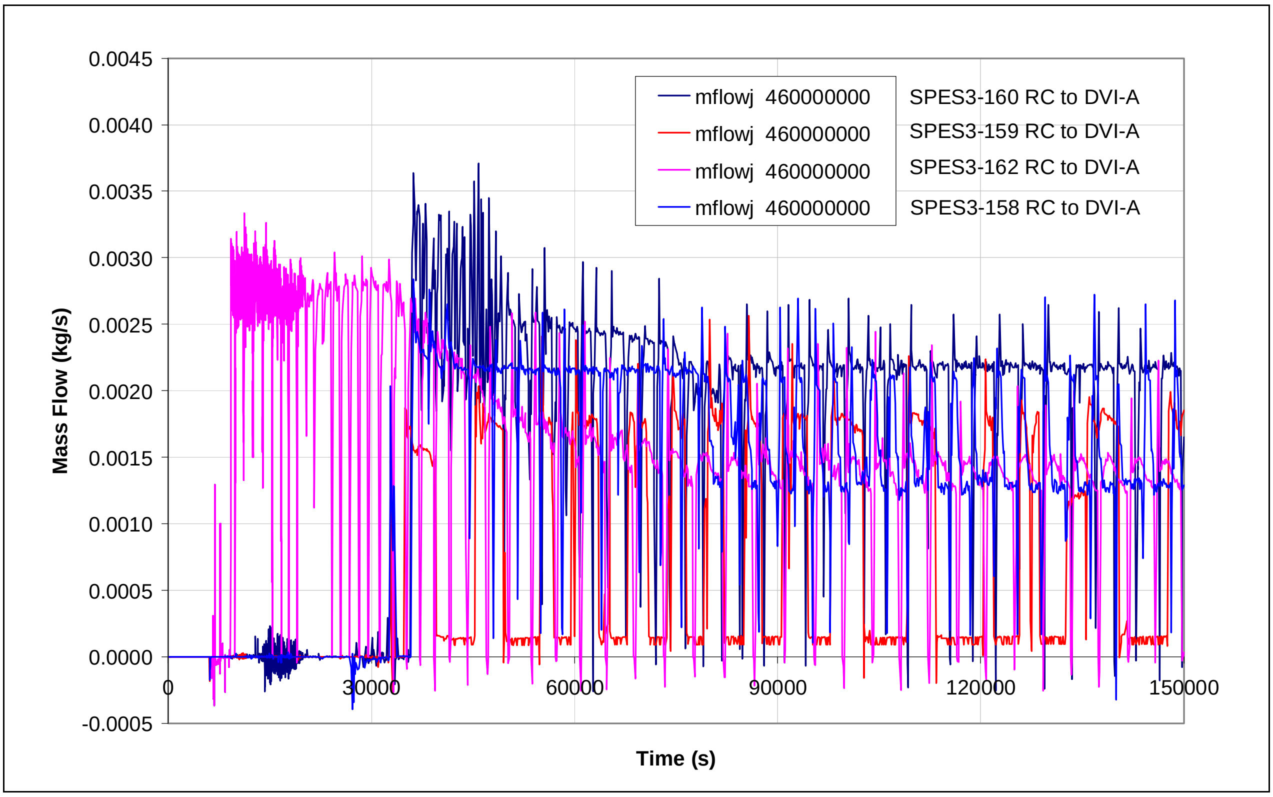


Fig.5. 11 – SPES3-159, 162, 158 and 160 DVI break line (RPV side) mass flow (window)

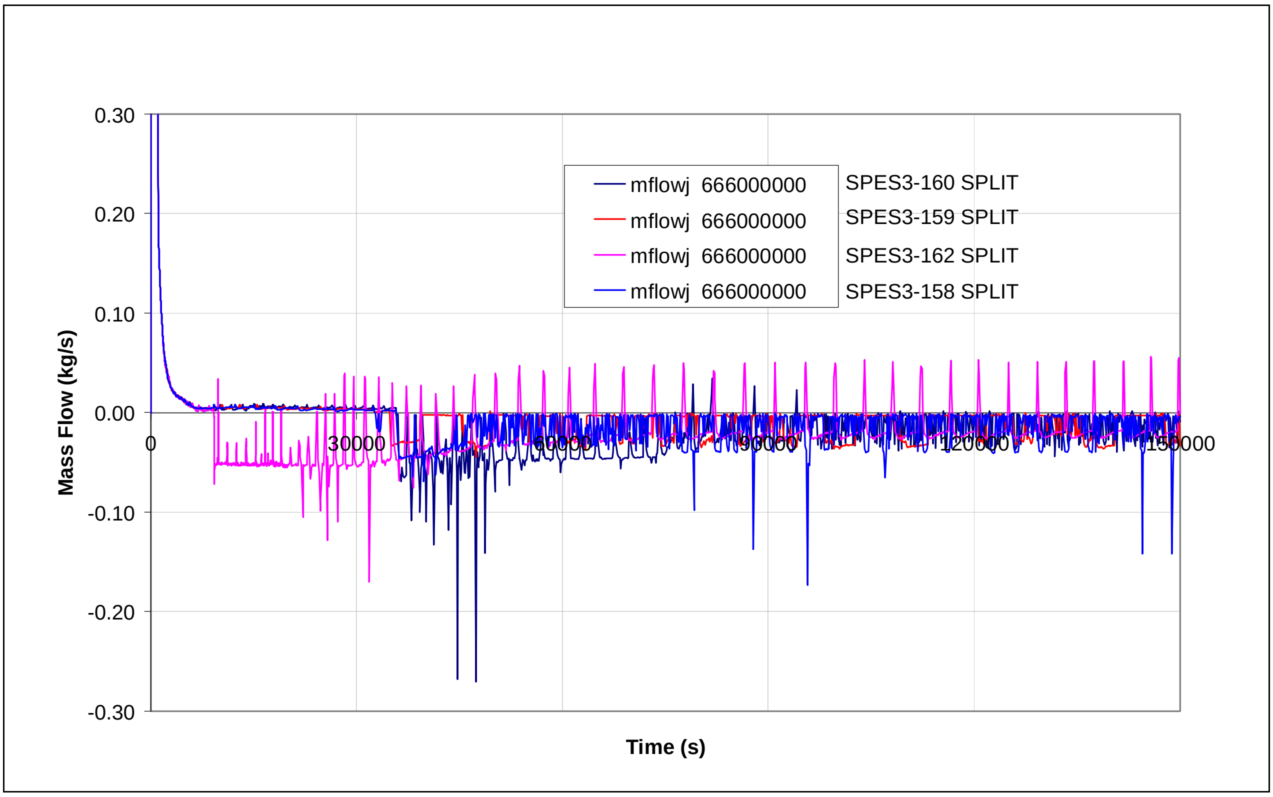


Fig.5. 12 – SPES3-159, 162, 158 and 160 RPV mass

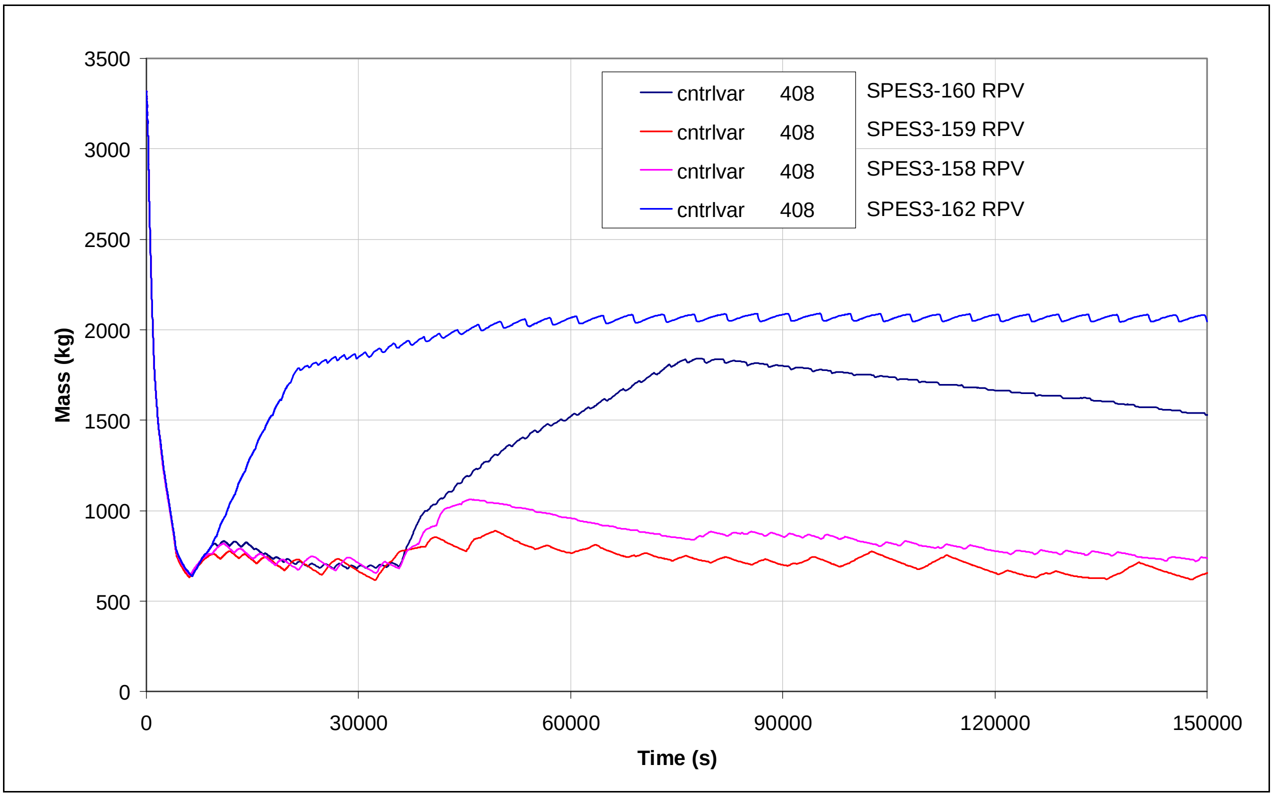


Fig.5. 13 – SPES3-159, 162, 158 and 160 Core heater rod clad surface temperature (normal rods)

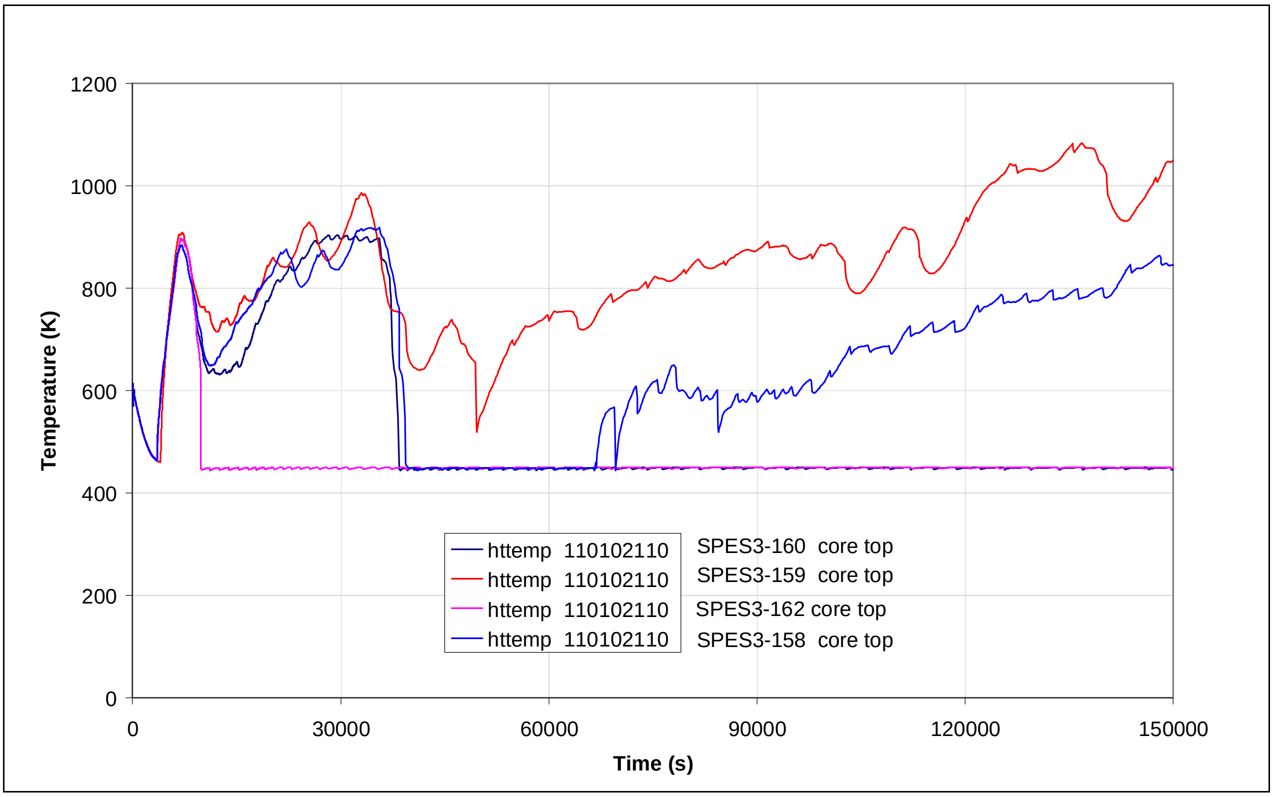


Fig.5. 14 – SPES3-159, 162, 158 and 160 Core heater rod clad surface temperature (hot rods)

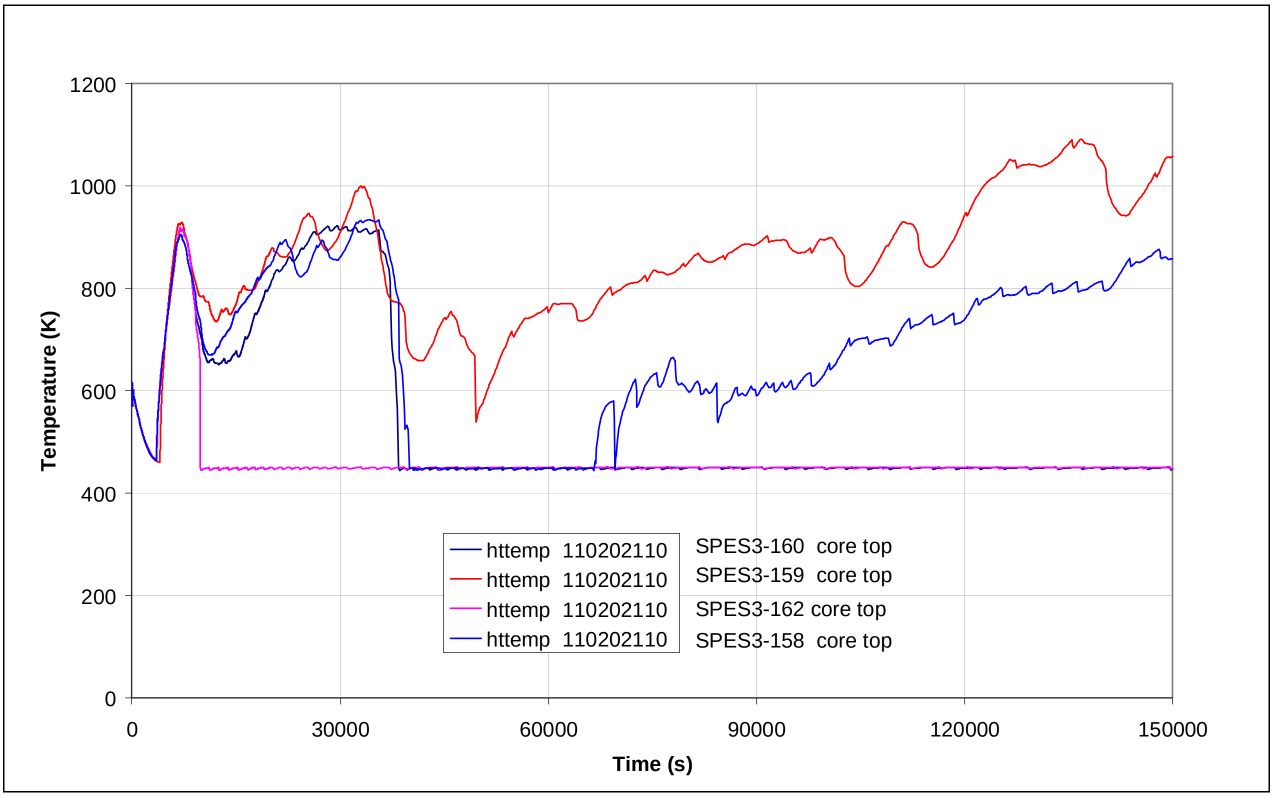


Fig.5. 15 – SPES3-163, 164, 165 and 166 DW pressure (window)

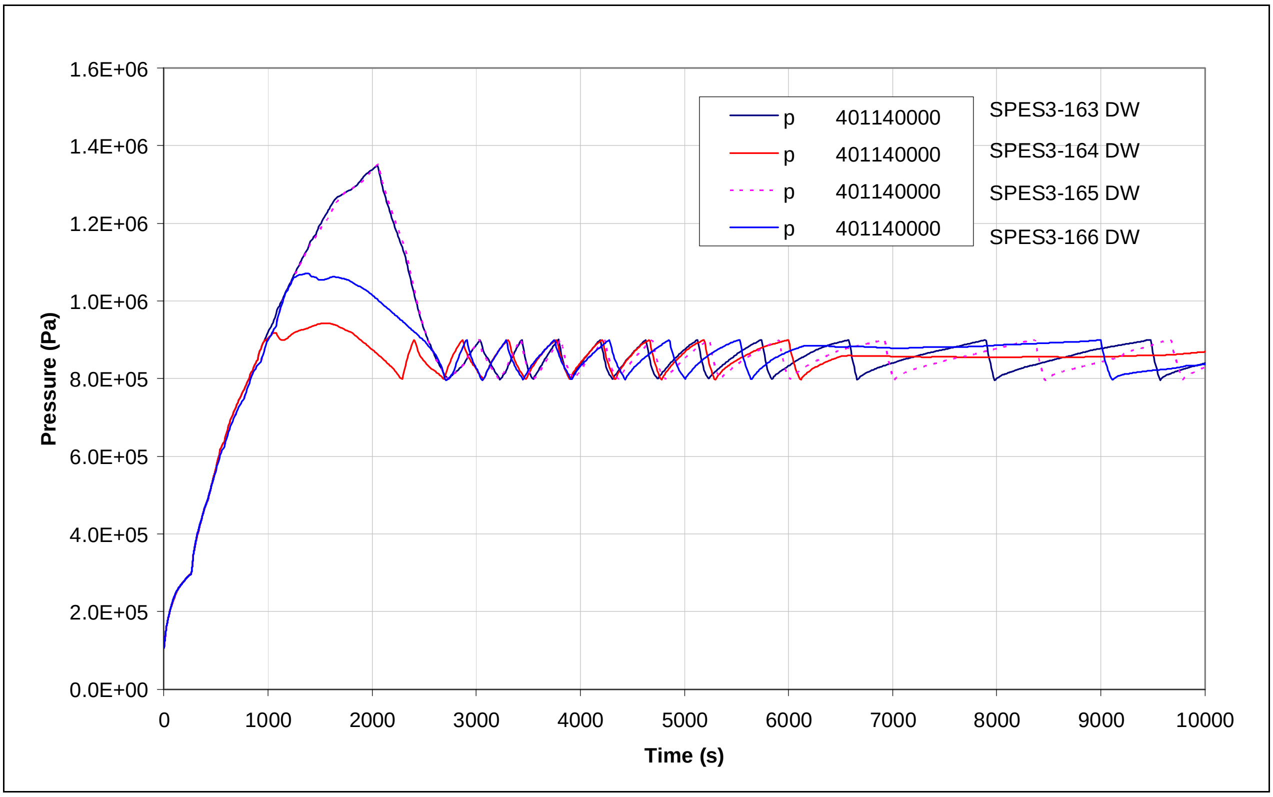


Fig.5. 16 – SPES3-163, 164, 165 and 166 DW pressure

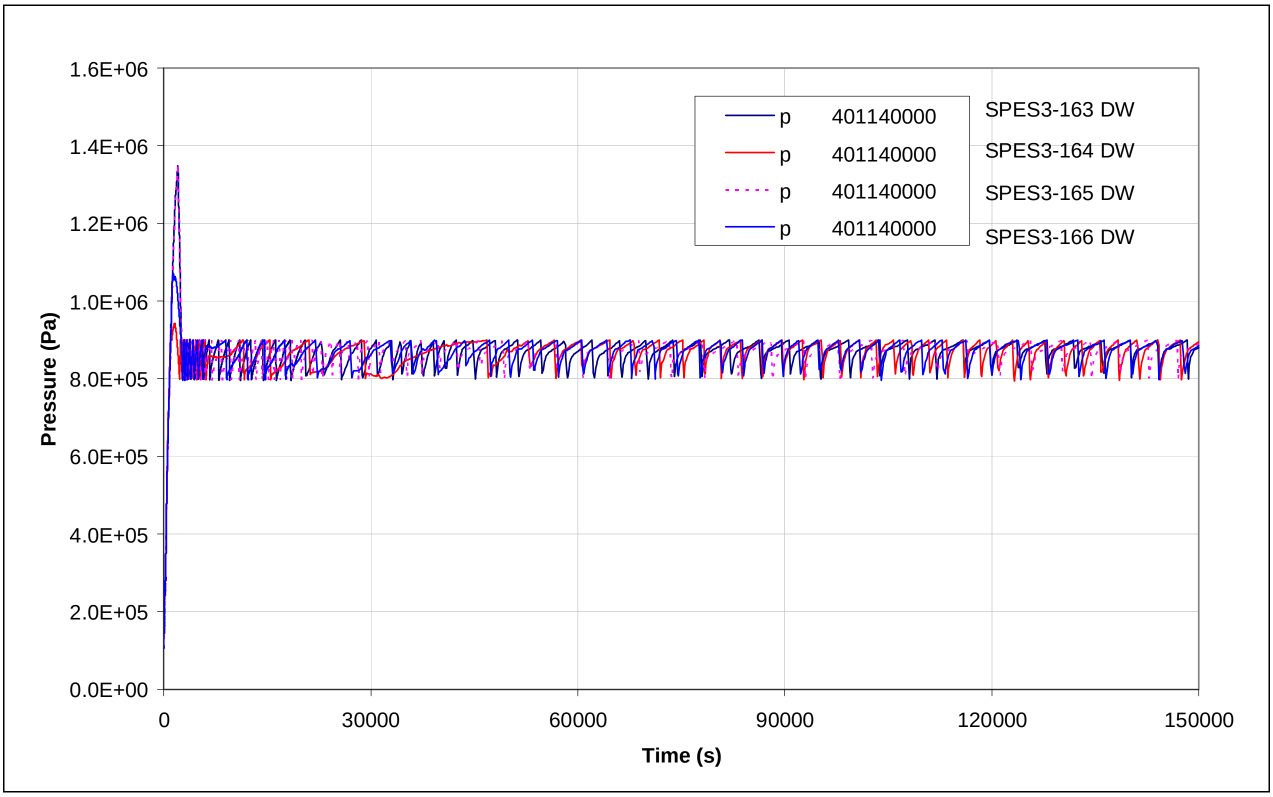


Fig.5. 17 – SPES3-163, 164, 165 and 166 PSS pressure (window)

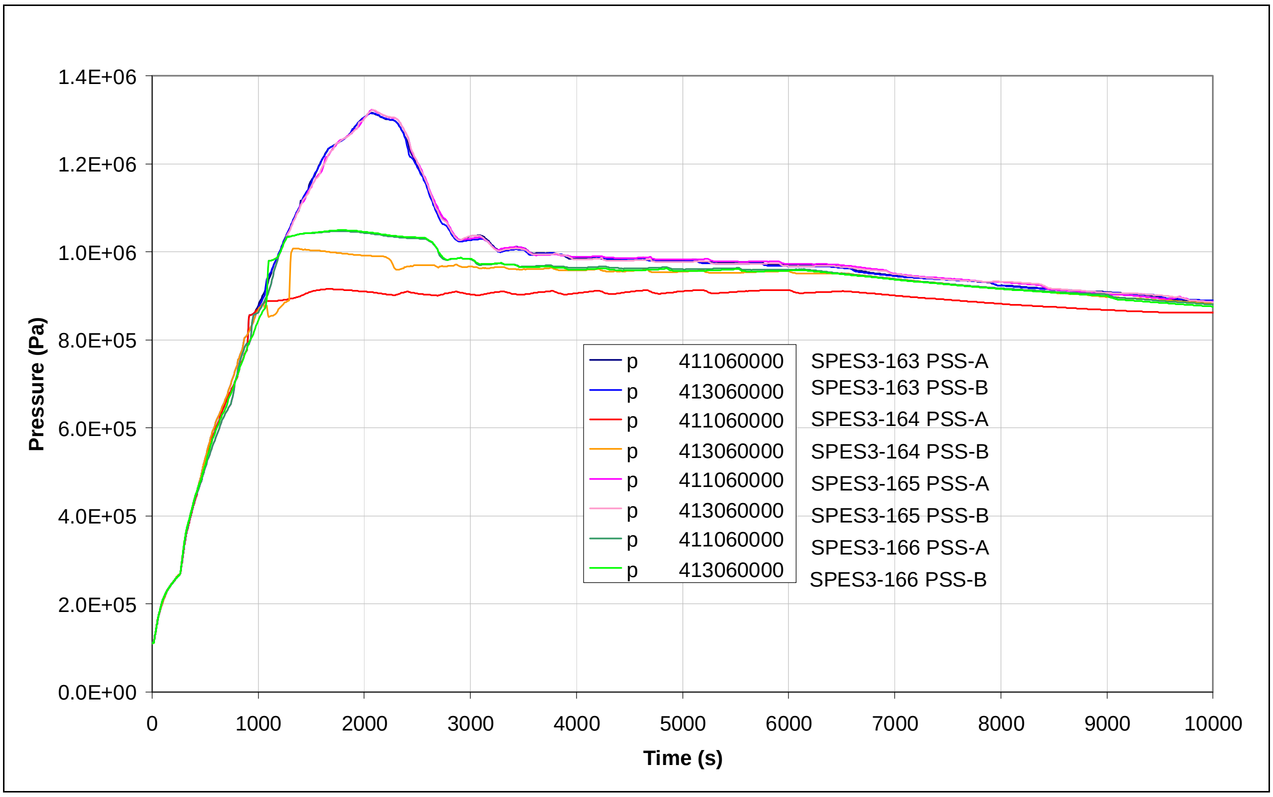


Fig.5. 18 – SPES3-163, 164, 165 and 166 PSS pressure

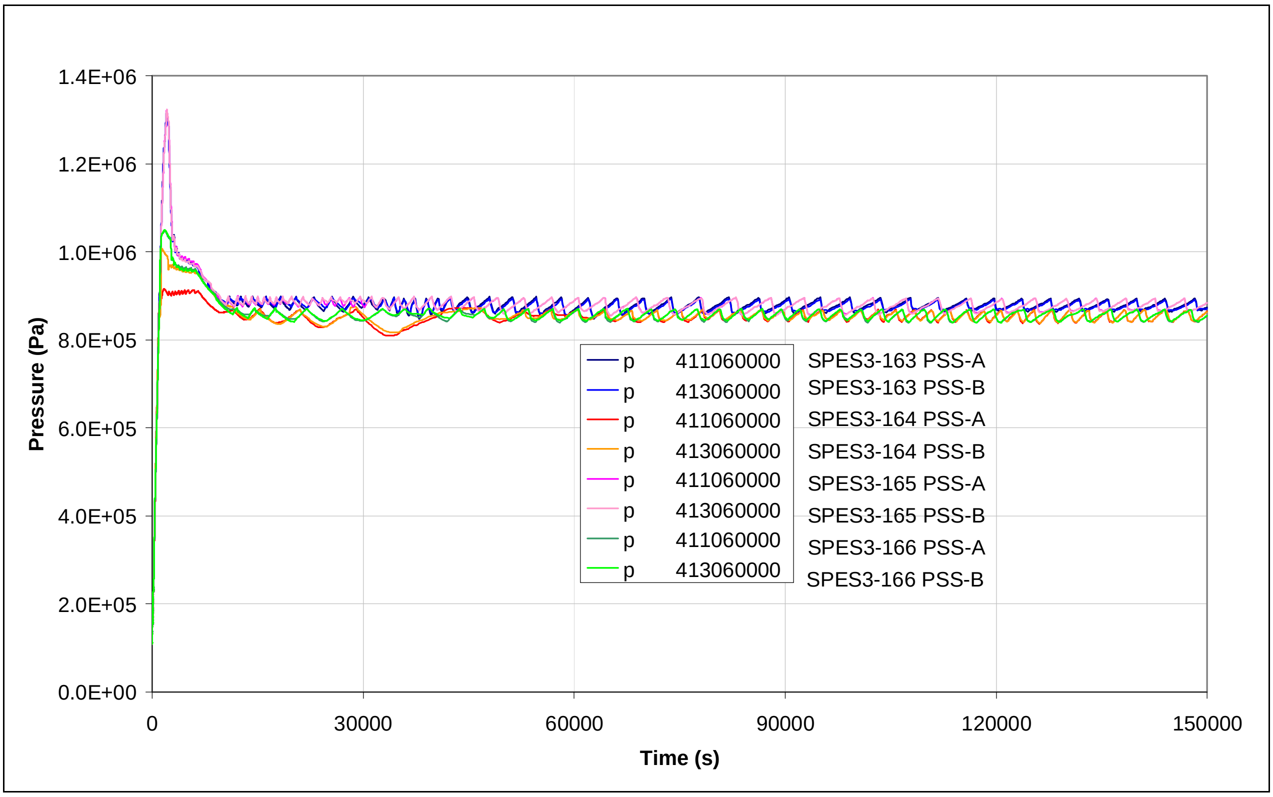


Fig.5. 19 – SPES3-163, 164, 165 and 166 PSS to DW mass flow (window)

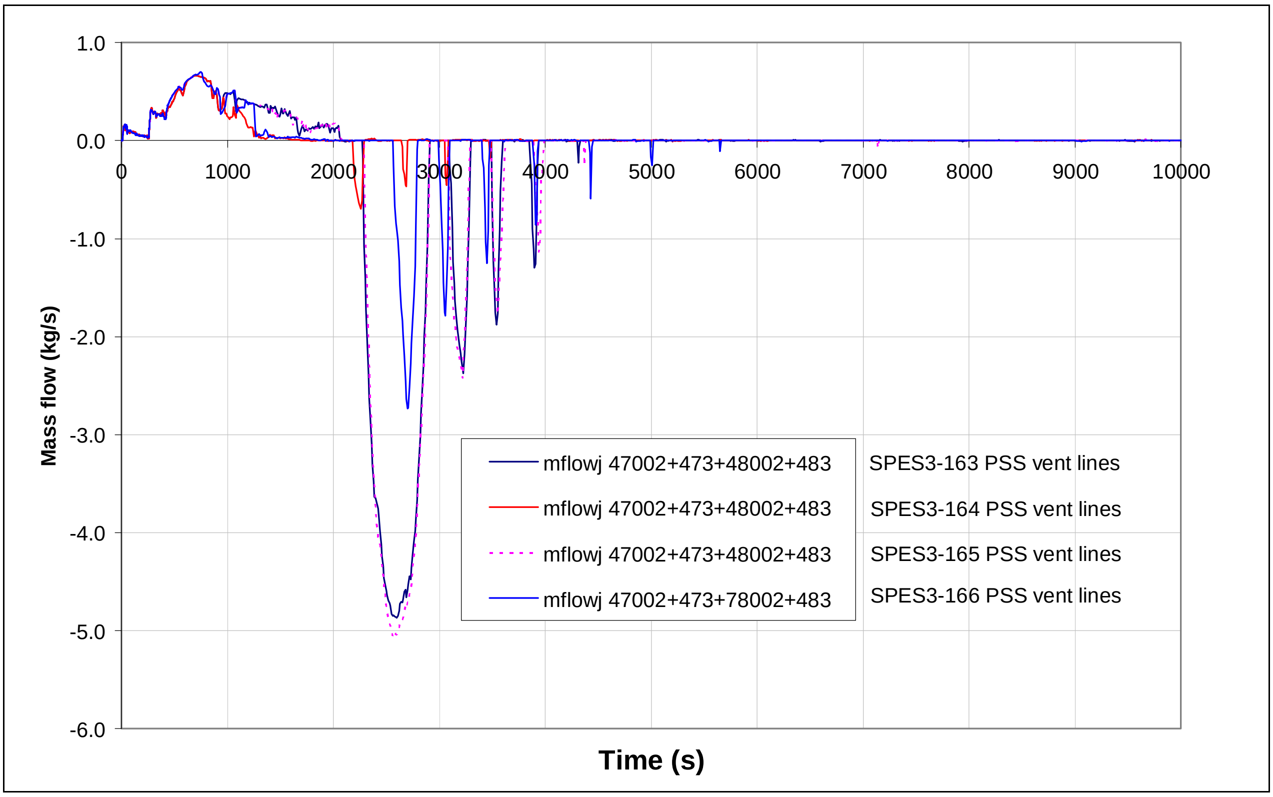


Fig.5. 20 – SPES3-163, 164, 165 and 166 PSS to DW mass flow

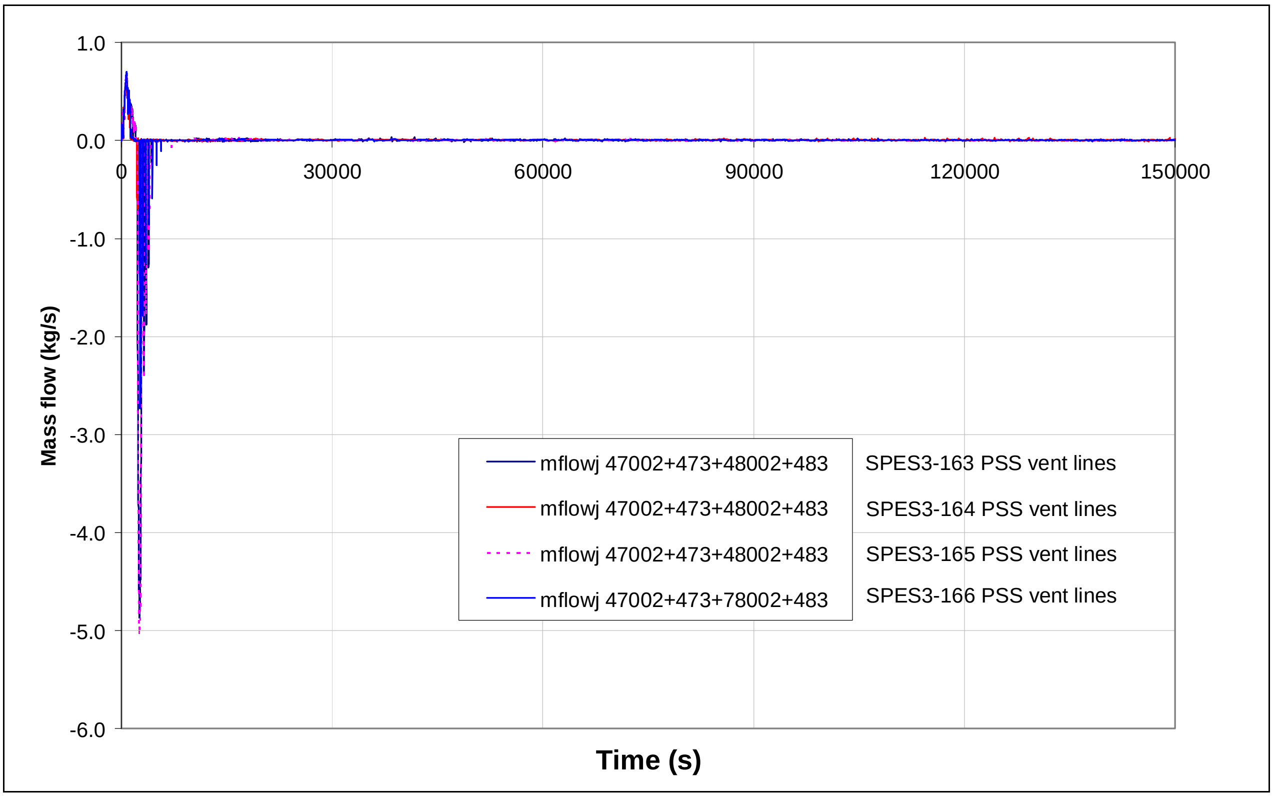


Fig.5. 21 – SPES3-163, 164, 165 and 166 PSS mass

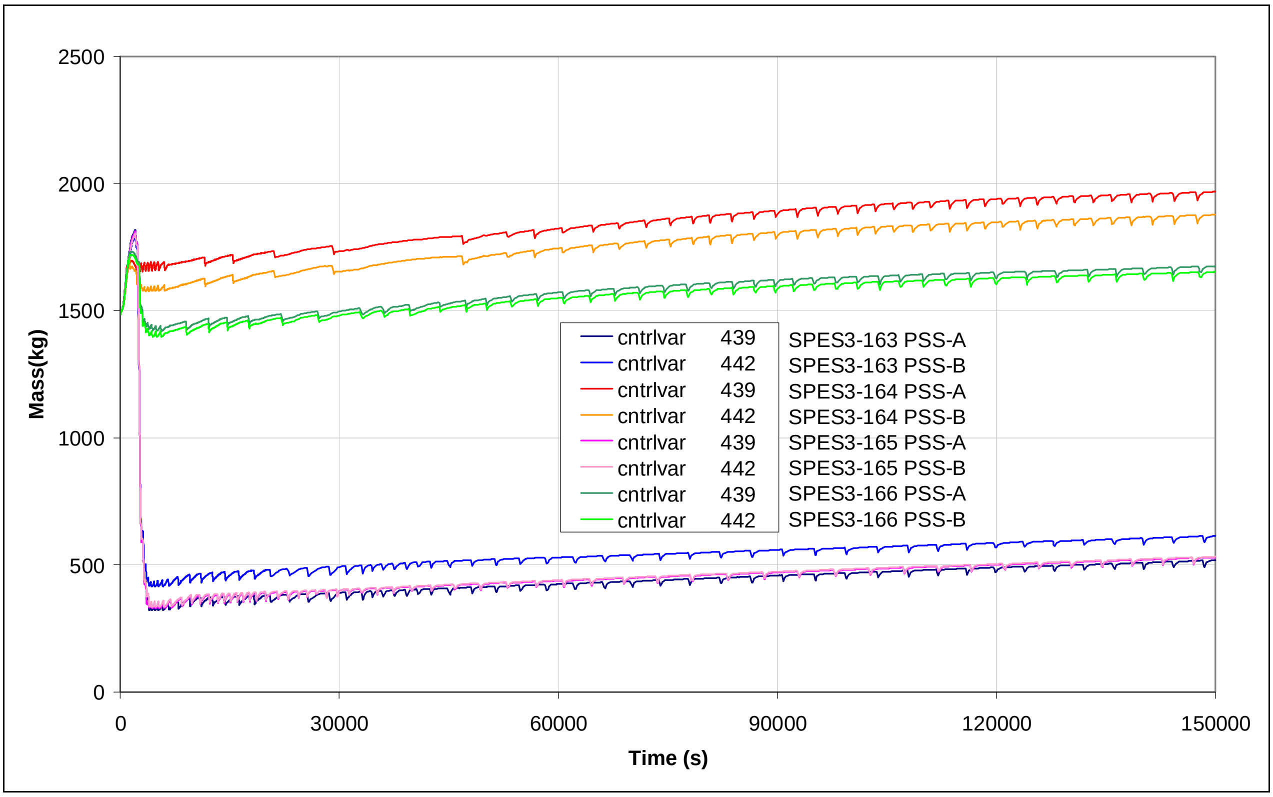


Fig.5. 22 – SPES3-163, 164, 165 and 166 LGMS-A mass (intact loop)

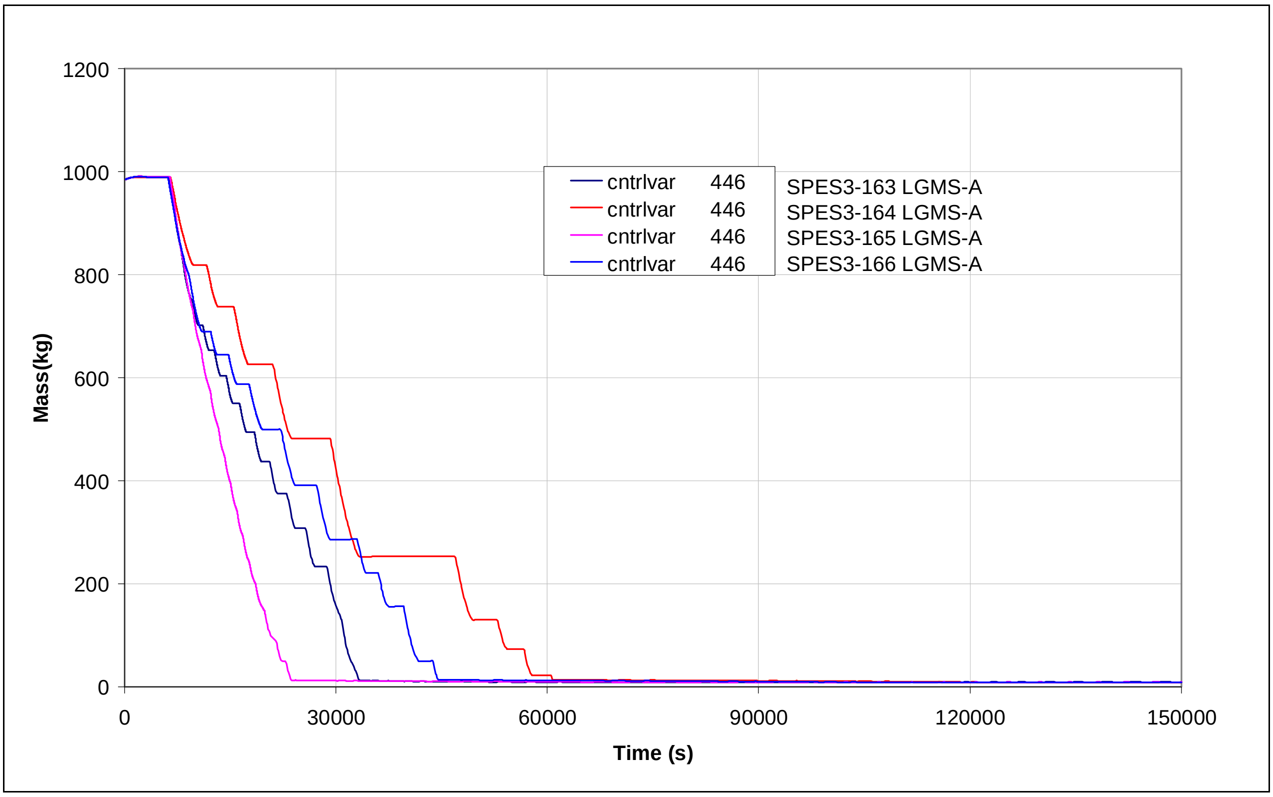


Fig.5. 23 – SPES3-163, 164, 165 and 166 LGMS to DVI line mass flow (intact loop)

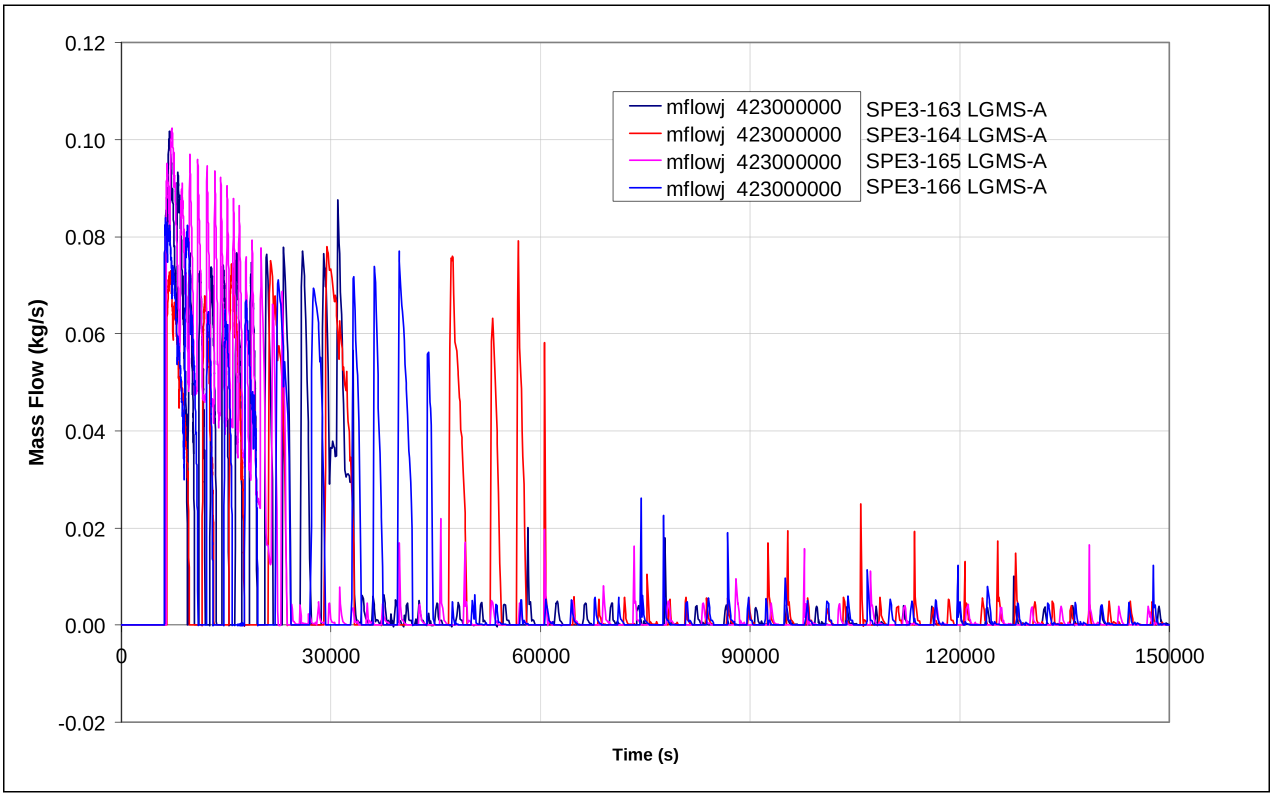


Fig.5. 24 – SPES3-163, 164, 165 and 166 RC to DVI line mass flow (intact loop)

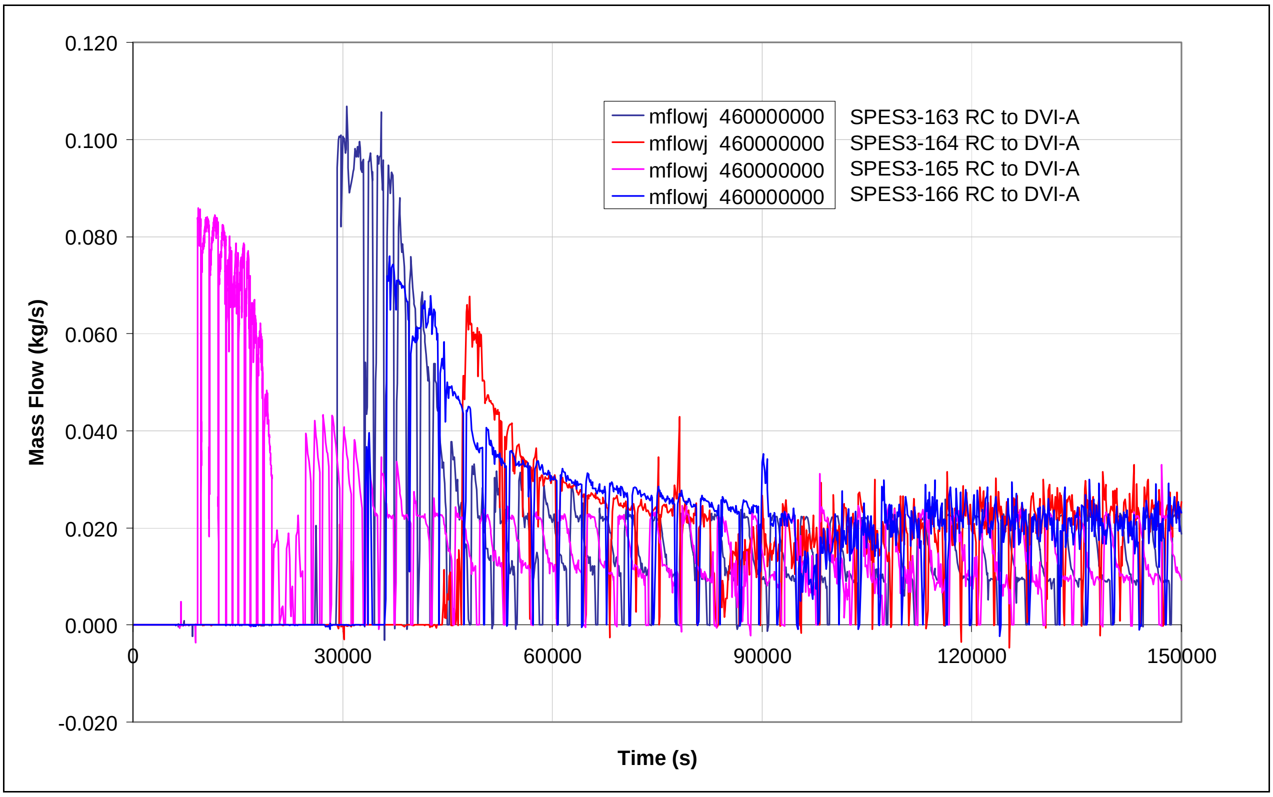


Fig.5. 25 – SPES3-163, 164, 165 and 166 DVI break line (RPV side) mass flow (window)

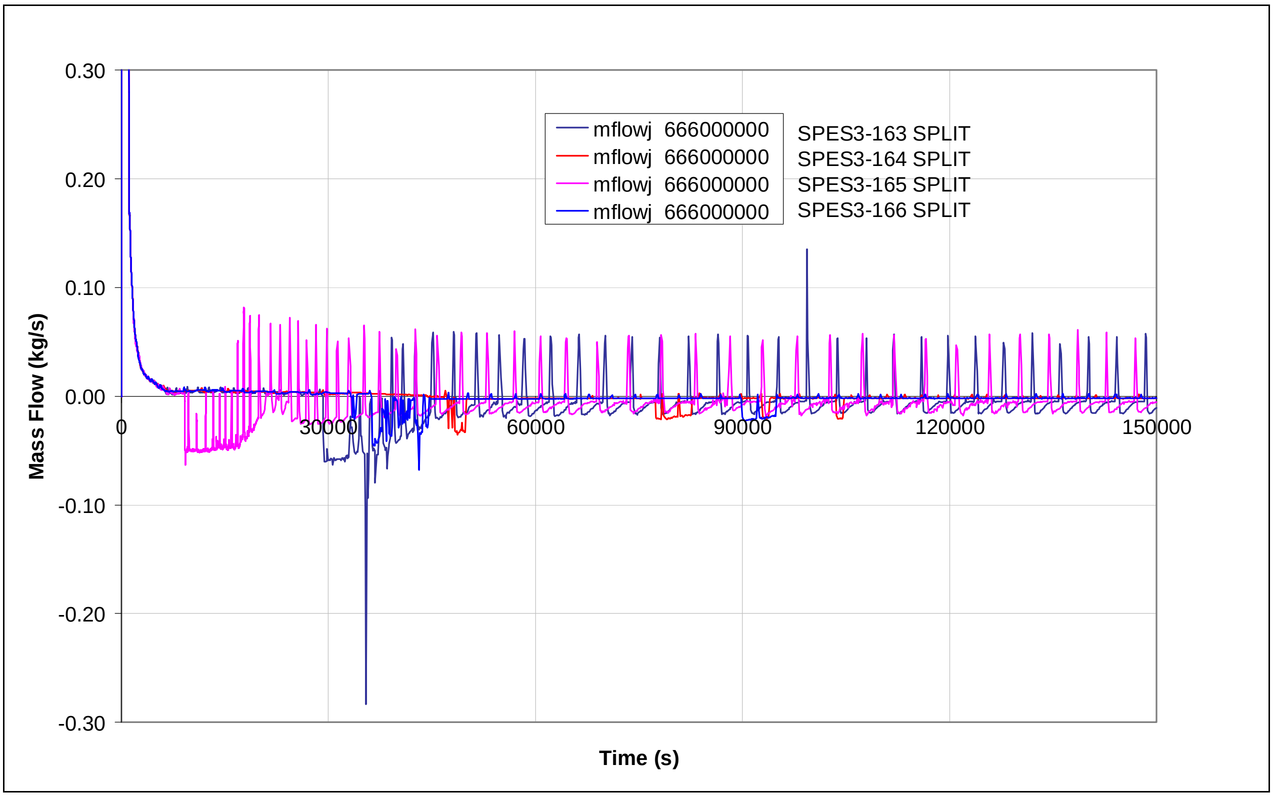


Fig.5. 26 – SPES3-163, 164, 165 and 166 RPV mass

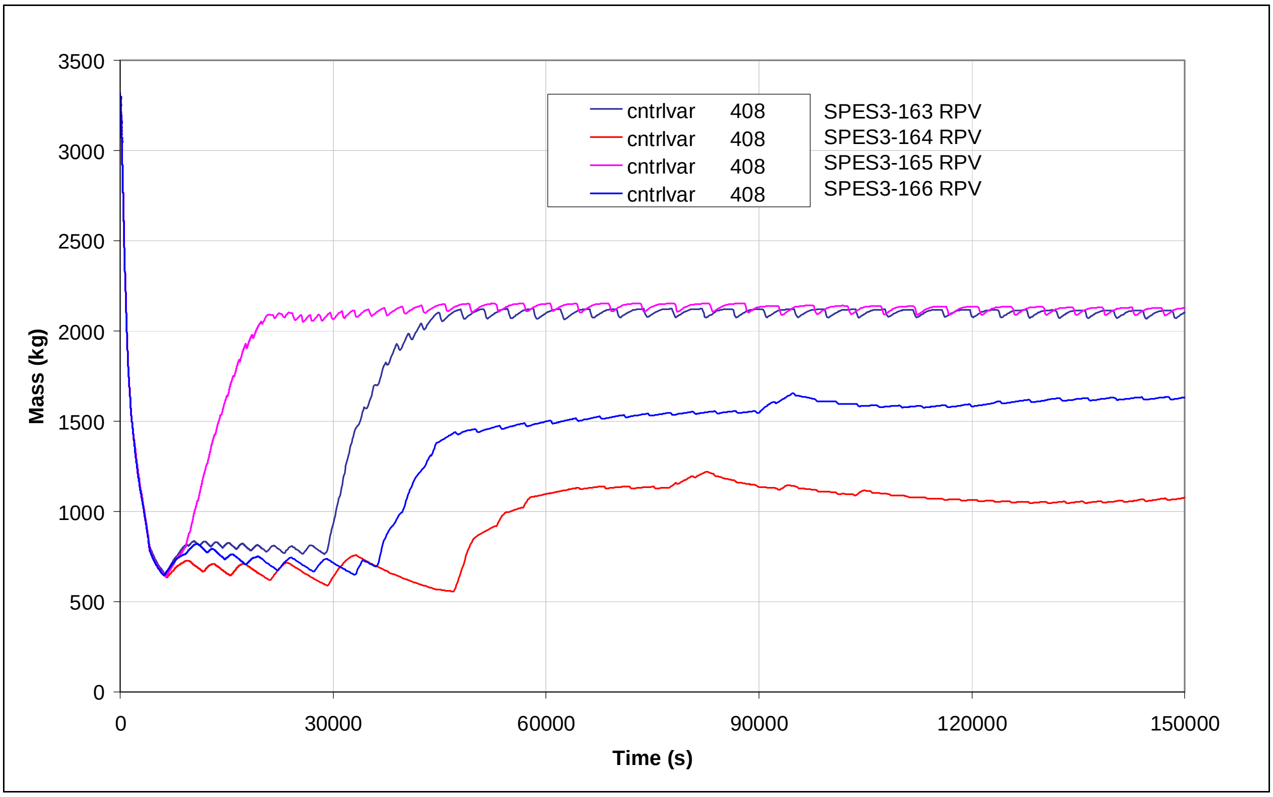


Fig.5. 27 – SPES3-163, 164, 165 and 166 Core heater rod clad surface temperature (normal rods)

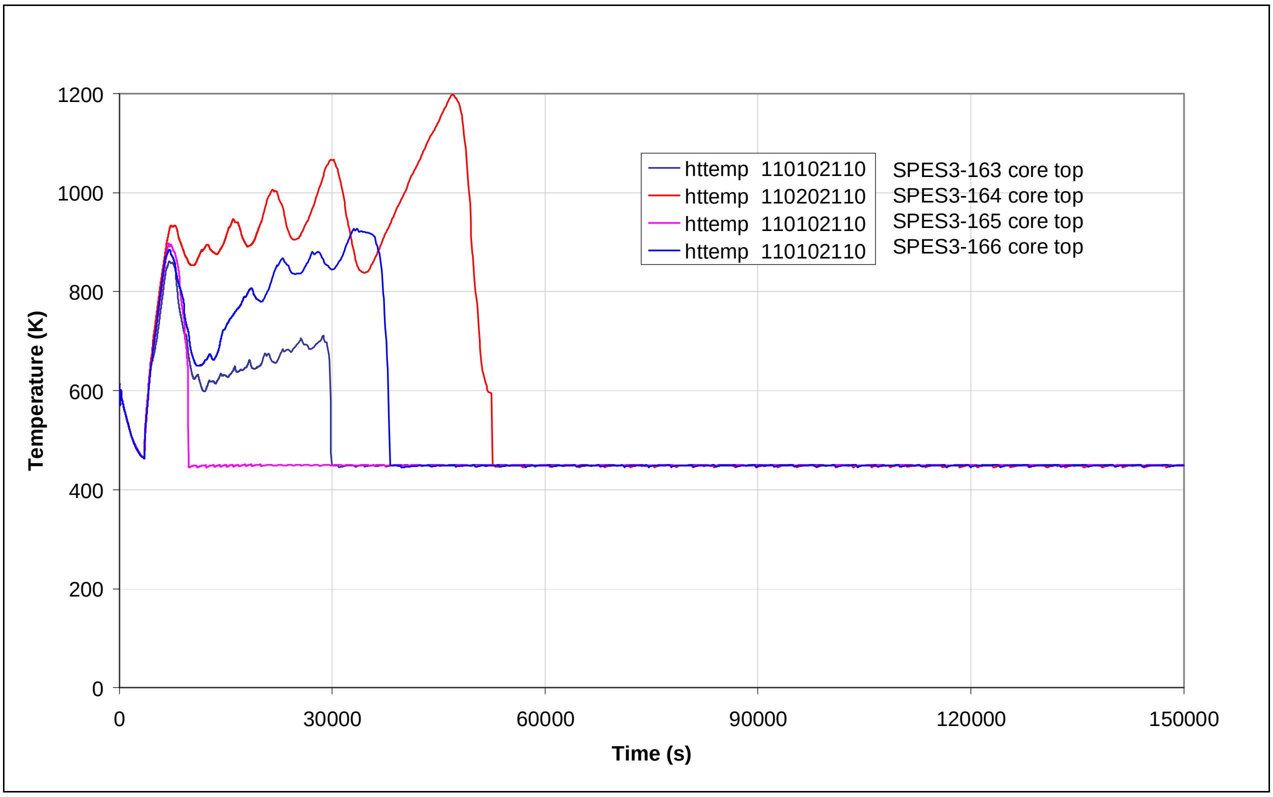


Fig.5. 28 – SPES3-163, 164, 165 and 166 Core heater rod clad surface temperature (hot rods)

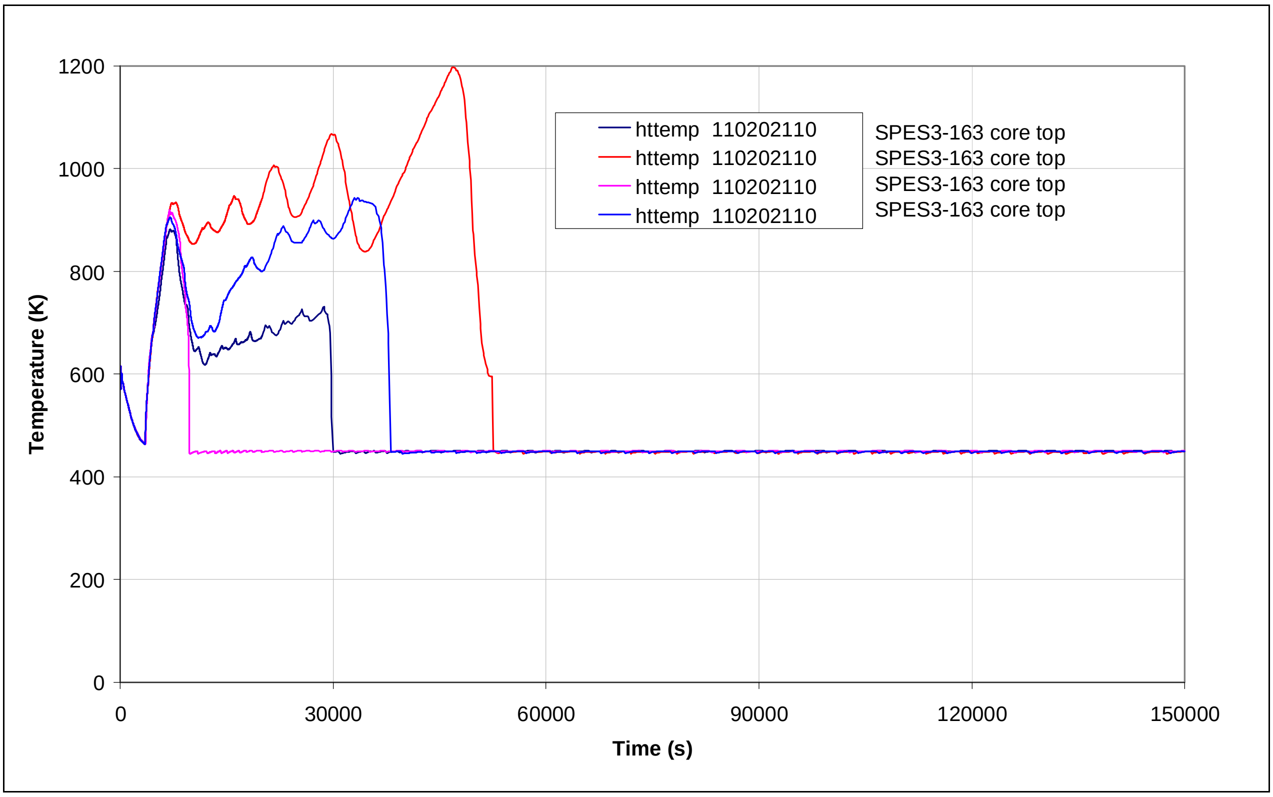


Fig.5. 29 – IRIS plant RPV mass

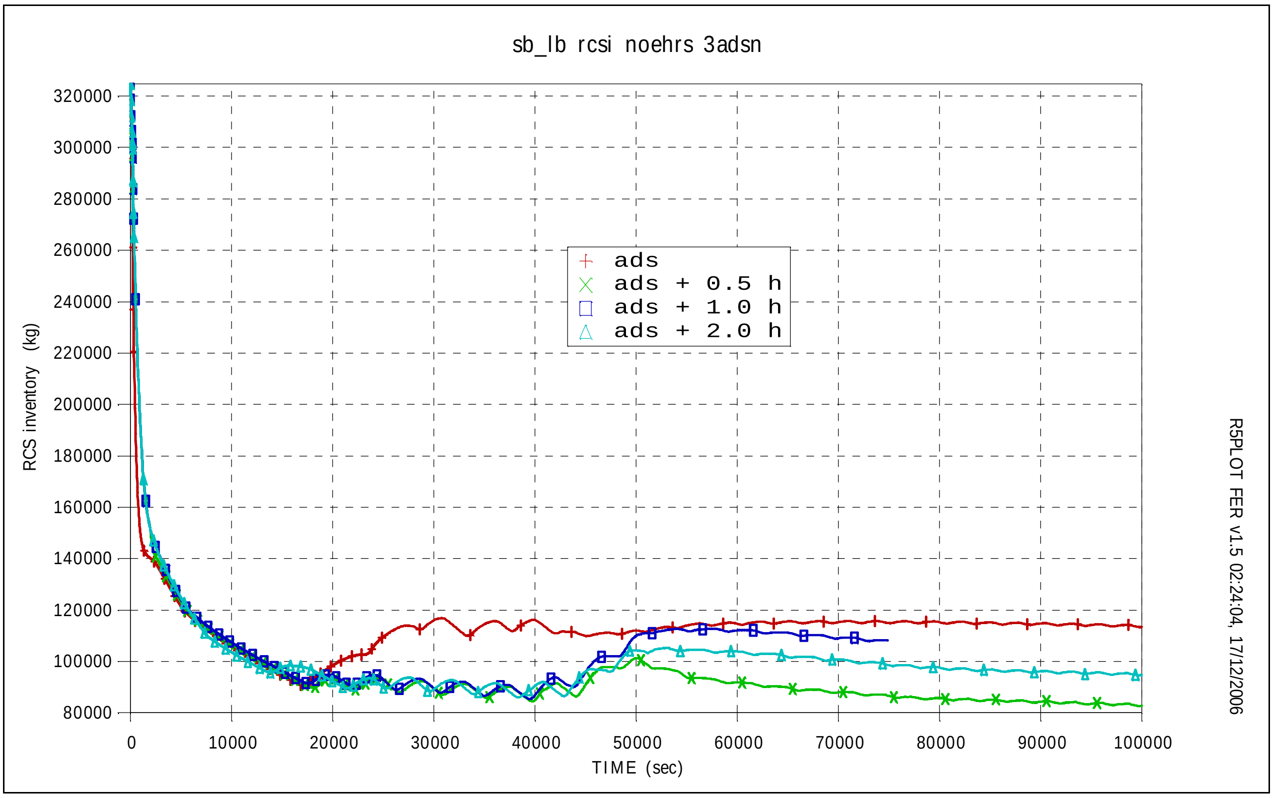


Fig.5. 30 – IRIS plant core mass

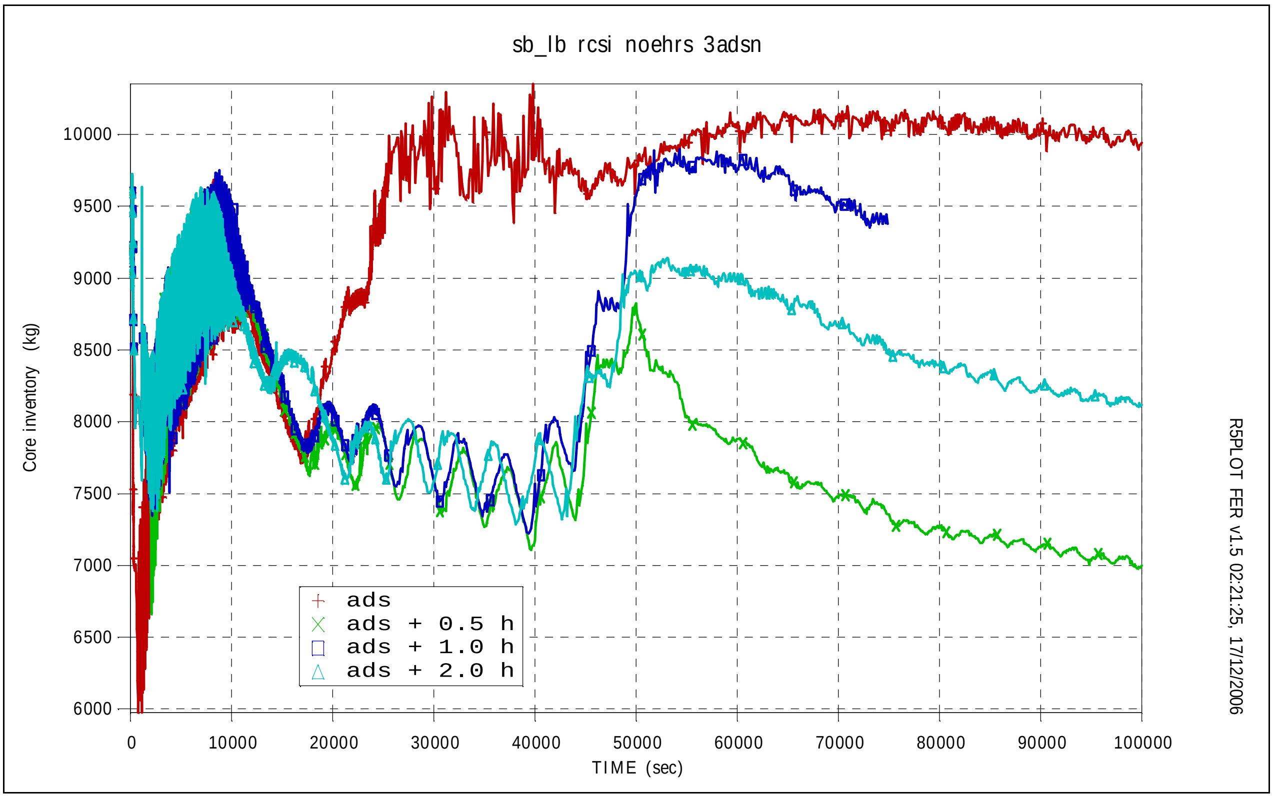


Fig.5. 31 – IRIS plant heater rod clad surface temperature (TAF)

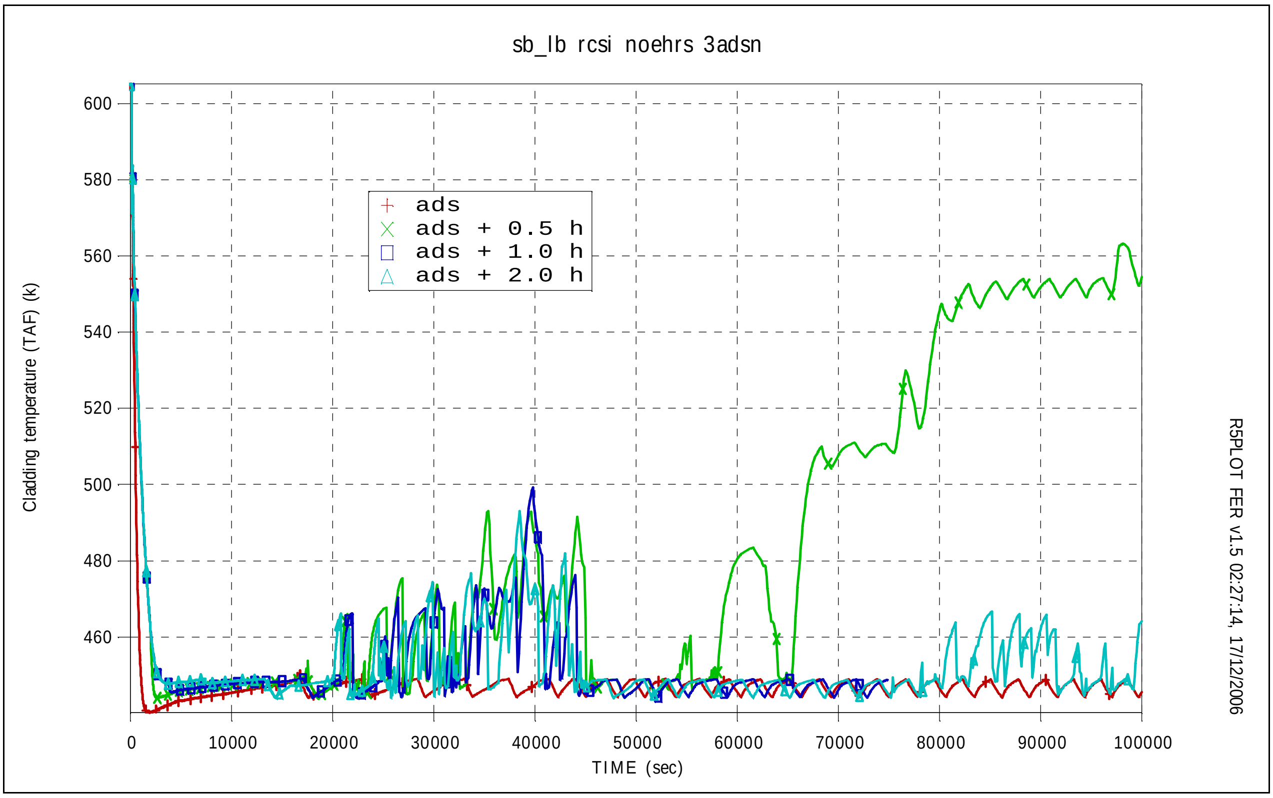


Fig.5. 32 – IRIS plant DW pressure

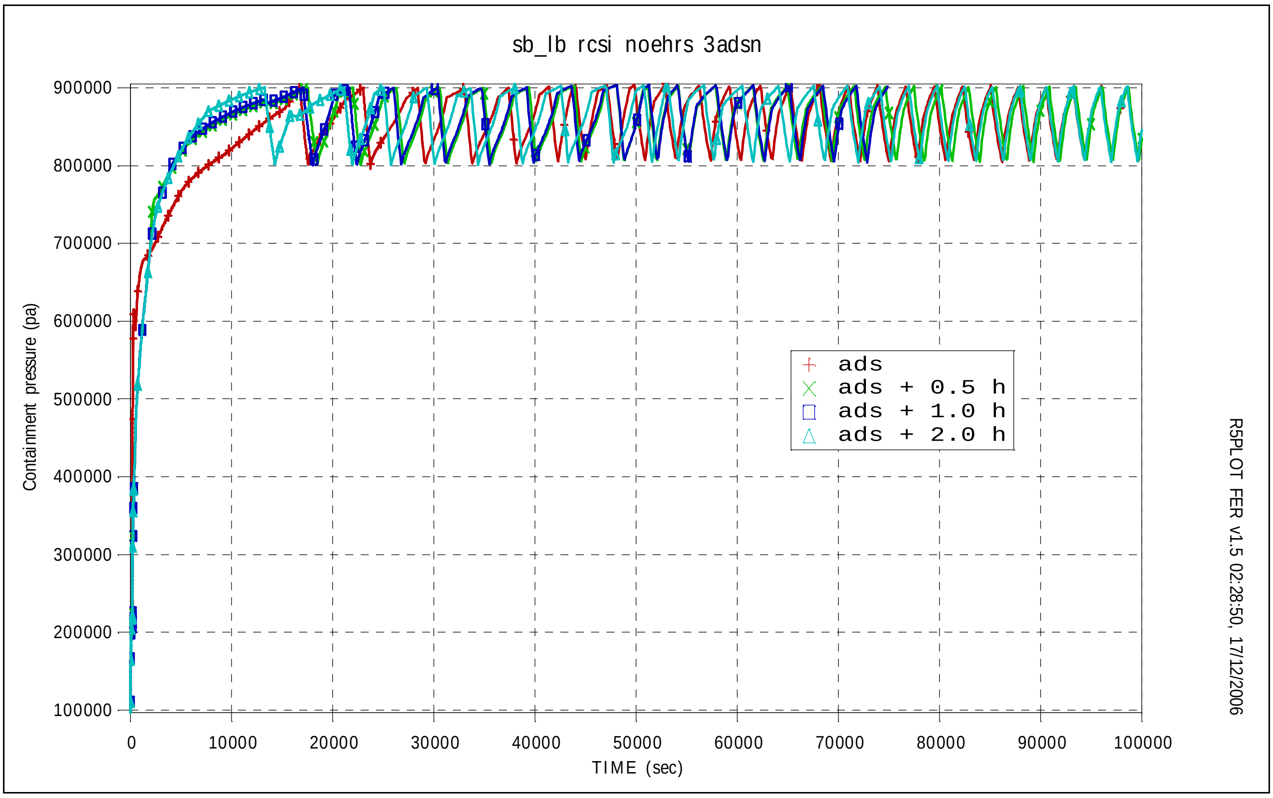


Fig.5. 33 – IRIS plant LGMS mass

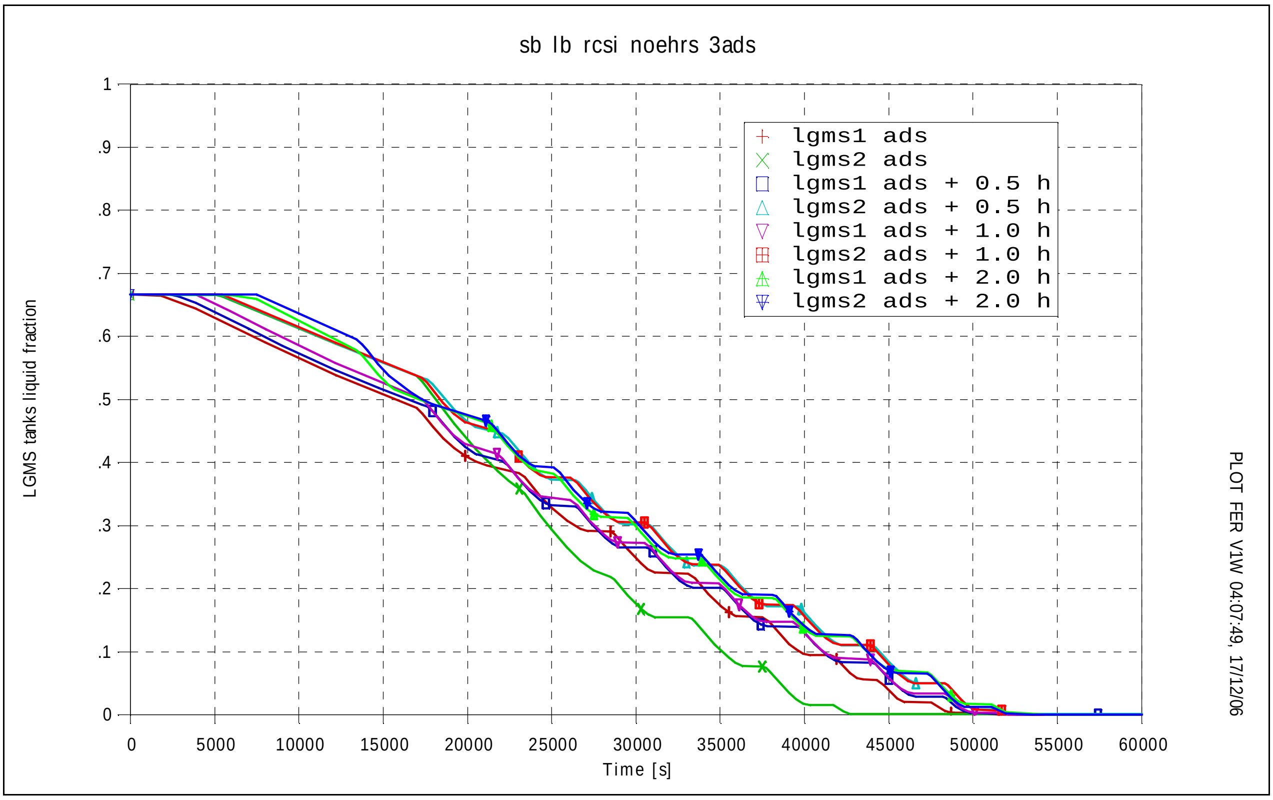


Fig.5. 34 – IRIS plant RC to DVI mass flow

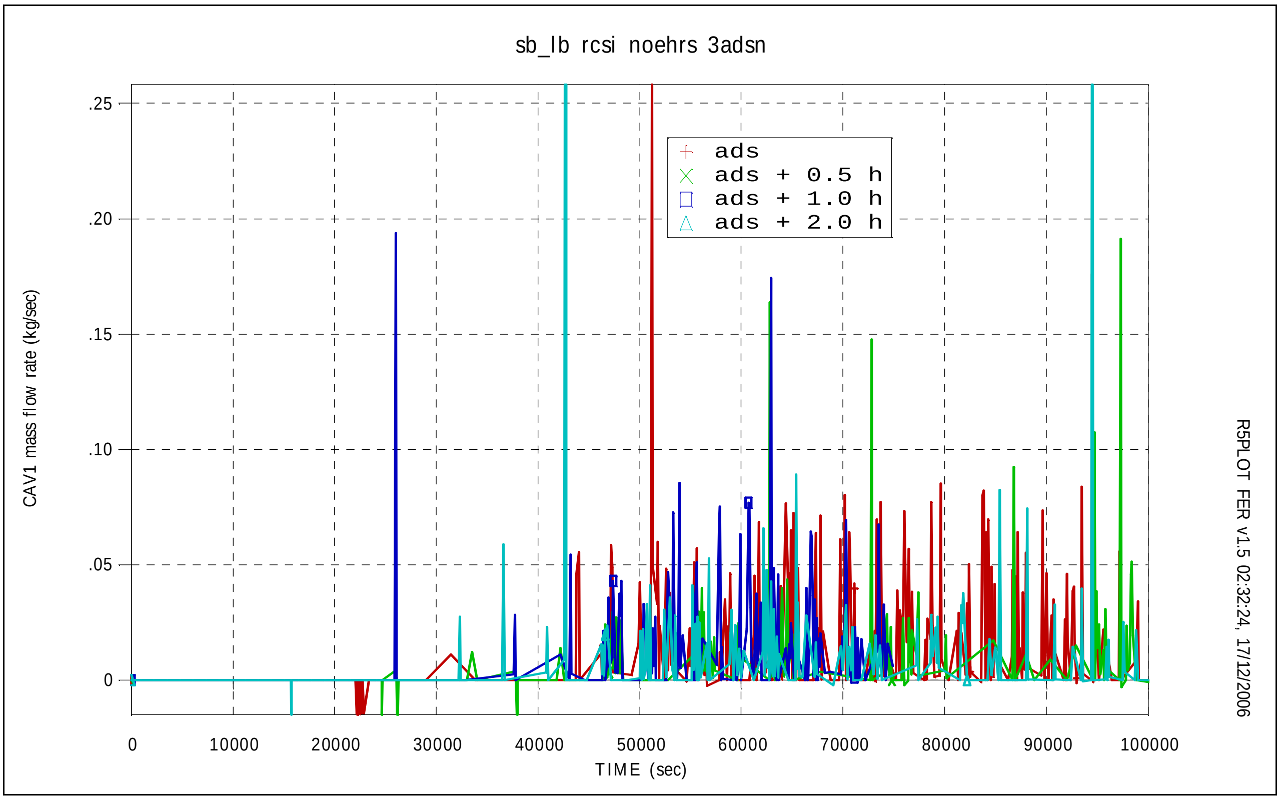
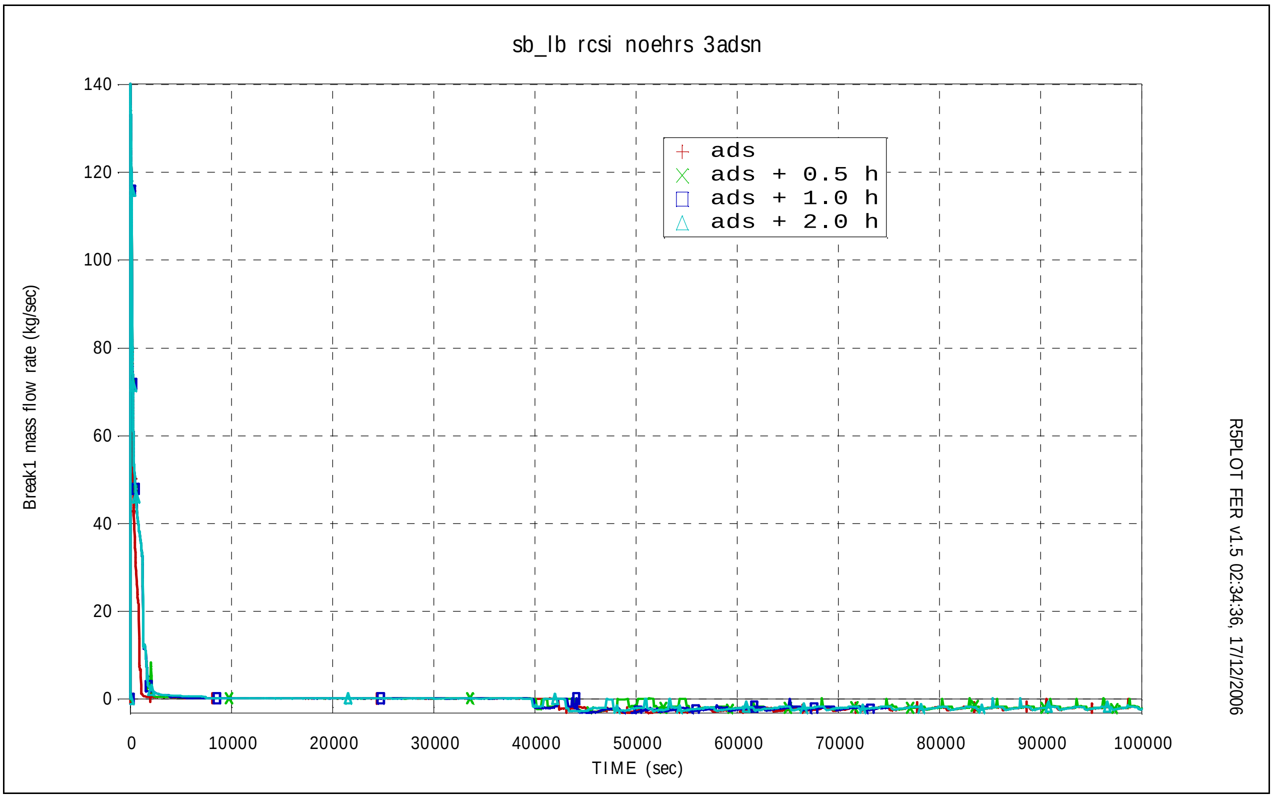


Fig.5. 35 – IRIS plant break mass flow (RPV side)



6. STEADY STATE AT 100% AND 65% POWER: SPES3-167 AND SPES3-169

The maximum electric power supply available for SPES3 facility rod bundle is 6.5 MW. This requires to run the facility at reduced mass flows, in steady state, in order to maintain prototypical fluid pressures, temperatures and enthalpies.

6.1 Steady state: SPES3-167 and SPES3-169

As described in Paragraph 3.1, the SG configuration is with 13 tubes per row (tube number to correctly scaling IRIS 656 tubes per SG), that allows to have average primary side temperature closer to IRIS than with 14 SG tubes, at reduced mass flow conditions. At 65% power, the 14 SG tube configuration resulted in the same core ΔT but 5 °C primary average temperature lower than I RIS. The 13 SG tube case resulted in 3 °C primary average temperature lower than IRIS with about 2 °C gain.

The need to adjust primary side temperatures together with secondary side ones and SG tube collapsed levels, led to investigate how possible rise of secondary side pressure, together with reduction of secondary mass flow, could help to reach steady state values acceptably close to IRIS.

It was found that secondary side mass flow variation, per SG, affects primary average temperature of $0.6593\frac{°C}{g/s}$ and that secondary side pressure affects primary average temperature of $1\frac{°C}{bar}$. Moreover, SG tube collapsed level is affected by secondary side mass flow of $3.73\frac{cm}{g/s}$ and by secondary pressure of $2\frac{cm}{bar}$.

So, it was decided to intervene both on secondary side pressure and mass flow to get steady state conditions at reduced power close to IRIS full power ones.

At 65% power, with 13 SG tubes, the final condition combination was:

1) secondary side pressure: 6 MPa (~3.5% higher than in SPES3-147 [18]);
2) secondary side mass flow at SG-A and SG-B: 0.8095 kg/s; secondary side mass flow at SG-C: 1.619 kg/s (0.4% lower than 65% scaled mass flow of 0.8125 kg/s);

At 100% power, with 13 SG tubes, secondary side mass flow was slightly adjusted to have steady conditions closer to IRIS than those of case SPES3-147 [18]. In particular, SG-A and SG-B mass flow were set to 1.260 kg/s (0.8% higher than in SPES3-147) and SG-C mass flow at 2.520 kg/s.

On the basis of achievements described in Chapter 5., that imposed the increase of the RC to DVI line orifice diameter from 1 mm to 6 mm, further diameter increase was performed up to 7 mm, after calculation refinements on the basis of the following assumptions:

1) SPES3 DVI line scaling by WEC provided a theoretical line diameter of 9.311 mm [25];
2) required mass flow from RC to DVI is 0.02 kg/s, to remove 50 kW long term decay power;
3) speed in the DVI, corresponding to the required mass flow, is 0.326 m/s with 900 kg/m^3 water density;
4) distributed pressure drop in a pipe connecting RC to DVI (assumed 1 m long and of the same diameter of the DVI) is 100 Pa;
5) adding equivalent value of concentrated pressure drop, the total pressure drop of 200 Pa is assumed;
6) the orifice that guarantees required 0.02 kg/s mass flow, under 200 Pa DP, has 6.5 mm diameter.

7) 7 mm diameter was chosen to leave a margin on the estimate.

SPES3-167 and SPES3-169 cases include all optimized parameters as described above.

The final steady conditions for cases at 100% and 65% power are summarized in Tab.6. 1 and Tab.6. 2, respectively, and compared with the IRIS steady conditions at full power.

6.2 Case conclusion

Reached SPES3-167 steady conditions, for 100% power case, show a good agreement with the IRIS ones. SPES3 primary side average temperature is 1.2 °C higher than IRIS (0.4% difference). SPES3 secondary side outlet steam is 1.2 °C less superheated than IRIS (0.4% difference). SPES3 RPV mass is 65 kg greater than IRIS (2% difference) due to SPES3 PRZ level 0.212 m (10.5%) higher. SPES3 SG tube collapsed level is, on average, 0.152 m (8.4%) lower than IRIS.

Reached SPES3-169 steady conditions, for the 65% power case, show a good agreement with the IRIS ones. SPES3 primary side average temperature is 0.5 °C lower than IRIS (0.15% difference). SPES3 secondary side outlet steam is 7.25 °C more superheated than IRIS (2.3% difference). SPES3 RPV mass is 68 kg greater than IRIS (2% difference) due to SPES3 PRZ level 0.126 m (6.2%) higher. SPES3 SG tube collapsed level is, on average, 0.378 m (24%) lower than IRIS.

From the point o view of fluid enthalpies, reached steady conditions are suitable to reproduce IRIS ones. Optimization of initial levels will be performed for the test execution. At the moment, reached steady states are considered satisfactory for DBE and BDBE DVI line DEG break transient simulations.

Tab.6. 1 – SPES3-167 and IRIS-HT6_rwstc 100% power steady state conditions

SPES3-167	Primary/Core	SG-A	SG-B	SG-C	EBTA/B	QT	DW	PSSA/B	RC	LGMSA/B	RWSTAB	RWSTC
Pressure (MPa)	15.51 (PRZ) 0.104 (pump head)	5.83 (out)	5.83 (out)	5.87 (out)	Primary	Cont.	0.1013	Cont.	Cont.	Cont.	0.1013	0.1013
Tin (℃)	292.5	223.9	223.9	223.9	48.9	48.9	48.9	48.9	48.9	48.9	20	20
Tout (℃)	329.9	318.0	315.0	315.0								
DT (℃)	37.4	94.1	91.1	91.1								
Superheating (℃)		44.3 (Tsat 273.7)	41.3 (Tsat 273.7)	41.3 (Tsat 274.2)								
Mass flow (kg/s)	45.64 (2.14 in by-pass)	1.260	1.260	2.520								
Power (MW)	10	2.509	2.497	4.991								
Level (m) -collapsed-	2.231 (PRZ)	1.684	1.849	1.877	3.14 full	empty	empty	3.77	empty	2.454	6.961	6.954
Mass (kg)	3319 (RPV)				127			1480		985	11869	11876

IRIS HT6_rwstc	Primary/Core	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8	EBTA/B	QT	DW	PSSA/B	RC	LGMSA/B	RWST1	RWST2
Pressure (MPa)	15.5 (PRZ) 0.129 (pump head)	5.81 (out)	5.79 (out)	5.79 (out)	5.78 (out)	5.78 (out)	5.79 (out)	5.79 (out)	5.81 (out)	Primary	Cont.	0.1013	Cont.	Cont.	Cont.	0.1013	0.1013
Tin (℃)	291	223.7	223.7	223.7	223.7	223.7	223.7	22 3.7	223.7	48.9	48.9	48.9	48.9	48.9	48.9	20	20
Tout (℃)	329	318.05	316.24	318.22	316.52	316.52	318.22	316.24	318.05								
DT (℃)	38	94.35	92.54	94.52	92.82	92.82	94.52	92.5 4	94.35								
Superheating (℃)		44.55 (Tsat 273.5)	43.04 (Tsat 273.2)	45.02 (Tsat 273.2)	43.42 (Tsat 273.1)	43.42 (Tsat 273.1)	45.02 (Tsat 273.2)	43.04 (Tsat 273.2)	44.55 (Tsat 273.5)								
Mass flow (kg/s)	45.24 (2.13 in by-pass)	1.257	1.257	1.257	1.257	1.257	1.257	1.257	1.257								
Power (MW)	10	1.24	1.26	1.24	1.26	1.26	1.24	1.26	1.24								
Level (m) -collapsed-	2.019 (PRZ)	1.93	1.99	1.92	1.98	1.98	1.92	1.99	1.93	3.14 full	empty	empty	3.00	empty	2.668	9.099	9.099
Mass (kg)	3254 (RPV)									127			1453		989	11942	11942

Tab.6. 2 – SPES3-169 and IRIS-HT6_rwstc 65% power steady state conditions

SPES3-169	Primary/Core	SG-A	SG-B	SG-C	EBTA/B	QT	DW	PSSA/B	RC	LGMSA/B	RWSTAB	RWSTC
Pressure (MPa)	15.51 (PRZ) 0.041 (pump head)	6.01 (out)	6.01 (out)	6.03 (out)	Primary	Cont.	0.1013	Cont.	Cont.	Cont.	0.1013	0.1013
Tin (℃)	290.6	223.8	223.8	223.8	48.9	48.9	48.9	48.9	48.9	48.9	20	20
Tout (℃)	328.5	324.8	324.4	324.3								
DT (℃)	37.9	101.0	100.6	100.5								
Superheating (℃)		49.1 (Tsat 275.7)	48.7 (Tsat 275.7)	48.4 (Tsat 275.3)								
Mass flow (kg/s)	29.566 (1.342 in by-pass)	0.8125	0.8125	1.619								
Power (MW)	6.5	1.625	1.624	3.246								
Level (m) -collapsed-	2.145 (PRZ)	1.466	1.625	1.640	3.14 full	empty	empty	3.77	empty	2.454	6.961	6.954
Mass (kg)	3322 (RV)				127			1480		985	11869	11876

IRIS HT6_rwstc	Primary/Core	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8	EBTA/B	QT	DW	PSSA/B	RC	LGMSA/B	RWST1	RWST2
Pressure (MPa)	15.5 (PRZ) 0.129 (pump head)	5.81 (out)	5.79 (out)	5.79 (out)	5.78 (out)	5.78 (out)	5.79 (out)	5.79 (out)	5.81 (out)	Primary	Cont.	0.1013	Cont.	Cont.	Cont.	0.1013	0.1013
Tin (℃)	291	223.7	223.7	223.7	223.7	223.7	223.7	22 3.7	223.7	48.9	48.9	48.9	48.9	48.9	48.9	20	20
Tout (℃)	329	318.05	316.24	318.22	316.52	316.52	318.22	316.24	318.05								
DT (℃)	38	94.35	92.54	94.52	92.82	92.82	94.52	92.5 4	94.35								
Superheating (℃)		44.55 (Tsat 273.5)	43.04 (Tsat 273.2)	45.02 (Tsat 273.2)	43.42 (Tsat 273.1)	43.42 (Tsat 273.1)	45.02 (Tsat 273.2)	43.04 (Tsat 273.2)	44.55 (Tsat 273.5)								
Mass flow (kg/s)	45.24 (2.13 in by-pass)	1.257	1.257	1.257	1.257	1.257	1.257	1.257	1.257								
Power (MW)	10	1.24	1.26	1.24	1.26	1.26	1.24	1.26	1.24								
Level (m) -collapsed-	2.019 (PRZ)	1.93	1.99	1.92	1.98	1.98	1.92	1.99	1.93	3.14 full	empty	empty	3.00	empty	2.668	9.099	9.099
Mass (kg)	3254 (RV)									127			1453		989	11942	11942

7. DBE DVI LINE DEG BREAK FROM 100% AND 65% POWER: SPES3-172 AND SPES3-175

The same DBE DVI line DEG break transient was simulated starting from steady conditions reached at 100% and 65% power (Chapter 6.) and the results compared to verify similarity of quantities and capability of SPES3 to reproduce the IRIS transients, even starting from reduced power.

Case SPES3-172 is the full power transient, starting from steady conditions as reported in Tab.6. 1.

Case SPES3-175 is the reduced power transient, starting from steady conditions as reported in Tab.6. 2.

The details of the DVI line DEG break transient are deeply described in [18]. This chapter reports the main events and compares the quantities, considered fundamental in the simulation of the IRIS reactor.

In the reduced power transient, the core power decay curve and primary cooling pump coastdown curve, initially at reduced rate, join the corresponding curves, starting from full power, simply extending in time the steady state reduced value up to intersect the decay curve. From this point on, the curves are overlapped.

The list of the main events occurring during the transients, with timing and quantities, is reported in Tab.7. 1 for both full and reduced power cases.

7.1 SPES3-172 and SPES3-175 transient phases and description

The first 10 s of data (-10 s to 0 s) are steady state conditions.

All times of the events are given with respect to the break time assumed as time 0 s.

Break

Break line mass flow, RPV side (SPLIT) and containment side (DEG), is shown in Fig.7. 1, Fig.7. 2, Fig.7. 3 and Fig.7. 4, for the full and reduced power cases. Trend is very similar for the two cases, both RPV and containment side. The peak of 1.33 kg/s is observed at 2 s, RPV side.

Mass flow, containment side (DEG), is related to safety injection of EBT (~200 s) and later of LGMS (~2220 s), Fig.7. 2, Fig.7. 5, Fig.7. 6.

Reverse flow from containment to RPV is observed through the SPLIT line, after RC level reaches the DVI line elevation, accordingly to phases when containment pressure is higher than RPV pressure, Fig.7. 2, Fig.7. 4, Fig.7. 7.

Blowdown, RPV depressurization, containment pressurization

The blowdown phase depressurises the RPV with mass and energy transfer to containment.

PRZ pressure is shown in Fig.7. 8, Fig.7. 9, Fig.7. 10. Depressurization rate is very similar in the full power (SPES3-172) and the reduced power case (SPES3-175).

While PRZ depressurizes, containment pressure increases as shown in Fig.7. 11 and Fig.7. 12. Pressurization trend is very similar in the two cases with reaching of the same 0.914 MPa peak.

Pressure increase around 200 s is due to ADS Stage-I intervention that discharges mass and energy into the DW, Fig.7. 13. The first mass flow peak is very similar in the two cases, while the reduced power case shows smaller second peak of flow due to lower liquid entrainment.

When RPV and DW pressures equalize, ADS Stage-I mass flow stops and DW pressure decreases thanks to LGMS injection into the RPV (intact loop) and into the RC (broken loop), Fig.7. 13, Fig.7. 14, Fig.7. 6.

Faster DW depressurization occurs when reverse flow from PSS to DW starts through the vent lines, Fig.7. 18. Injected mass is very similar in the two cases, Fig.7. 19.

Steam dumping into PSS

Containment space (DW and RC) pressurization causes transfer of steam-gas mixture from DW to PSS through the vent lines (~16 s) lasting until mass flow exits the ADS-Stage-I, Fig.7. 18, Fig.7. 13. Mass transferred from PSS to DW is shown in Fig.7. 19.

Non-condensable gas quality in the DW is shown in Fig.7. 20 and Fig.7. 21. The way steam sweeps away gas from DW is similar in SPES3-172 and SPES3-175. In the long term of the transient, the full power case has DW non-condensable gas quality stable around 0.5, while in the low power case it stabilizes around 0.6, except at the DW top, probably due to the presence of steam entering the DW from RPV through the ADS Stage-II.

Steam is dumped underwater through the PSS sparger and air pressurizes PSS and LGMS gas space, Fig.7. 18, Fig.7. 22, Fig.7. 23, Fig.7. 24, Fig.7. 25. PSS and LGMS pressure follows the DW pressure trend. When PSS pressure is high enough to overcome the PSS vent line gravity head, water is pushed backward to the DW, enhancing containment depressurization. PSS and LGMS pressure remains above DW pressure until the PSS sparger is uncovered (~4500 s), i.e. the PSS vent pipes are empty. Afterwards, air flows from PSS to DW and DW, PSS and LGMS pressures equalize, Fig.7. 18, Fig.7. 26, Fig.7. 27, Fig.7. 28.

PSS water temperature increases, thanks to mass transfer from DW, Fig.7. 18, Fig.7. 29, Fig.7. 30. Temperature increases more in SPES3-172 than in SPES3-170 accordingly to higher DW pressure and steam energy. Both liquid and gas temperatures are reported in Fig.7. 29 and Fig.7. 30. During the pressurization phase, liquid and gas temperatures are similar. After pressure equalization with the DW, gas temperature is higher than liquid, for the initially preheated heat structures that heat-up gas in the air zone. In the long term, temperature decreases according to containment pressure.

Temperatures always remain below saturation at maximum PSS pressure and also when pressure decreases, Fig.7. 29, Fig.7. 30, Fig.7. 22, Fig.7. 23.

S-Signal: Reactor scram, secondary loop isolation, EHRS-A and B actuation

The high containment pressure set-point (1.7e5 Pa), reached at 32.78 s in SPES3-172 and 31.58 s in SPES3-175, triggers the S-signal.

The S-signal (Safeguard) starts the reactor SCRAM, isolates the three secondary loops and actuates the EHRS-A and B.

Power released to fluid in the core is shown in Fig.7. 31 and Fig.7. 32. Steady state power is 10 MW for SPES3-172 and 6.5 MW for SPES3-175. After the scram signal, the reduced power curve continues at 6.5 MW for 3.35 s, until it intersects the nominal decay power curve. Little lower energy is provided to primary fluid, between the scram signal and 3.35 s later, in the 65% power case than in 100% case. It is about 4 MJ, that correspond to 1.3 kJ/kg of primary fluid. Such value is about 0.08% of fluid enthalpy at nominal conditions and it has no effect on the transient.
Power transferred to steam generators is shown in Fig.7. 33 and Fig.7. 34. The peak of removed power occurs following the EHRS-C intervention with similar values in SPES3-172 and SPES3-175 (1.64 MW at 318 s). In the long term of the transient, power removed by SGs is the same in the two cases.
The MFIV and MSIV of secondary loops are contemporarily closed in 5 s. Secondary loop mass flows are shown in Fig.7. 35 and Fig.7. 36. They stop at secondary loop isolation and re-start at EHRS actuation. EHRS-A and B are actuated at secondary side isolation and natural circulation flow establishes. EHRS-C is actuated at LM-signal, starting secondary loop natural circulation after about 150 s from the loop isolation. After loop isolation, very similar mass flows are observed in the full power and reduced power case.

EHRS-A and B are actuated by opening in 2 s the related isolation valves (EHRS-C is actuated later on LM-signal). The peak mass flow of 0.262 kg/s is reached at 38 s. Between 1000 s and 10000 s, quite steady condition is reached with natural circulation mass flow of about 0.16 kg/s in the loops A and B, Fig.7. 37. After 10000 s, larger oscillations appear and mass flow decreases to low values around 0.02 kg/s in the long term, Fig.7. 38.

Power removed by EHRSs is shown in Fig.7. 39 and Fig.7. 40. The EHRS-A and B peaks of removed power occur at very close times with very similar values. The same for the EHRS-C removed power peak. Power removed in the long term is very similar in the 65% and 100% power cases.

Secondary side pressures are shown in Fig.7. 41 and Fig.7. 42. After isolation, pressure increases due to heat transfer from the primary side that makes water contained in the SG tubes evaporate. SG tube levels decrease until water stored in EHRS heat exchangers is poured into the loops and power begins to be removed, Fig.7. 37, Fig.7. 39. Similar trends are observed for the two cases. Fig.7. 43 and Fig.7. 44 show SG-A secondary side collapsed level, very similar in SPES3-172 and SPES3-175.

Pump coastdown and primary circulation through RI-DC check valves

PRZ level is shown in Fig.7. 45. The early phase of level decrease, until ADS Stage-I intervention (~200 s), is due to loss of mass from the break. Level increase after the ADS Stage-I actuation is similar, but lower in SPES3-175. This justifies lower water entrainment at the ADS nozzle in this case, Fig.7. 13. When RPV and containment pressure equalize (~2300 s), ADS discharge stops and PRZ level decreases down to zero, Fig.7. 14.

Liquid fraction at the pump inlet is reported in Fig.7. 46. Due to loss of mass from the break, the pump uncovers soon.

The pump coastdown is triggered by the Low PRZ level signal delayed of 15 s. The pump velocity curve is shown in Fig.7. 47. Run at reduced velocity in the steady state, the reduced power case curve intersects the full power one, continuing at constant velocity for 2 s after the coastdown signal. Afterwards, the curves are exactly overlapped.

Soon after the pump suction is uncovered, RPV natural circulation through the pump interrupts.

Core inlet flow is shown in Fig.7. 48 and Fig.7. 49. The trend is similar in the two cases.

The pump stop and pressure decreasing in the DC let the RI-DC check valves open around 150 s and allow natural circulation from riser to SG annuli at lower level in the RPV. The RI-DC check valve mass flow is shown in Fig.7. 50 and Fig.7. 51 for each SG annulus. The trend and value of the RI-DC check valve mass flow is strictly related to core flow, Fig.7. 48, Fig.7. 49.

The fast RPV loss of mass and depressurization rapidly cause flashing of the primary circuit and void begins at core outlet at 177 s in SPES3-172 and 237 s in SPES3-175, Fig.7. 52, Fig.7. 53, Fig.7. 54. Low liquid fraction period in the core lasts until about 6000 s in SPES3-172 and 5000 s in SPES3-175.

LM-Signal: EHRS-C, ADS Stage-I and EBT actuation

The LM-Signal (LOCA mitigation) occurs at 196.68 s in SPES3-172 and 196.42 s in SPES3-175 when the low PRZ pressure set-point (11.72e6 Pa) is reached, Fig.7. 8.

The LM-signal actuates the EHRS-C and opens the ADS stage-I and EBT actuation valves.

SPES3 EHRS-C is actuated by opening in 2 s the related isolation valves. The peak mass flow of 0.547 kg/s is reached at 200 s in SPES3-172 and SPES3-175. After the peak, quite steady natural circulation of about 0.32 kg/s is present between 3000 s and 9000 s. After that, strong oscillations appears and mass flow decreases. The long term values are similar in the two cases, Fig.7. 37, Fig.7. 38.

Power removed by SPES3 EHRS-C is shown in Fig.7. 39, Fig.7. 40. The EHRS-C peak of removed power occurs around 35 s with a value of 712 kW, in the two cases. Average power removed by EHRS-C in the long term is around 20 kW.

The three trains of ADS Stage-I are actuated contemporarily on LM-signal and the actuation valves are fully opened in 10 s. ADS Stage-I mass flows are shown in Fig.7. 13.

When ADS intervene, PRZ is empty, Fig.7. 45, and the ADS flow peak is due to steam flowing toward the QT. At ADS intervention, water is sucked upwards and PRZ level increases. The second ADS mass flow peak is caused by increasing liquid void fraction at the PRZ top that decreases when the PRZ empties. SPES3-172 case shows the second peak of flow greater than SPES3-175.

ADS Stage-I integral flow is shown in Fig.7. 55 and mass exited from the RPV through the ADS in SPES3-172 is about 50 kg more than in SPES3-175.

RPV mass is shown in Fig.7. 52 and Fig.7. 53. The trend is similar in the two cases until about 4500 s. Between 4500 s and 10000 s, the lower power case shows stronger mass increase, related to higher water back-flow from containment to RPV, through the RC to DVI line (intact loop) and break line, RPV side (split), Fig.7. 56, Fig.7. 3. The final value of mass in the RPV is around 2300 kg in both cases.

The LM-signal triggers EBT actuation, by fully opening the valves in 15 s. EBT injection mass flow is shown in Fig.7. 5 and it is very similar in SPES3-172 and SPES3-175. EBT injection into the broken DVI line is initially about 14 times larger than injection into the intact DVI line, due to the presence of the break. EBT injection continues until both EBTs are empty, Fig.7. 58.

Soon after EBT actuation, liquid circulation from the RPV toward the EBT starts at the EBT to RPV connection, then, after such connection is uncovered, steam replaces water contained in the EBT top lines and tanks, Fig.7. 59.

EBT actuation is responsible for mass flow through the break line, containment side, Fig.7. 2. EBT injected mass enters the RPV through the intact DVI line, while flow occurs through the broken DVI (SPLIT break line) toward the containment, Fig.7. 2. Such reverse flow lasts until RPV and containment pressures equalize, Fig.7. 14. After that, DVI line mass flow is driven by differential pressure between RPV and containment and by level of water in one or the other side of the plant.

RPV saturation

RPV mass decreases due to loss of mass from the break, Fig.7. 52, Fig.7. 53. Fast RPV depressurization leads to reach the saturation conditions (core bottom liquid fraction < 1) at 177 s in SPES3-172 and 237 s in SPES3-175. Two-phase mixture occurs in the core, but natural circulation through the RI-DC check valves allows to remove the decay heat and temperature difference establishes again between core inlet and outlet when core is under liquid single-phase, Fig.7. 54, Fig.7. 50, Fig.7. 60, Fig.7. 61. Inlet and outlet core temperatures are shown in Fig.7. 60, Fig.7. 61 and they are very similar in the two cases.

Core heater rod temperatures are shown in Fig.7. 62, Fig.7. 63, Fig.7. 64, Fig.7. 65 for the normal and hot rods, respectively. Notwithstanding the core liquid void fraction decrease, rod surface temperatures never overcomes maximum steady state temperature.

Low DP RPV-Containment signal, LGMS and RC to DVI line valve actuation

The containment pressure peak of 0.914 MPa occurs at 2270 s in SPES3-172 and SPES3-175, Fig.7. 11.

The “Low DP RV-Containment” signal set point (50 kPa) is reached at 2267.3 s in SPES3-172 and 2257.04 s in SPES3-175.

The combination of LM-signal AND Low DP RV-Containment signal actuates the LGMSs and opens the valves on the lines connecting the RC to the DVI lines.

The LGMS isolation valves are fully open in 2 s as well as the RC to DVI line isolation valves.

LGMS injection is related both to gravity and to LGMS air space pressurization (through PSS to LGMS balance lines) by non-condensable gas entering the PSS from DW. LGMS injection mass flow is shown in Fig.7. 6. Consequently to LGMS injection into the broken DVI line, mass flow from restarts, around 2200 s, through the break line, containment side, lasting until LGMS-B is empty, Fig.7. 2, Fig.7. 66.

Containment and RPV pressure equalization, PSS water flow to DW, RC flooding, reverse flow from containment to RPV

RPV and containment pressure equalize at 2390 s in SPES3-172 and SPES3-175. After this, loss of mass through the break, RPV side, depends on the periods when RRV pressure is higher than containment pressure, Fig.7. 2, Fig.7. 14.

After the peak, containment pressure decreases for steam condensation on containment wall and for LGMS injection. After RPV and containment pressure are coupled, pressures decreases due to EHRS heat removal from the primary side, Fig.7. 39, Fig.7. 40. At 2600 s, in both cases, DW pressure decreases below PSS pressure, Fig.7. 26. When differential pressure between PSS and DW is sufficient to overcome the hydrostatic head of PSS vent pipes, a reverse flow starts from PSS to DW through the vent line extension, lasting between 3520 s and 4500 s in both cases, Fig.7. 18.

RC level, initially increased for break and ADS mass flow collection, rapidly increases in correspondence of PSS injection up to the complete fill-up at 4490 s (11 m level from bottom), Fig.7. 7. After the RC is full, water partially fill-up also the DW, Fig.7. 67. In SPES3-175 case, RC level decreases below the top, in correspondence of strong water injection toward the RPV. Correspondingly, the DW fill-up is delayed. The RC level is definitively restored around 13000 s in SPES3-175.

When RC level is above the DVI connection and containment pressure overcomes RPV pressure, water enters the RPV through the RC to DVI line connections, Fig.7. 56, Fig.7. 57. The injection occurs soon after the RC to DVI line valves are open, according to primary side and containment differential pressure, Fig.7. 14, Fig.7. 15, Fig.7. 16.

Total water mass flow entering the RPV, from the containment (RC to DVI line and break line, RPV side), passes through the DVI line, as shown in Fig.7. 68, Fig.7. 69.

The QT, initially empty, is partially filled-up by the ADS discharge, Fig.7. 70, Fig.7. 13. Later fill-up is related to rapid increase of DW level after the RC fill-up, Fig.7. 70, Fig.7. 7.

Low LGMS mass signal: ADS Stage-II actuation

The LGMS low mass signal occurs when, in both tanks, mass reaches 20% of initial mass (198 kg, 20% of 1 m^3 water at 48.9 °C), Fig.7. 71.

The low LGMS mass signals actuates the ADS Stage-II valves, fully open in 10 s, to equalize primary and containment pressure and to allow steam circulation between RPV and DW in the upper part of the plant. This enhances steam condensation on the SG tubes in the long term, Fig.7. 72, Fig.7. 73.

SPES3 RWSTs begin to heat-up as soon as the EHRS are actuated, Fig.7. 74. Both in SPES3-172 and SPES3-175, temperature reaches the saturation around 83500 s.

RWST mass is shown in Fig.7. 75 and pressure in Fig.7. 76. Both in SPES3-172 and SPES3-175, the trend of mass is similar and a grater decrease is observed when water reaches saturation.

7.2 Case conclusions

The full power simulation of the DBE DVI line DEG break (SPES3-172), represents the base case for this transient, evolution of SPES3-147 [18], with the 13 SG tubes and 7 mm orifice diameter on the RC to DVI line.

The comparison between the DBE DVI line DEG break transients, starting from 100% (SPES3-172) and 65% power (SPES3-175), shows very good similarity of the results. This demonstrate that running the SPES3 facility at reduced power in steady state, with properly scaled mass flows, does not affect the transient trend and the IRIS reactor can be properly represented.

Tab.7. 1 – SPES3-172 and SPES3-175 list of the main events

	DVI-B line DEG break 2 inch equivalent	**SPES3-172**		**SPES3-175**		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Time (s)**	**Quantity**	**Notes**
Break						
1	Break initiation	0		0		break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RV side)	2	1.33 kg/s	2	1.33 kg/s	
Blowdown, RV depressurization, containment pressurization. Steam dumping into PSS						
4	Steam-air mixture begins to flow from DW to PSS	16		16		
S-Signal: Reactor scram, secondary loop isolation, EHRS-A and B actuation						
5	**High Containment pressure signal**	32.78	1.7e5 Pa	31.58	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	32.78		31.58		
7	MFIV-A,B,C closure start	32.78		31.58		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	32.78		31.58		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B opening start (EHRS 1 and 3 in IRIS)	32.78		31.58		EHRS-A,B IV stroke 2 s.
10	EHRS-A and B peak mass flow	38	0.262 kg/s	37	0.264 kg/s	
11	**High SG pressure signal**	46.47	9e6 Pa	48.58	9e6 Pa	
12	SG-A high pressure reached	46.47		48.58		
13	SG-B high pressure reached	47.52		49.96		
14	SG-C high pressure reached	47.28		50.38		
15	RWST-A/B begins to heat-up	59		59		
16	EHRS-A power peak	232	375 kW	220	380 kW	
17	EHRS-B power peak	238	368 kW	225	375 kW	
Pump coastdown and primary circulation through RI-DC check valves						
18	**Low PRZ water level signal**	122.64	1.189 m	121.72	1.189 m	
19	RCP coastdown starts	137.64		136.72		Low PRZ level signal + 15 s delay
20	Secondary loop pressure peak	68 70 72	107e5 Pa A 109e5 Pa B 113e5 Pa C	90 91 94	104e5 Pa 108e5 Pa 113e5 Pa	
21	Natural circulation begins through shroud valves	158, 161		154, 161		SG-A,B SG-C
22	Flashing begins at core outlet	177	voidf 110 (core)	237	voidf 110 (core)	<1
LM-Signal: EHRS-C, ADS Stage-I and EBT actuation. RV saturation						
23	**Low PRZ pressure signal**	196.68	11.72e6 Pa	196.42	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
24	EHRS-C opening start (EHRS 2 and 4 in IRIS)	196.68		196.42		EHRS-C IV stroke 2 s.
25	EHRS-C peak mass flow	200	0.547 kg/s	200	0.547 kg/s	
26	RWST-C begins to heat-up	217		217		
27	EHRS-C power peak	341	716 kW	334	719 kW	
28	ADS Stage I start opening (3 trains)	196.68		196.42		ADS valve stroke 10 s
29	ADS Stage I first peak flow (3 trains)	207	1.348 kg/s	207	1.301 kg/s	ST 0.454 kg/s; DT 0.854 kg/s SPES3-172 ST 0.454 kg/s; DT 0.854 kg/s SPES3-175
30	ADS Stage I second peak flow (3 trains)	266	2.39 kg/s	291	1.481 kg/s	ST 0.760 kg/s; DT 1.630 kg/s SPES3-172 ST 0.471 kg/s; DT 1.010 kg/s SPES3-175 Due to liquid fraction.
31	EBT-A and B valve opening start	196.68		196.42		EBT valve stroke 15 s
32	Break flow peak (Containment side)	214	0.695 kg/s	214	0.695 kg/s	Due to EBT intervention
33	EBT-RV connections uncovered	251, 279		242, 274		EBT-B, EBT-A
32	Natural circulation interrupted at SGs top	253		247		Pump inlet uncovered (voidf 176-01 ~0)
36	Core in saturation conditions	234		339		
37	EBT-B empty (broken loop)	670		670		530 s almost empty (670 s completely empty)
Low DP RV-Containment signal, LGMS and RC to DVI valve actuation						
38	Containment pressure peak	2260	9.14e5 Pa	2260	9.14e5 Pa	
39	**Low DP RV-Containment**	2267.3	50e3 Pa	2257.04	50e3 Pa	
40	LGMSA/B valve opening start	2267.3		2257.04		LM + low DP RV-cont. LGMS valve stroke 2 s.
41	RC to DVI line valve opening	2267.3		2257.04		RC to DVI valve stroke 2 s.
42	LGMS-B starts to inject into RC through DVI broken loop	2310		2257.04		
43	LGMS-A starts to inject into RV through DVI intact loop	2330		2330		
Containment and RV pressure equalization, PSS water flow to DW, RC flooding, reverse flow from containment to RV						
44	Containment and RV pressure equalization	2390		2390		
45	Mixture starts to flow from RC to DVI-A	2380		2380		
46	DW pressure lower than PSS pressure	2610		2610		
47	EBT-A empty (intact loop)	3060		3100		
48	Water starts to flow from PSS to DW	3600, 3520		3570, 3520		PSS A, PSS-B
49	Steam and gas mixture flows again from RV to QT	3750 to 4540		3750 to 4510		RPV P > DW P
50	RC level at DVI elevation	4130		4130		
51	RC full of water	4490		4490		
52	QT fill-up starts from DW connection	9740		4470		
Low LGMS mass signal: ADS Stage-II actuation						
53	Low LGMS mass	19854.98	20% mass (198 kg)	17480.73	(185 kg)	LGMS-A (intact loop)
54		24485.98	20% mass (198 kg)	23321.78	(185 kg)	LGMS-B (broken loop)
55	ADS stage-II start opening	24485.98		23321.78		ADS Stage-II valve stroke 10 s.
56	LGMS-A empty (intact loop)	36590		52790		~30 kg residual mass SPES3-172 ~30 kg residual mass SPES3-175
56	LGMS-B empty (broken loop)	46590		55990		~40 kg residual mass SPES3-172 ~40 kg residual mass SPES3-175
57	Flow from RC to RV (intact loop) stable	33190		37790		
Long Term conditions						
58	Core power	150000	46.00	150000	46.04	Average between 100000-150000 s
59	SG tot power	150000	43.50	150000	42.07	
60	RWST tot power	150000	41.35	150000	39.30	
61	RWST-A/B temperature	150000	100	150000	100	saturated
62	RWST-C temperature	150000	100	150000	100	saturated

Fig.7. 1 - SPES3-172 and SPES3-175 DVI break mass flow (window)

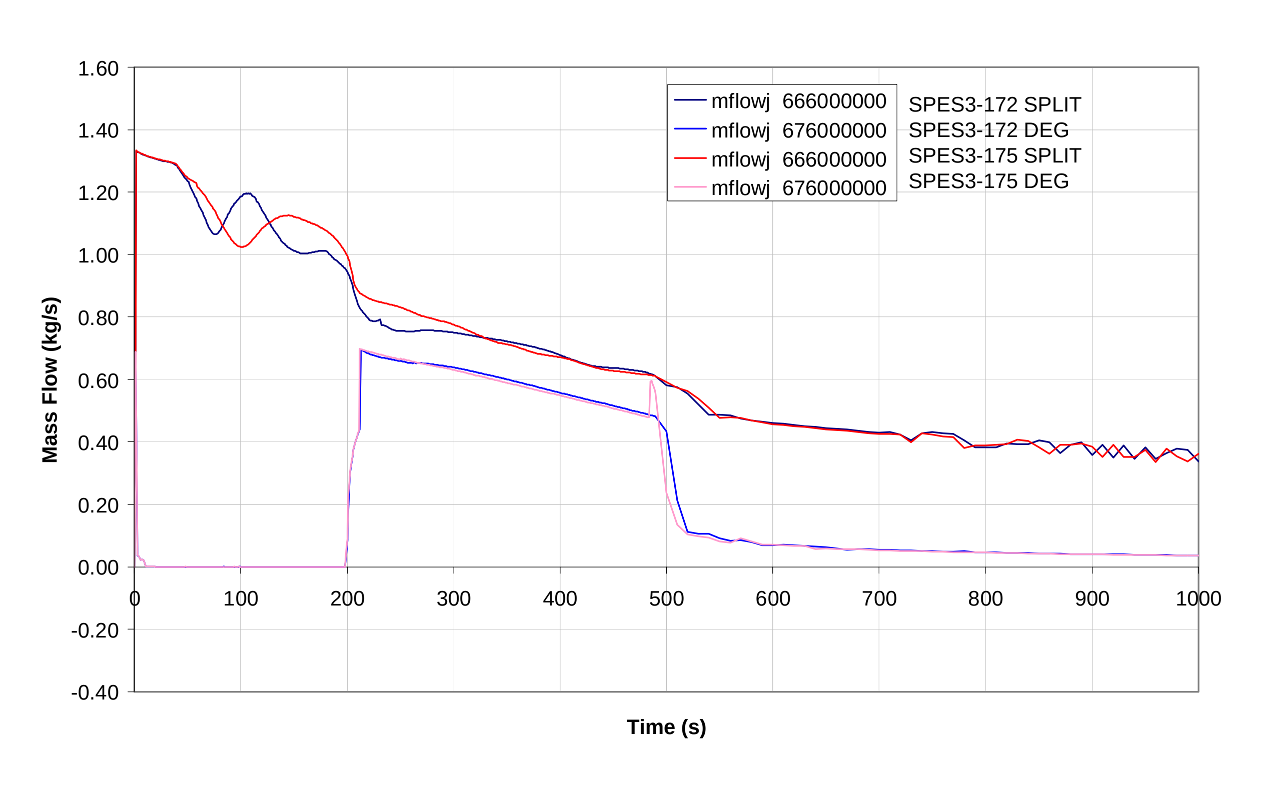


Fig.7. 2 - SPES3-172 and SPES3-175 DVI break mass flow (window)

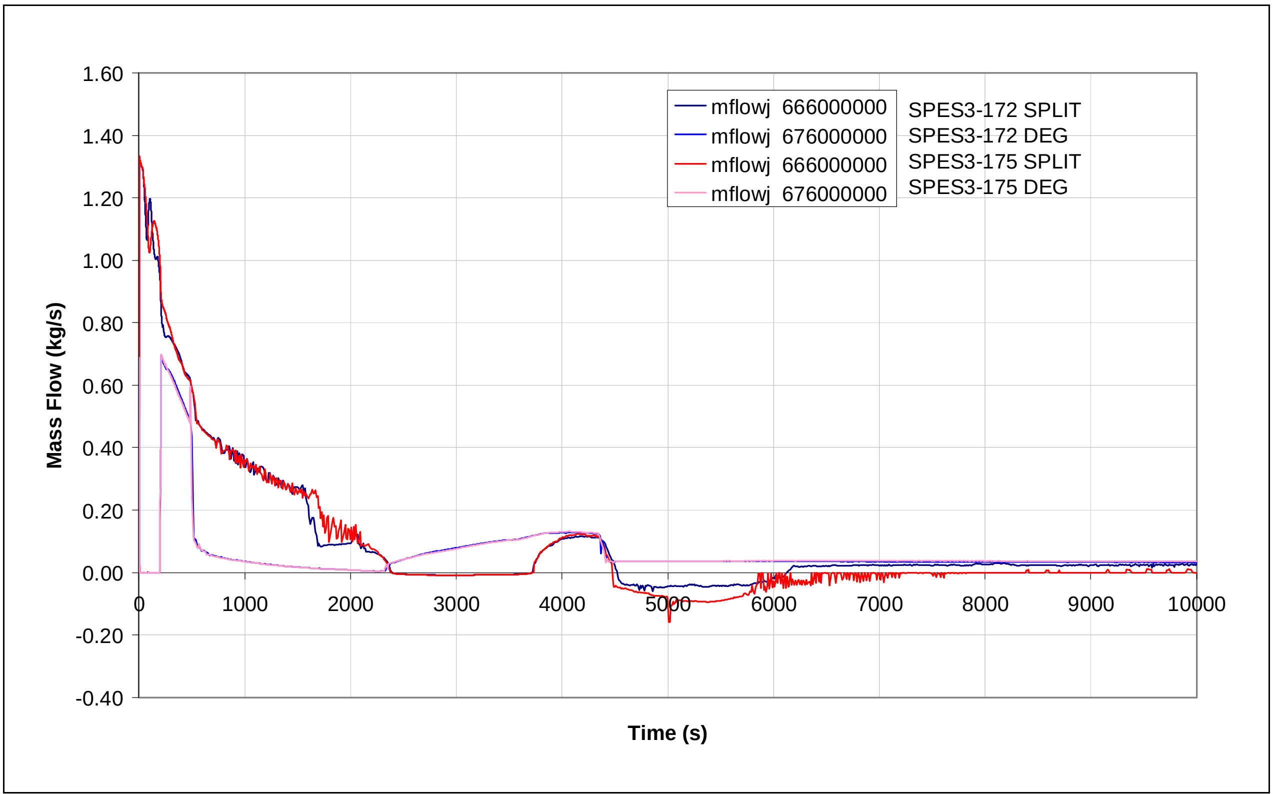


Fig.7. 3 - SPES3-172 and SPES3-175 DVI break mass flow (window)

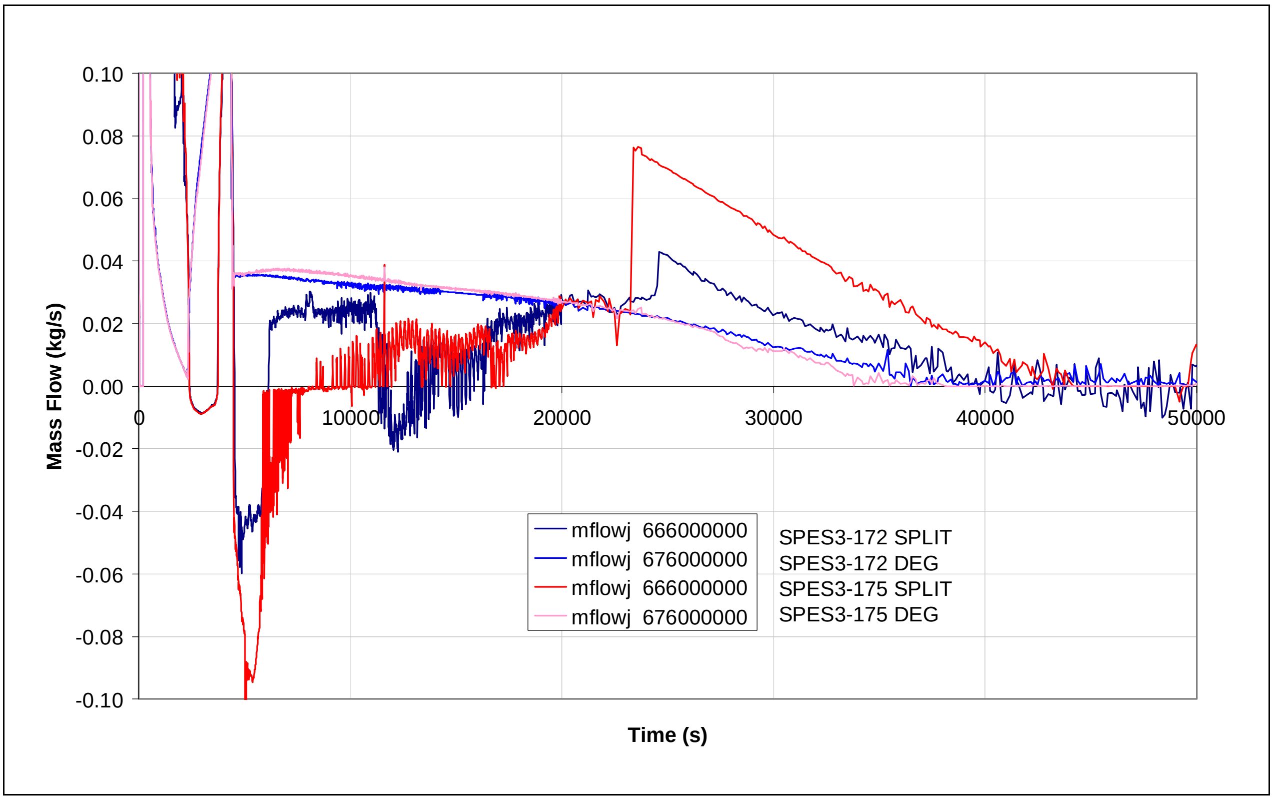


Fig.7. 4 - SPES3-172 and SPES3-175 DVI break mass flow

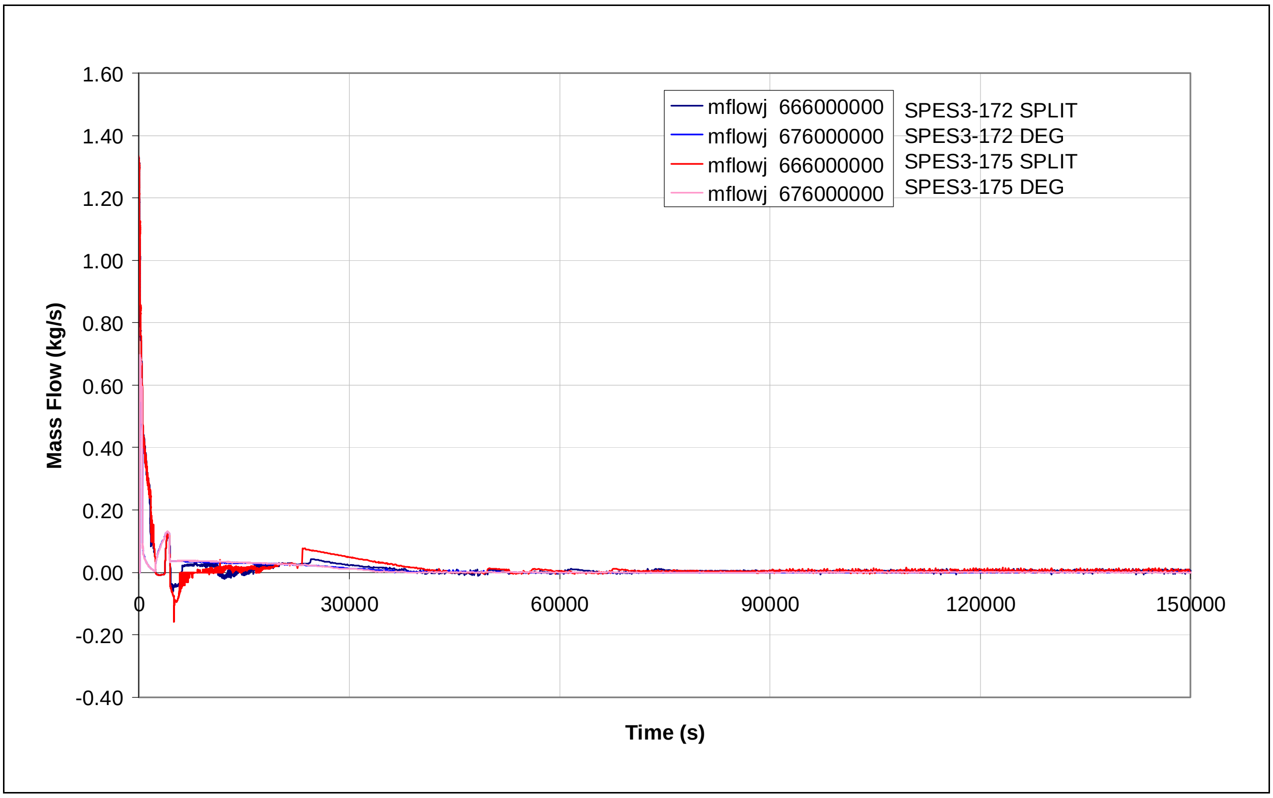


Fig.7. 5 - SPES3-172 and SPES3-175 EBT mass flow (window)

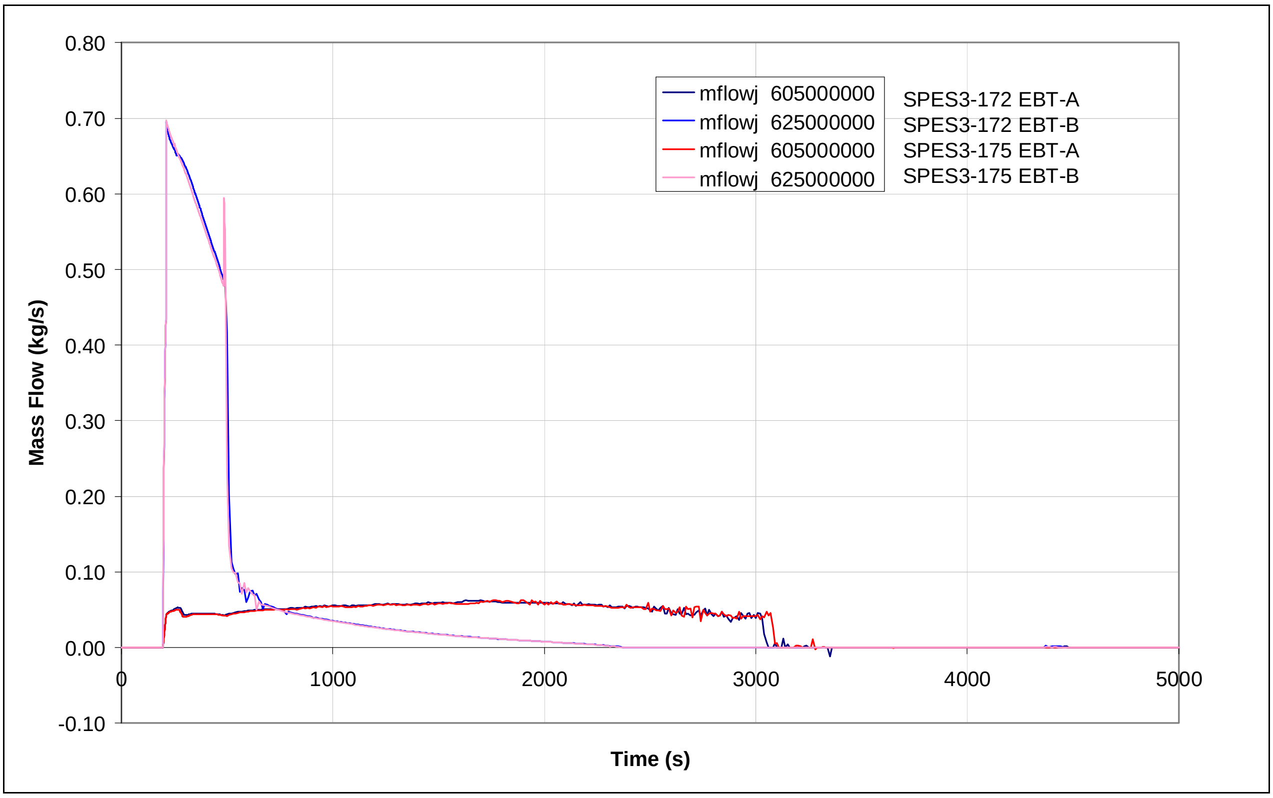


Fig.7. 6 - SPES3-172 and SPES3-175 LGMS mass flow (window)

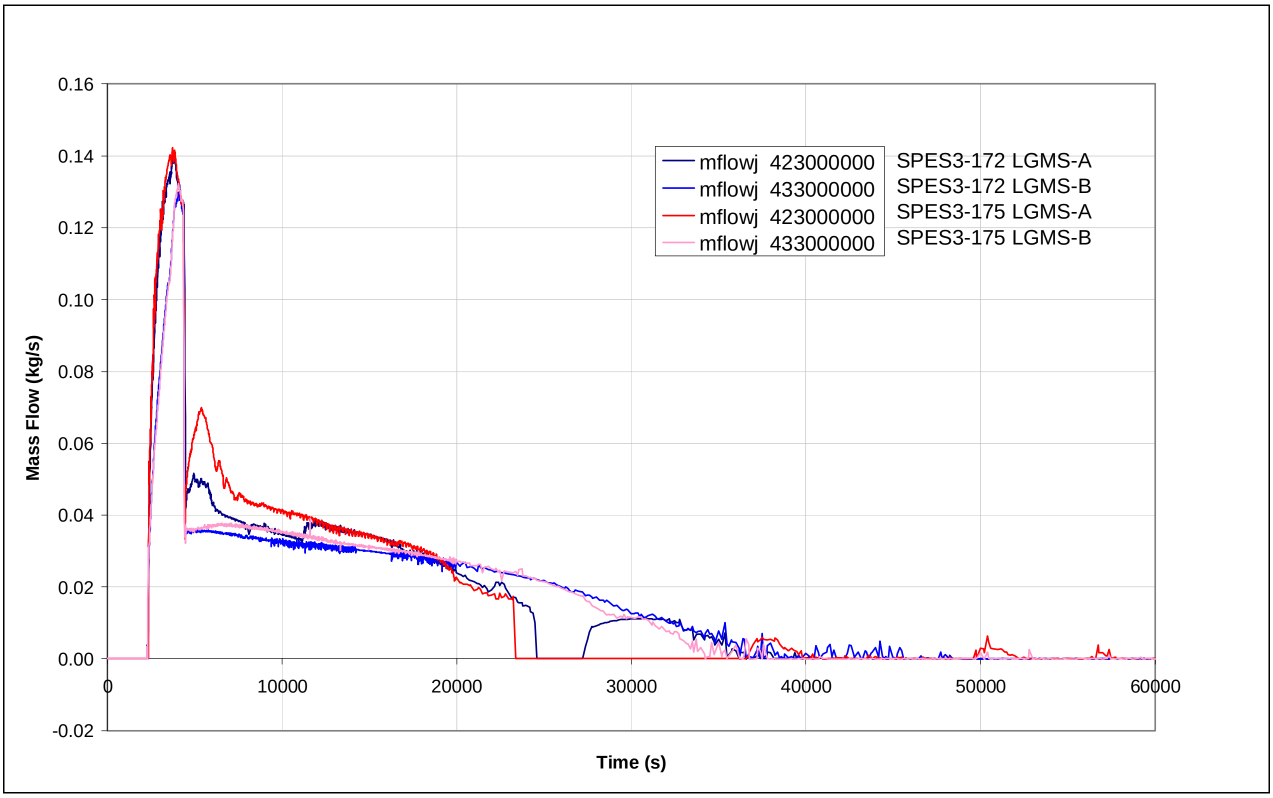


Fig.7. 7 - SPES3-172 and SPES3-175 RC level (window)

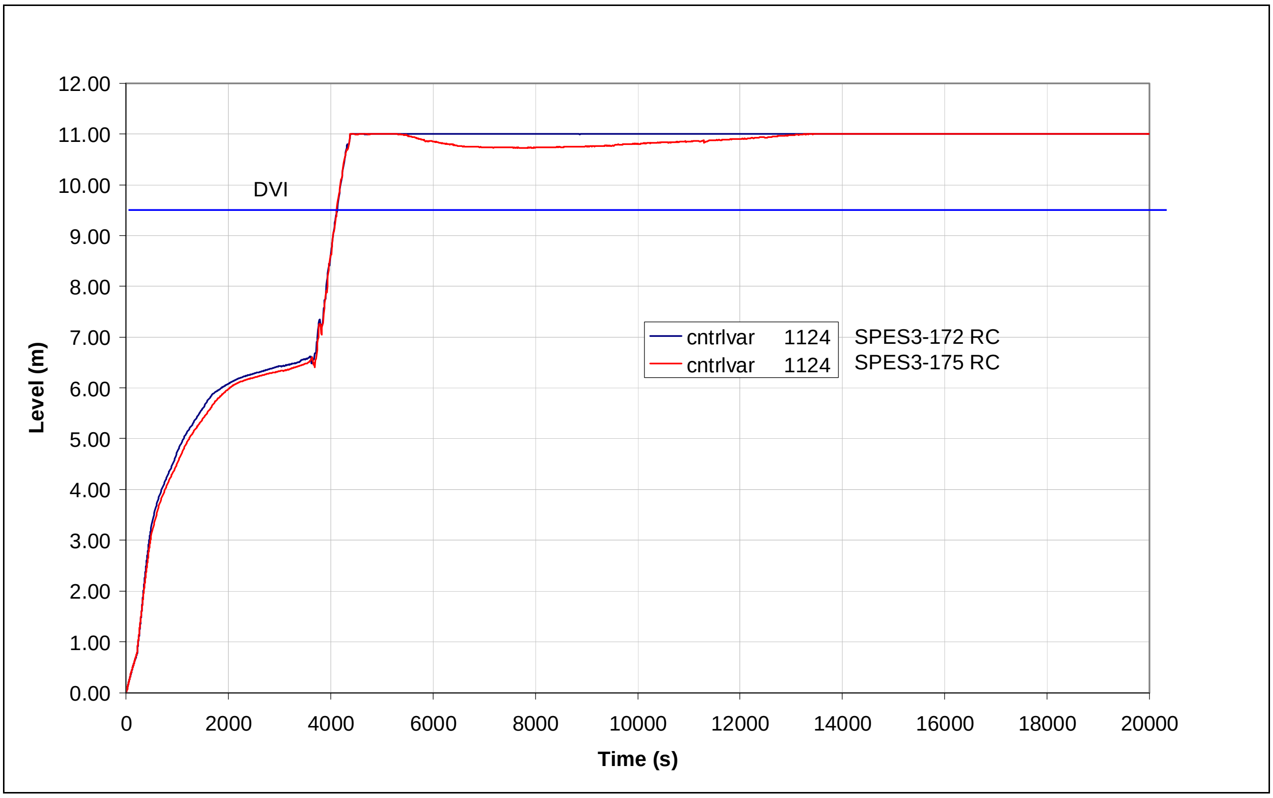


Fig.7. 8 - SPES3-172 and SPES3-175 PRZ pressure (window)

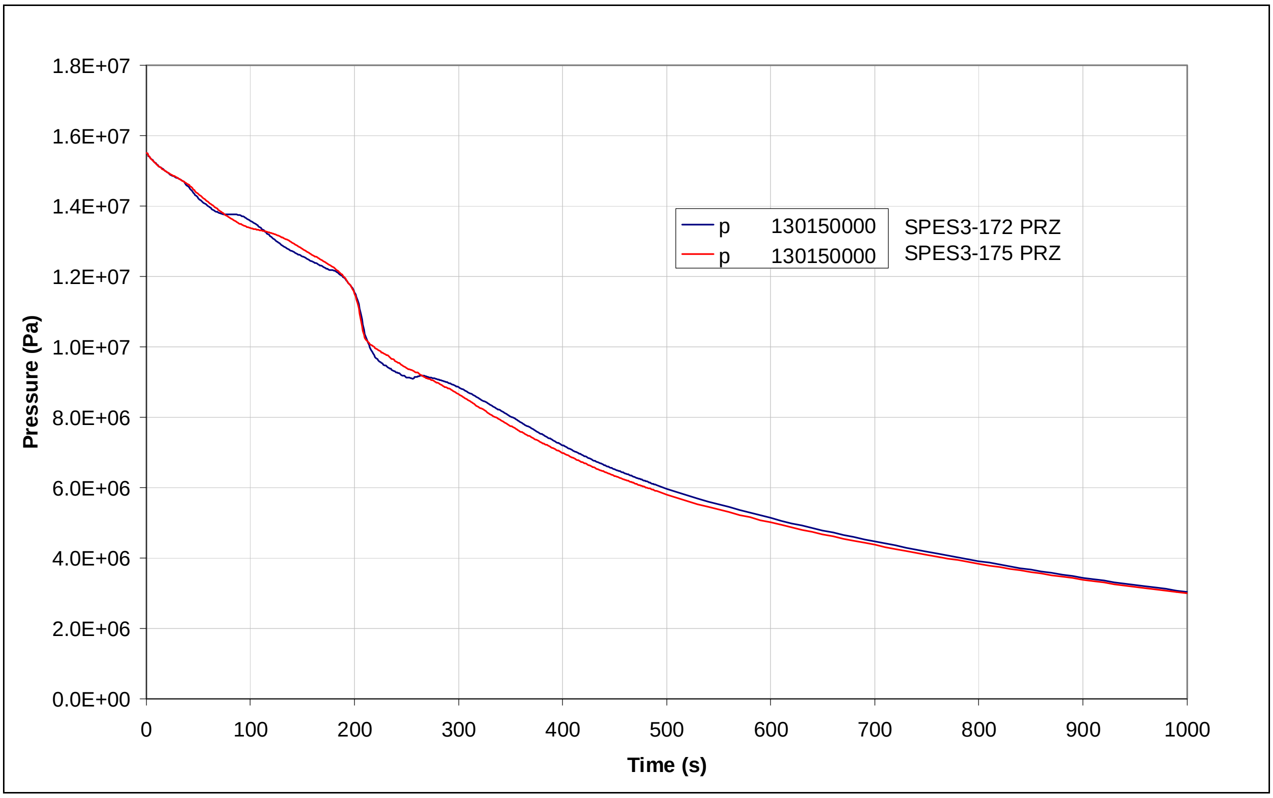


Fig.7. 9 - SPES3-172 and SPES3-175 PRZ pressure (window)

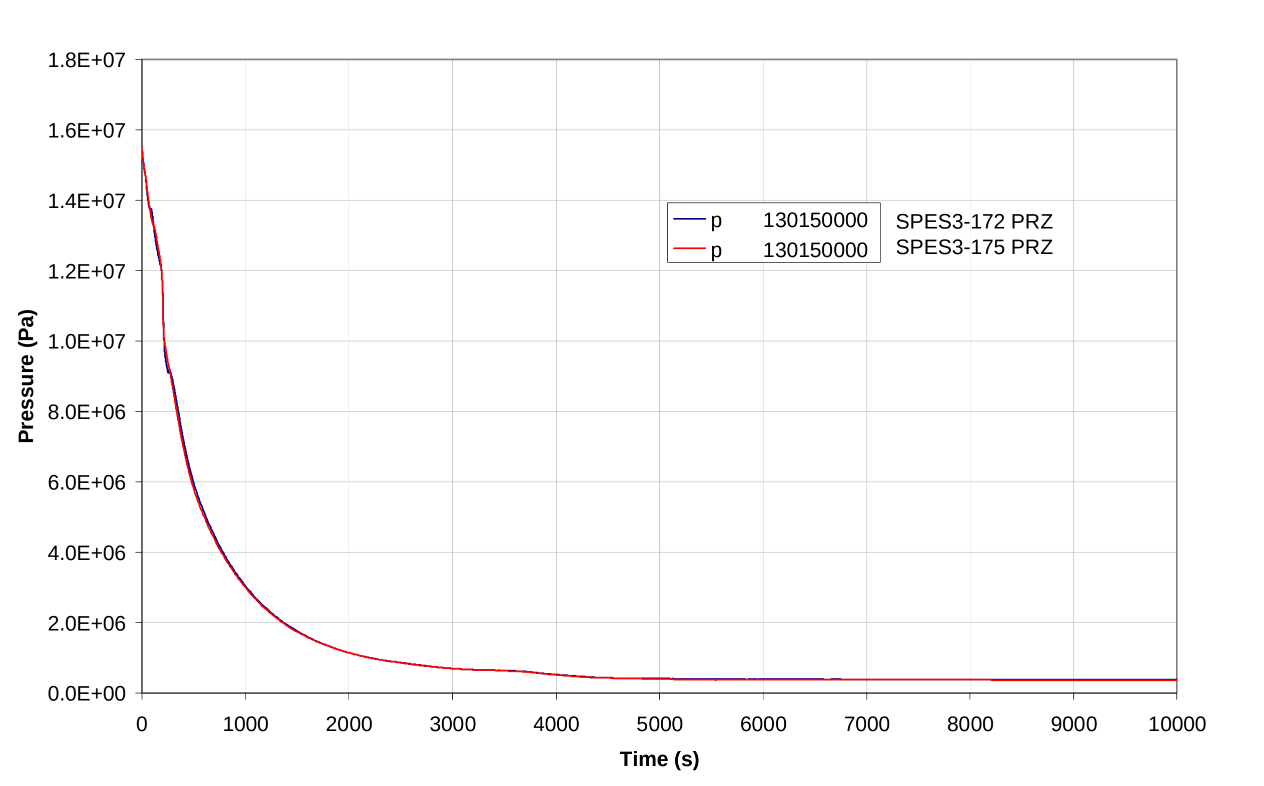


Fig.7. 10 - SPES3-172 and SPES3-175 PRZ pressure

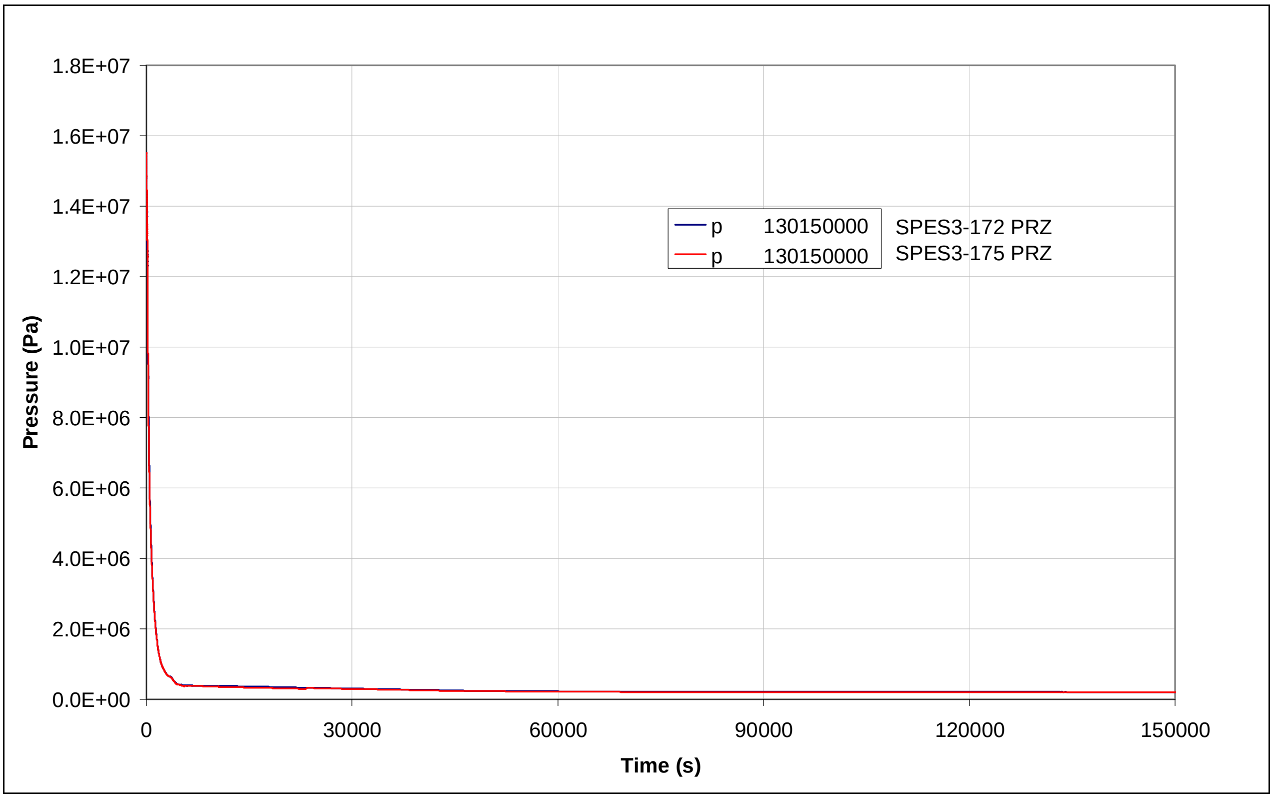


Fig.7. 11 - SPES3-172 and SPES3-175 DW pressure (window)

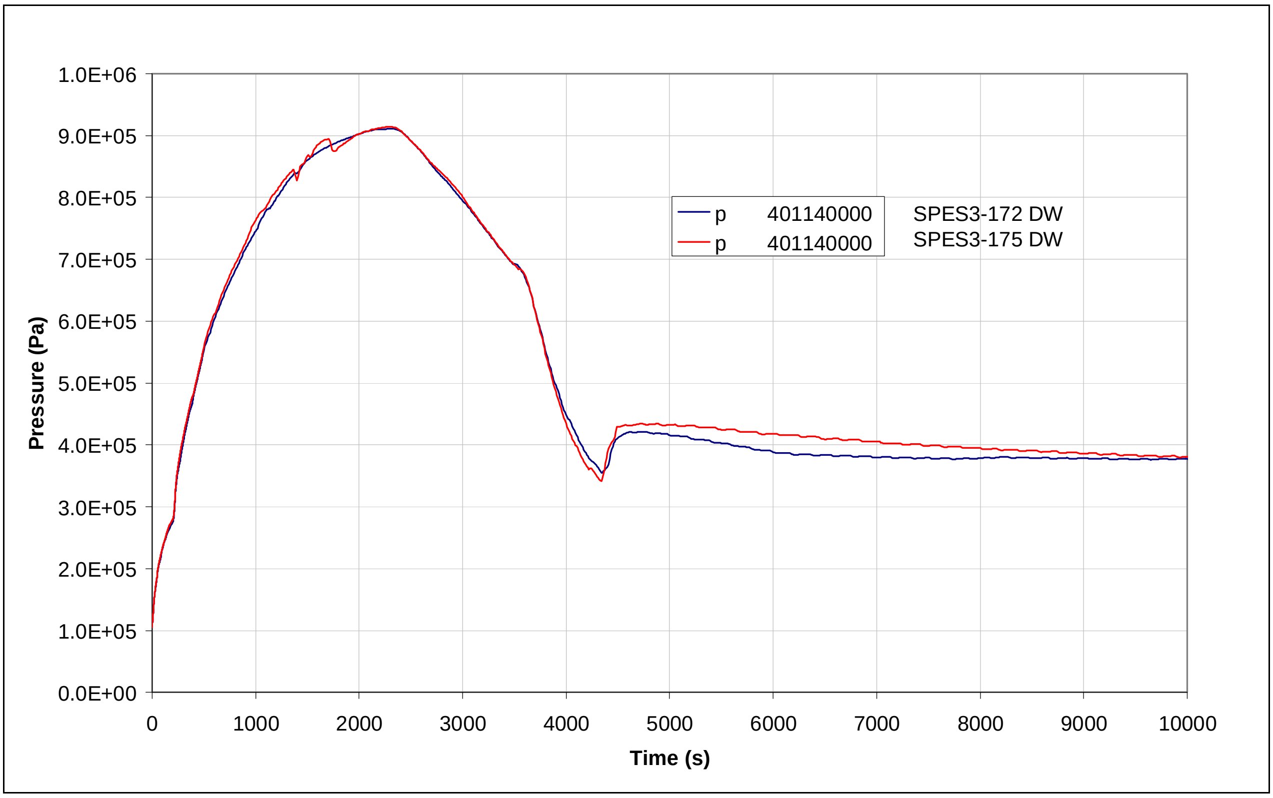


Fig.7. 12 - SPES3-172 and SPES3-175 DW pressure

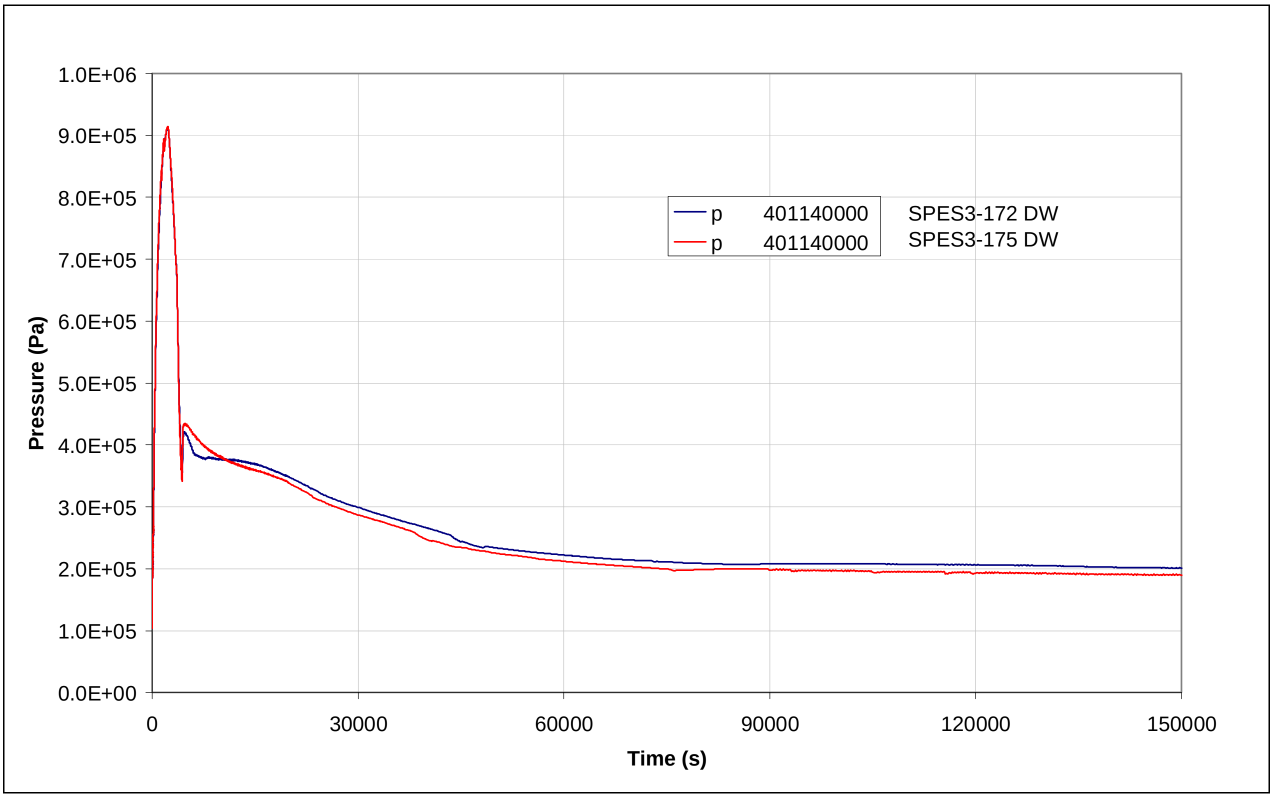


Fig.7. 13 - SPES3-172 and SPES3-175 ADS Stage-I mass flow (window)

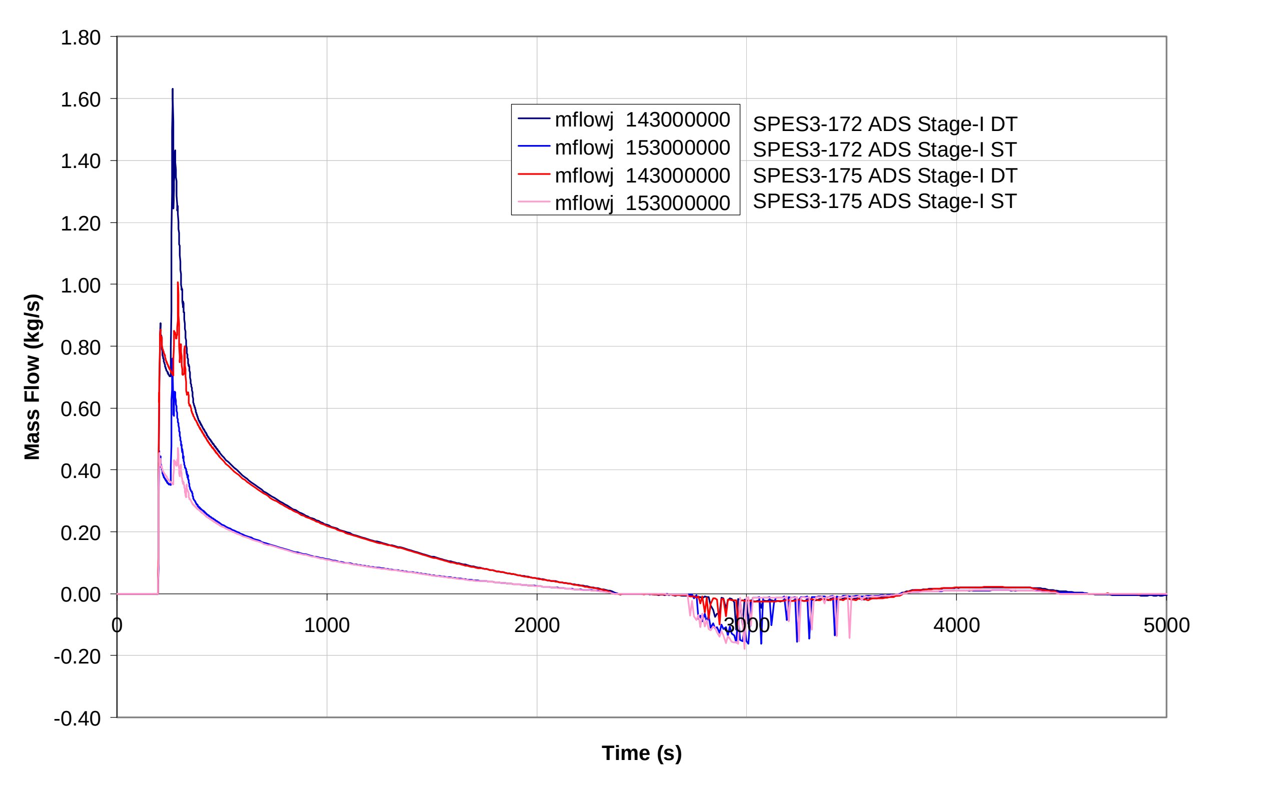


Fig.7. 14 - SPES3-172 and SPES3-175 PRZ and DW pressures (window)

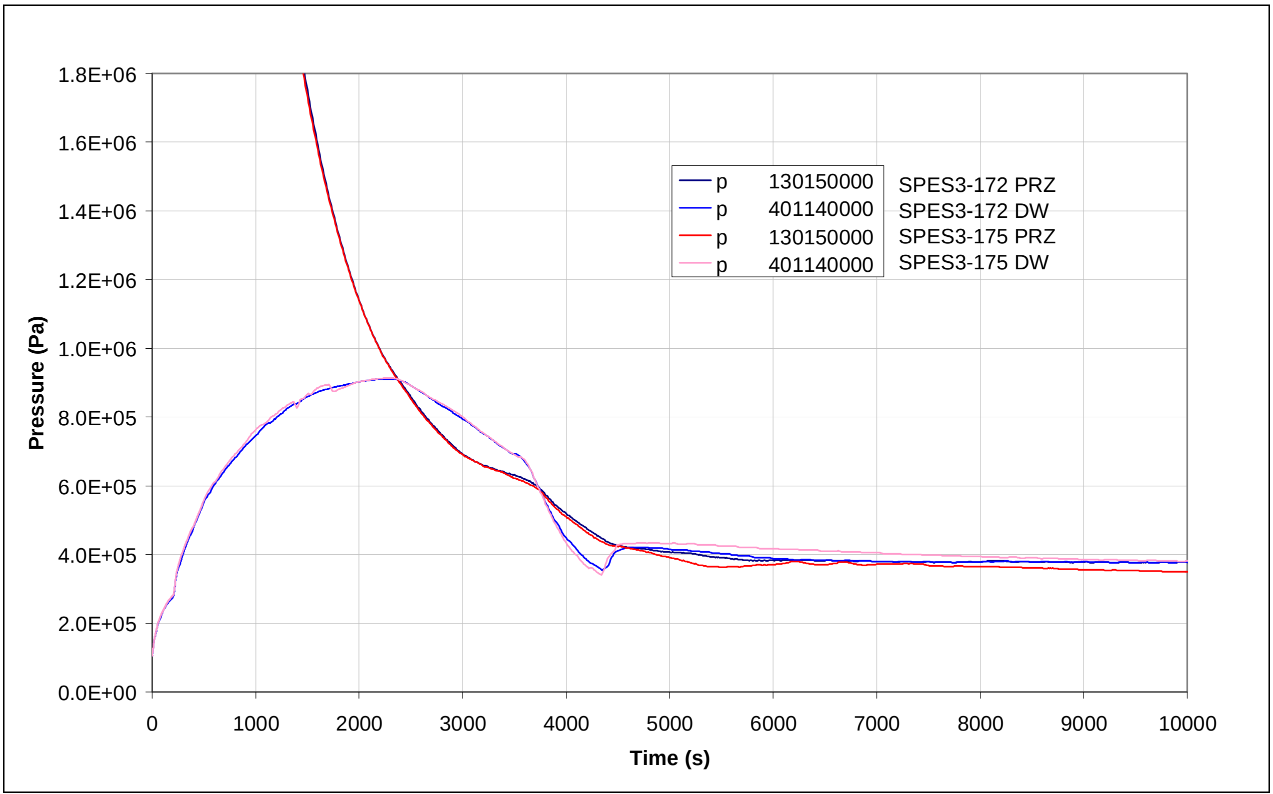


Fig.7. 15 - SPES3-172 and SPES3-175 PRZ and DW pressures (window)

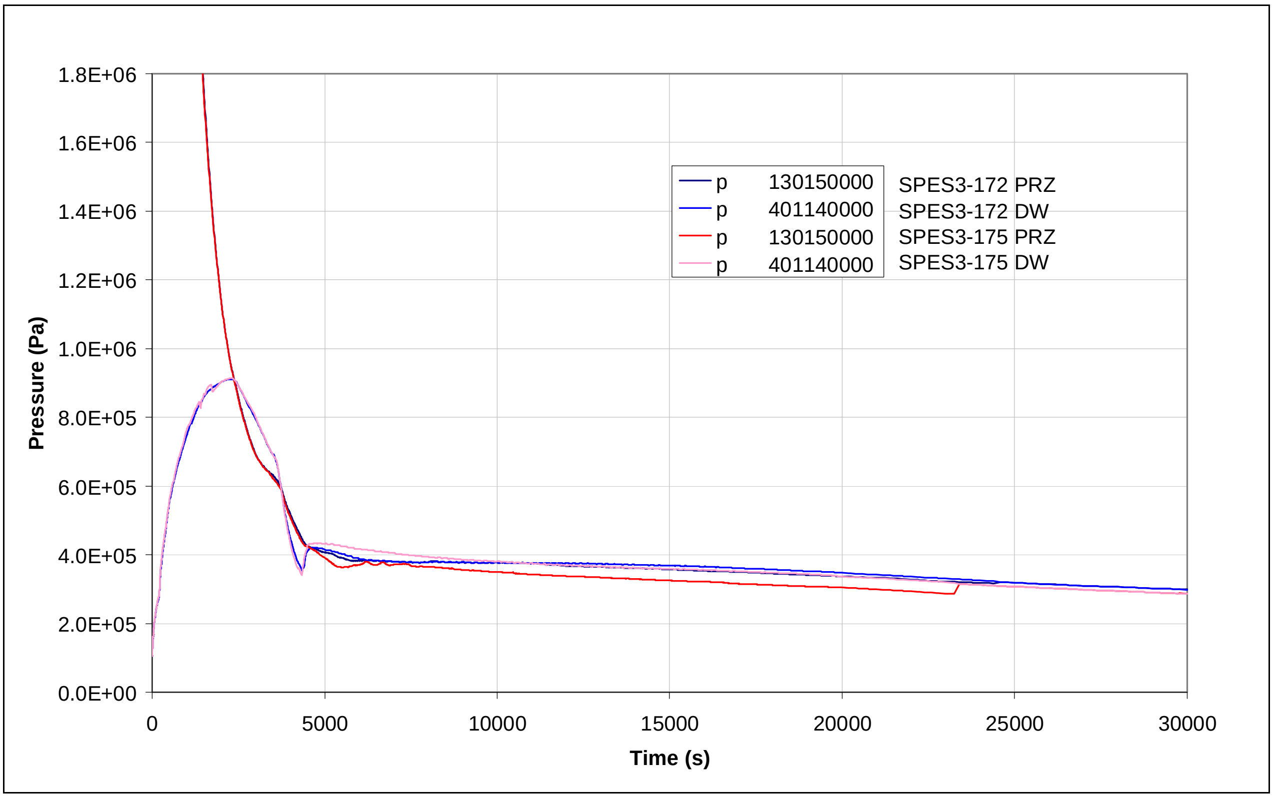


Fig.7. 16 - SPES3-172 and SPES3-175 PRZ and DW pressures

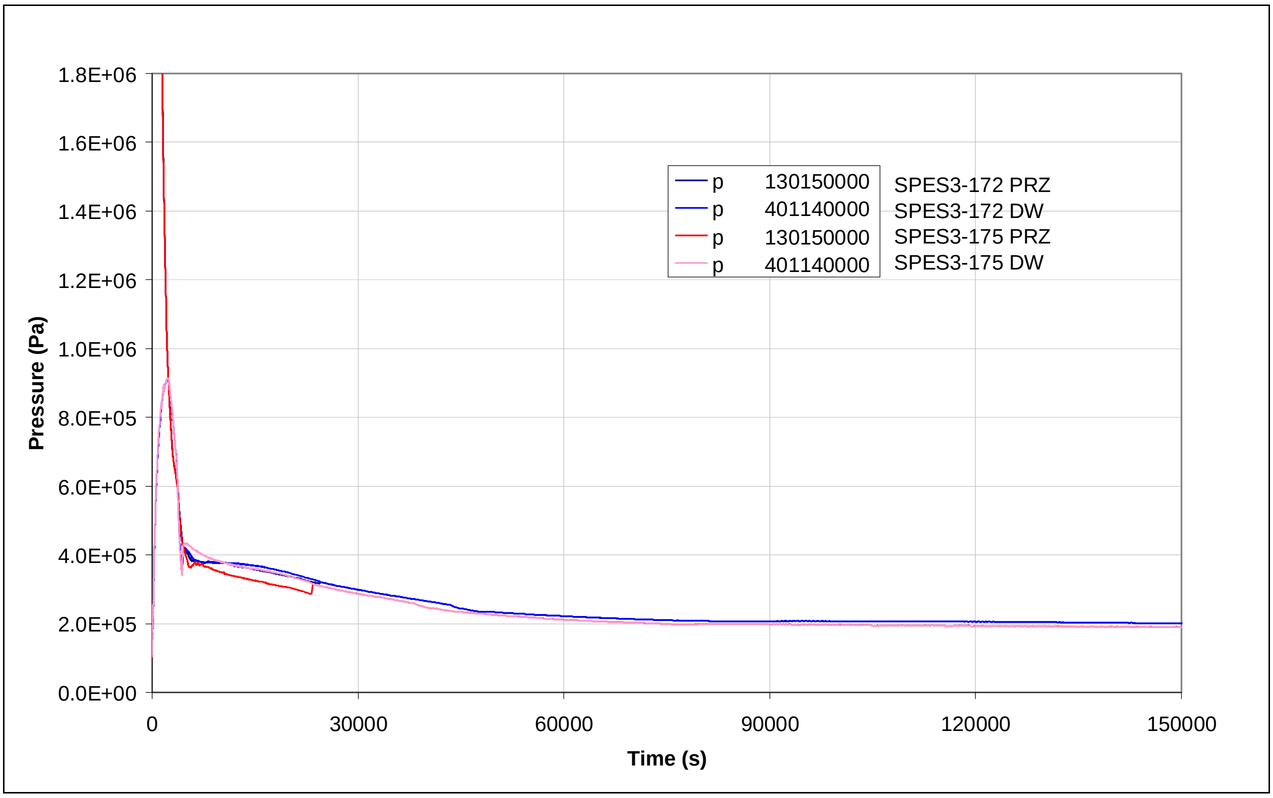


Fig.7. 17 - SPES3-172 and SPES3-175 PRZ and DW pressures (detail)

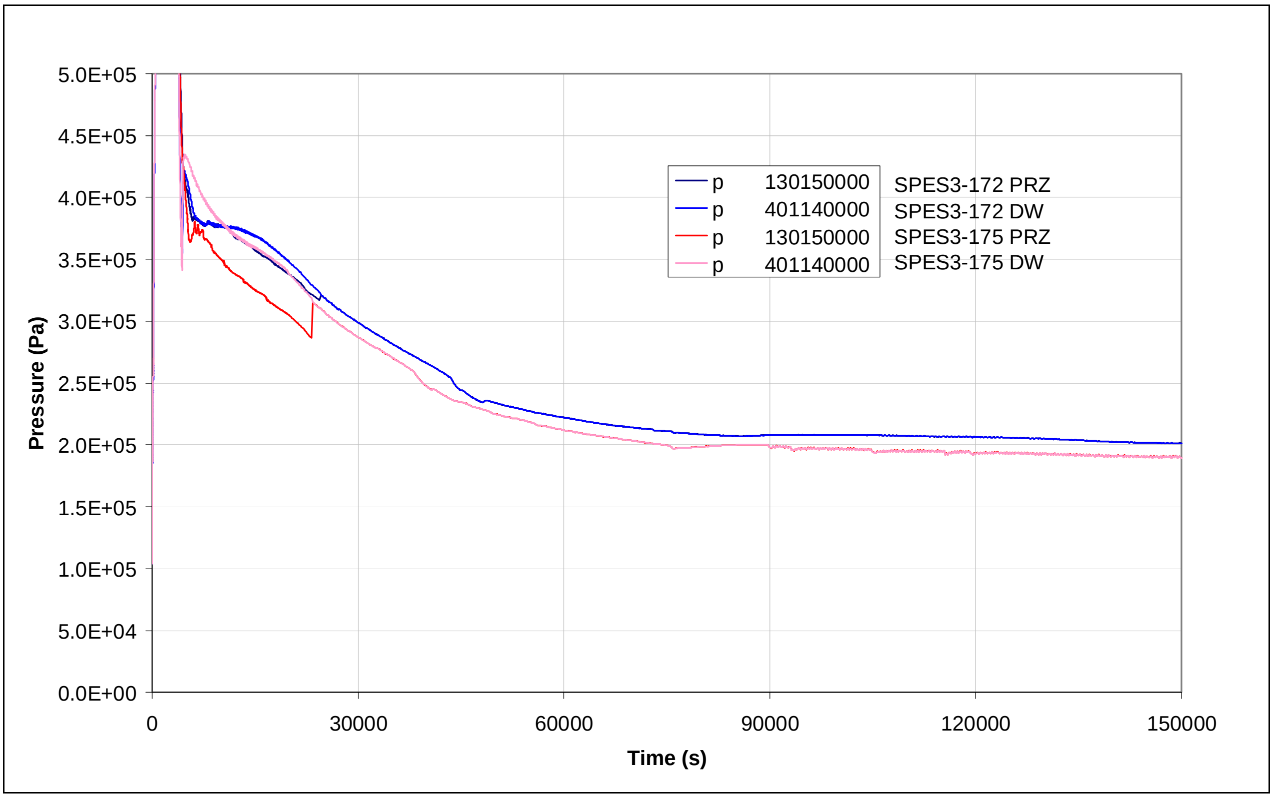


Fig.7. 18 - SPES3-172 and SPES3-175 DW to PSS mass flow (window)

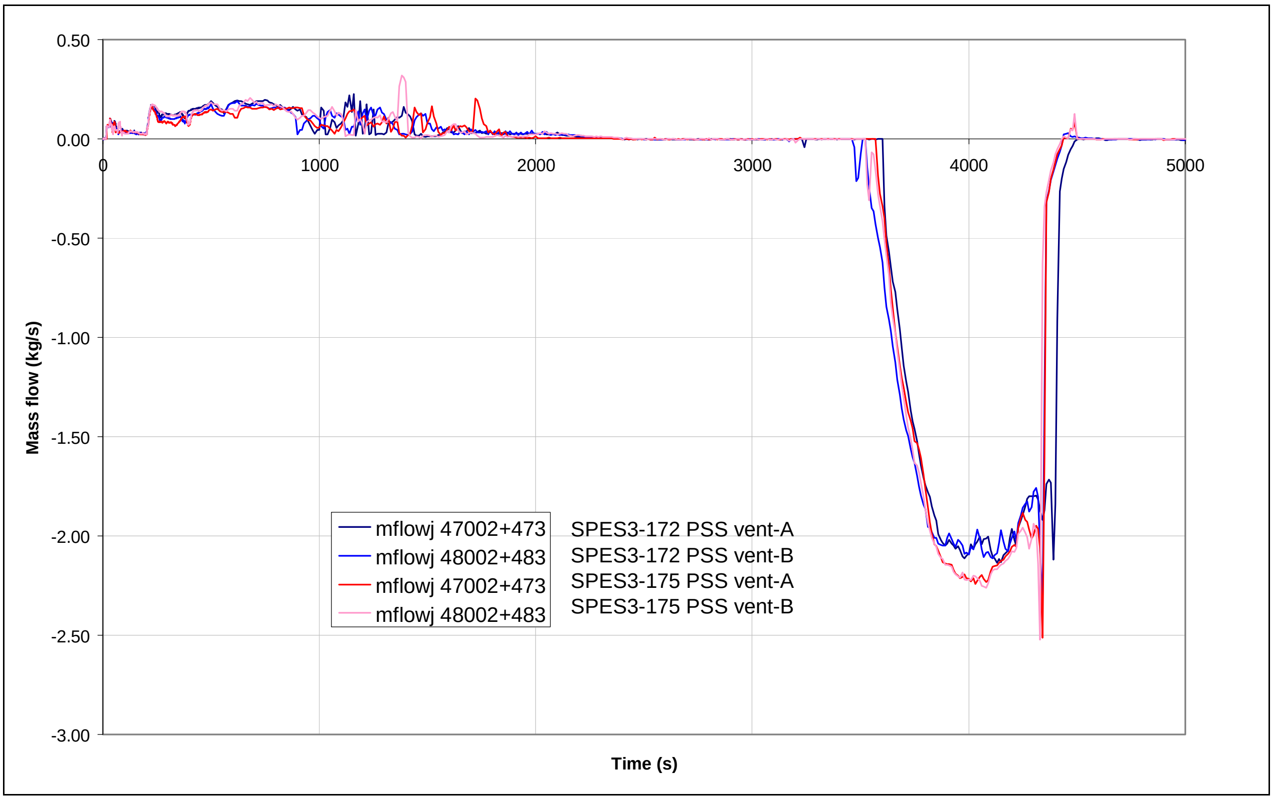


Fig.7. 19 - SPES3-172 and SPES3-175 PSS to DW integral flow (window)

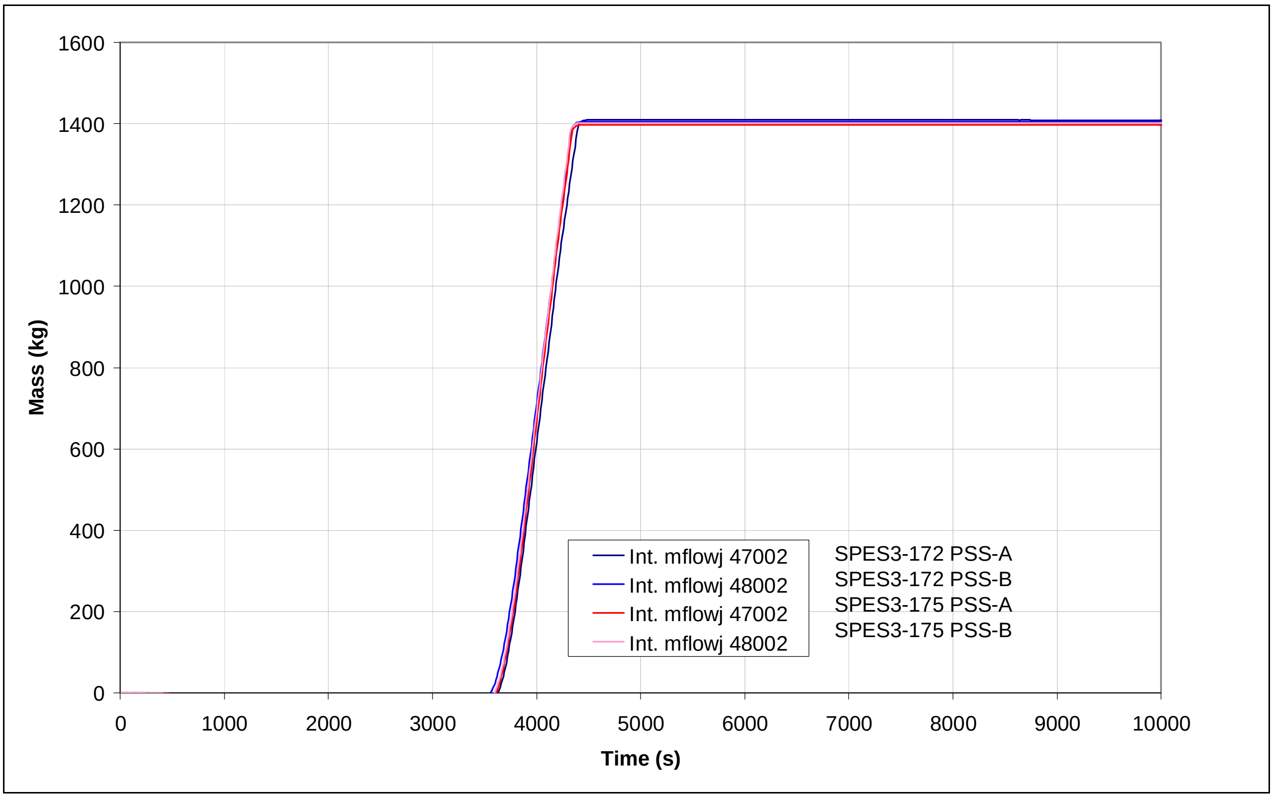


Fig.7. 20 - SPES3-172 and SPES3-175 DW non-condensable gas quality (window)

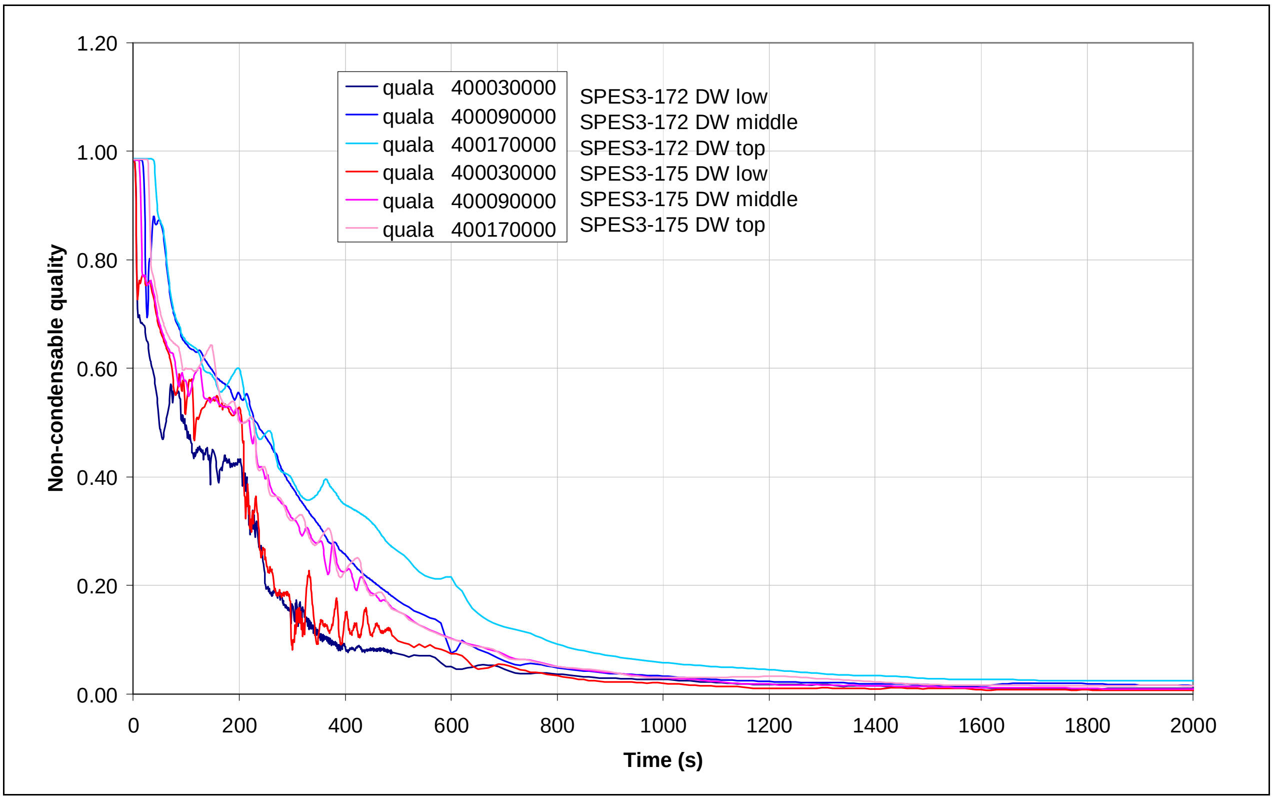


Fig.7. 21 - SPES3-172 and SPES3-175 DW non-condensable gas quality

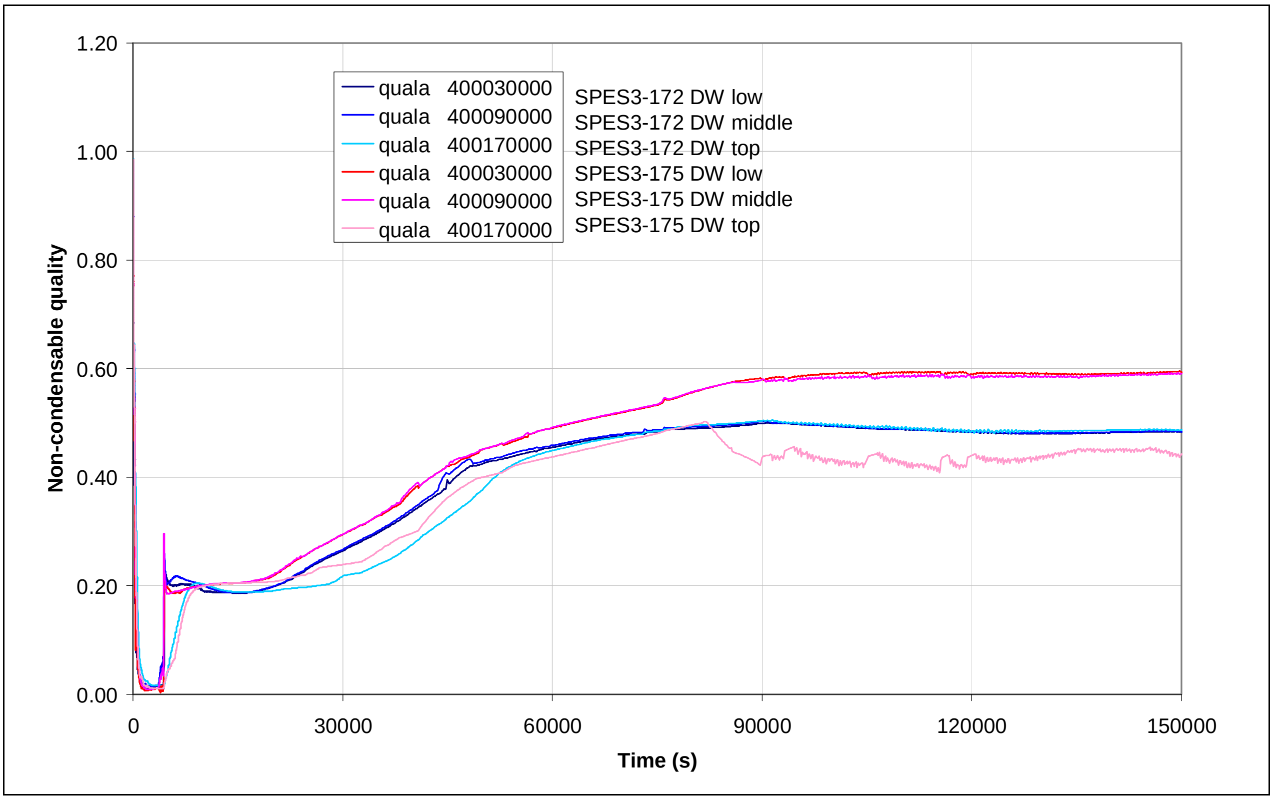


Fig.7. 22 - SPES3-172 and SPES3-175 PSS pressure (window)

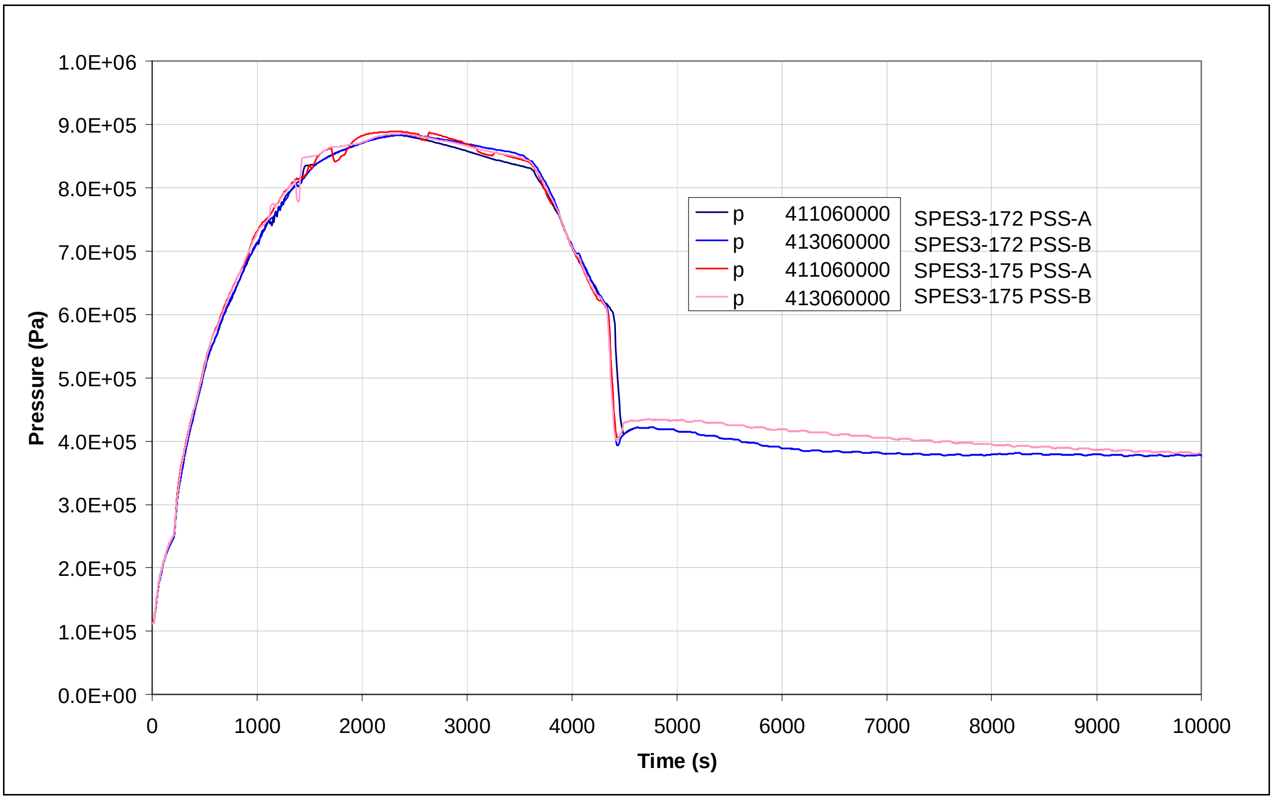


Fig.7. 23 - SPES3-172 and SPES3-175 PSS pressure

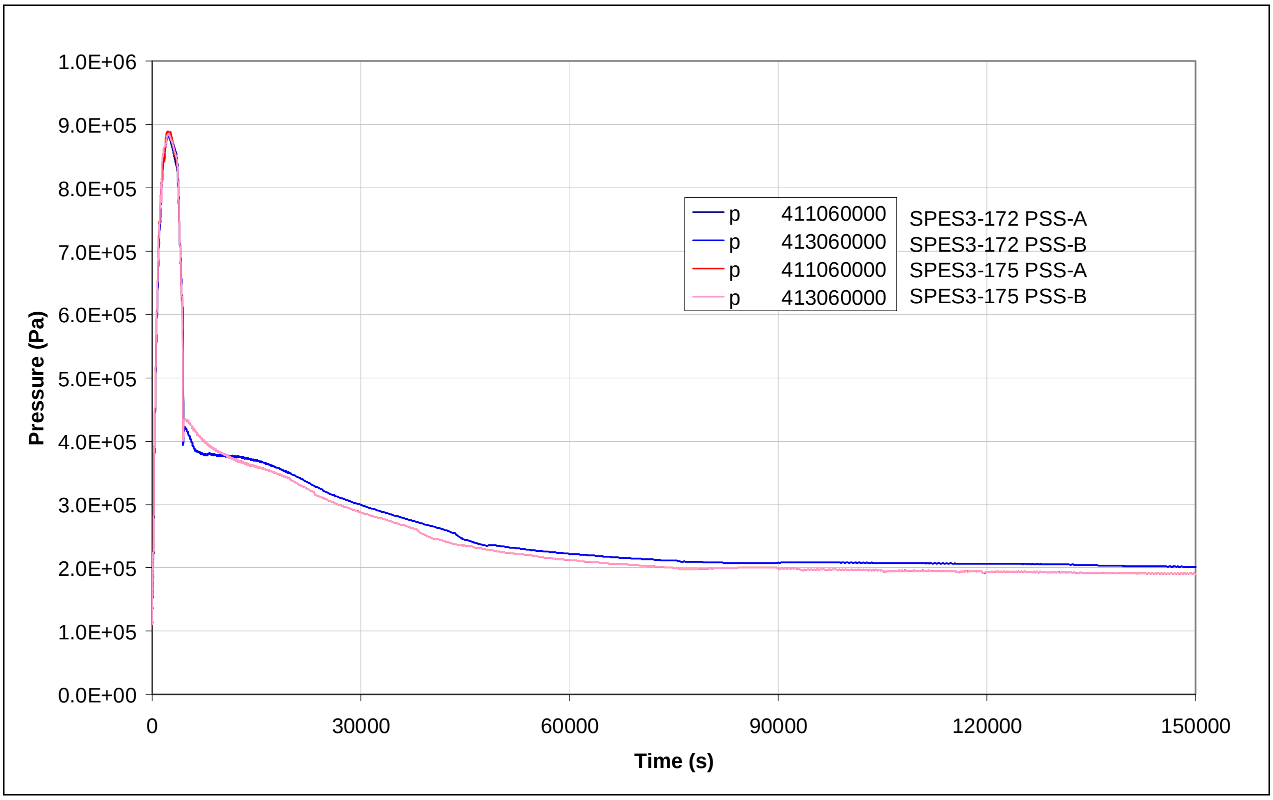


Fig.7. 24 - SPES3-172 and SPES3-175 LGMS pressure (window)

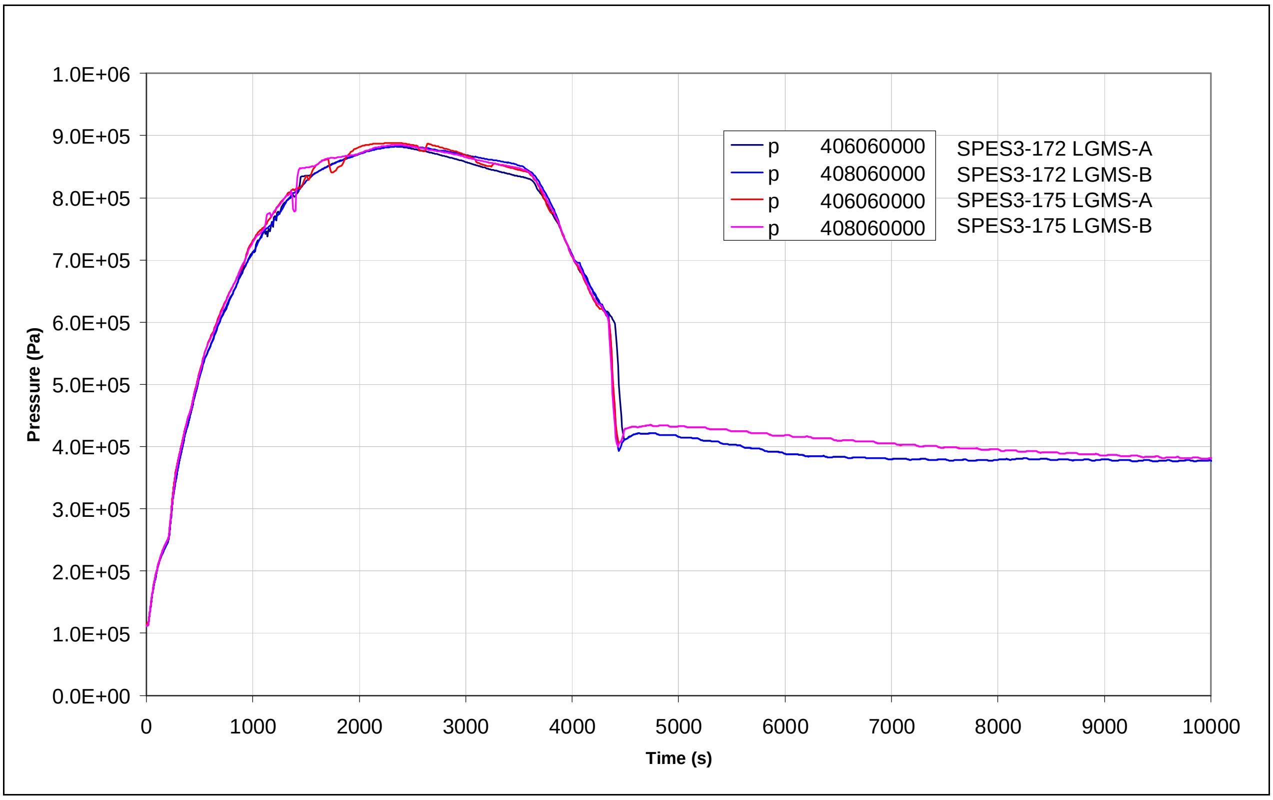


Fig.7. 25 - SPES3-172 and SPES3-175 LGMS pressure

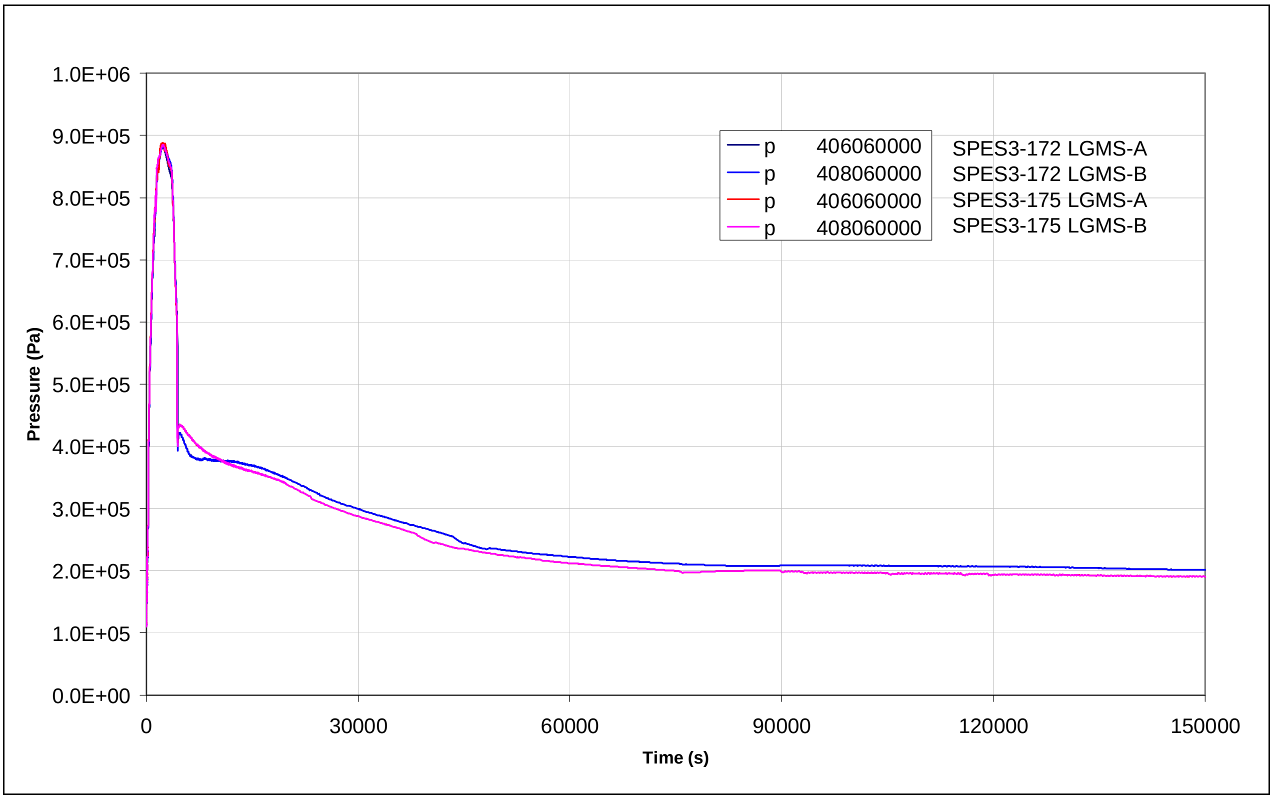


Fig.7. 26 - SPES3-172 and SPES3-175 DW and PSS pressure (window)

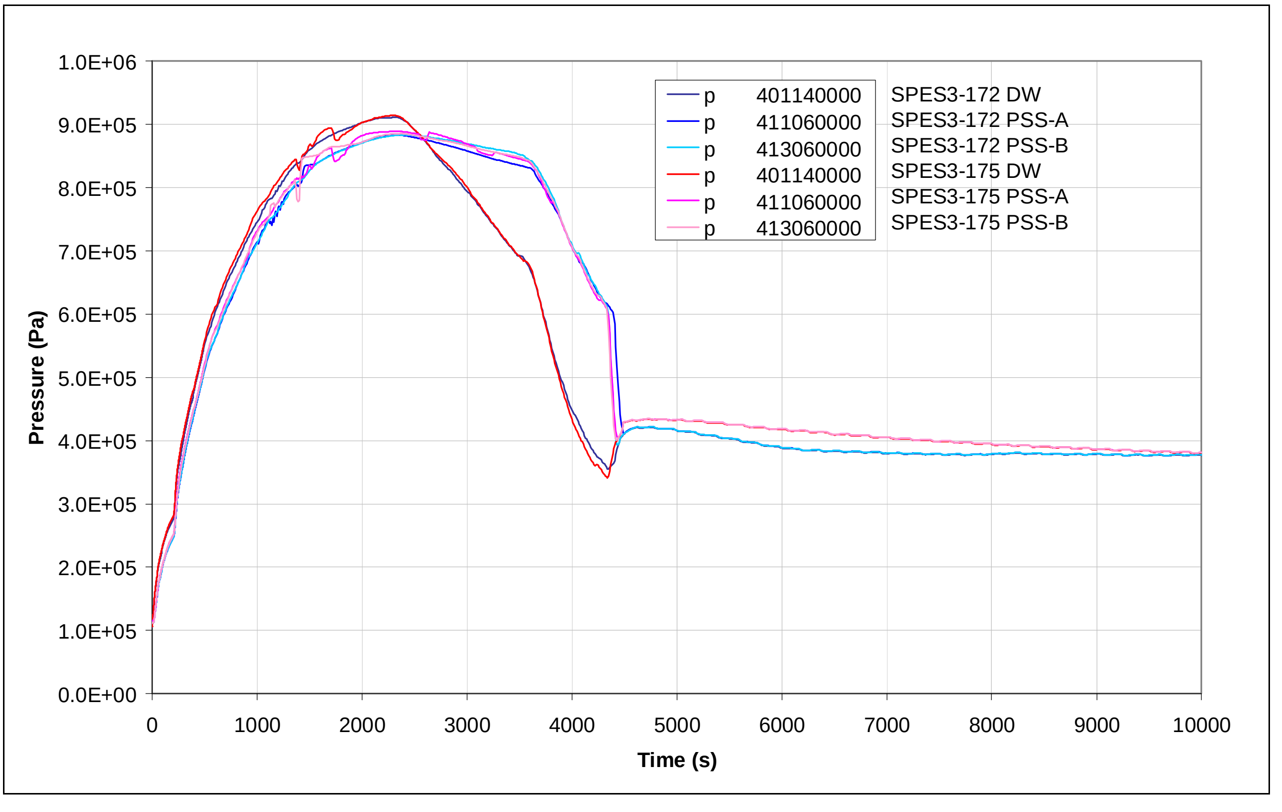


Fig.7. 27 - SPES3-172 and SPES3-175 DW and PSS pressure

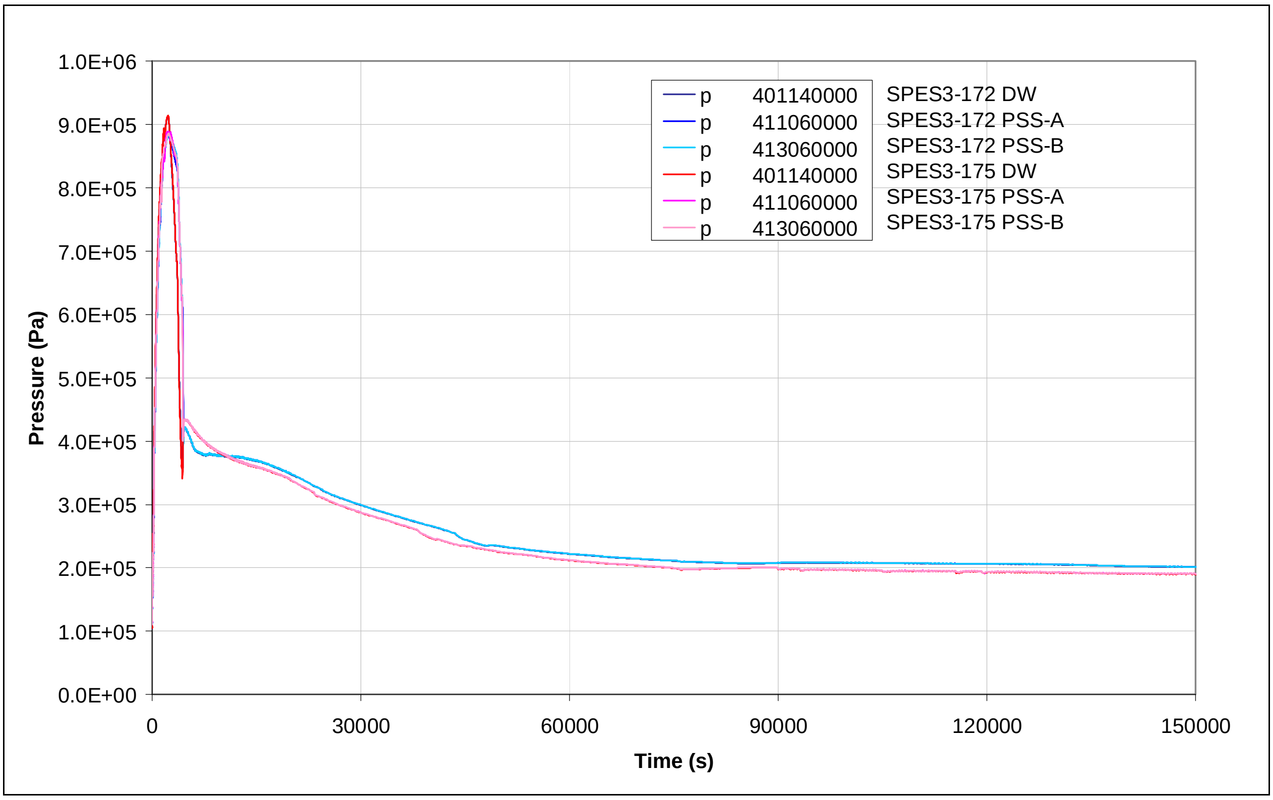


Fig.7. 28 - SPES3-172 and SPES3-175 PSS vent pipe level (window)

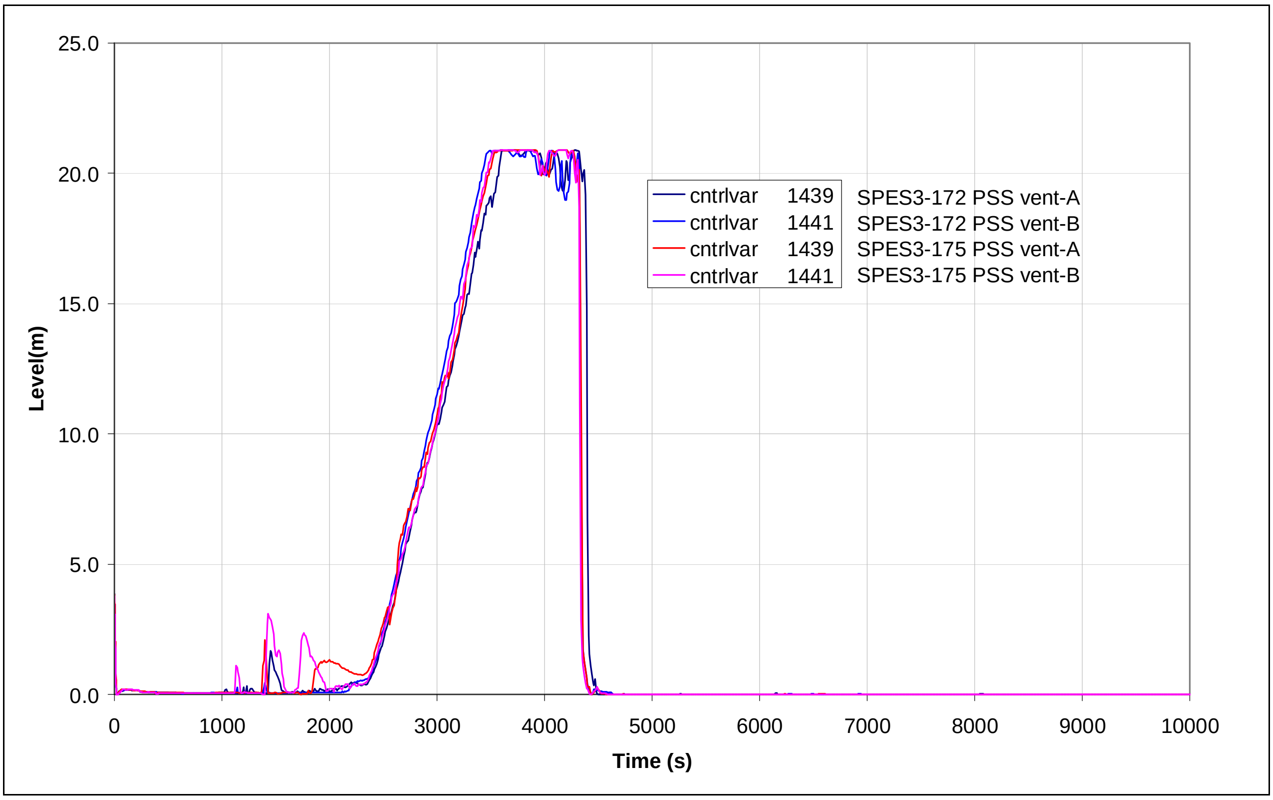


Fig.7. 29 - SPES3-172 and SPES3-175 PSS temperatures (window)

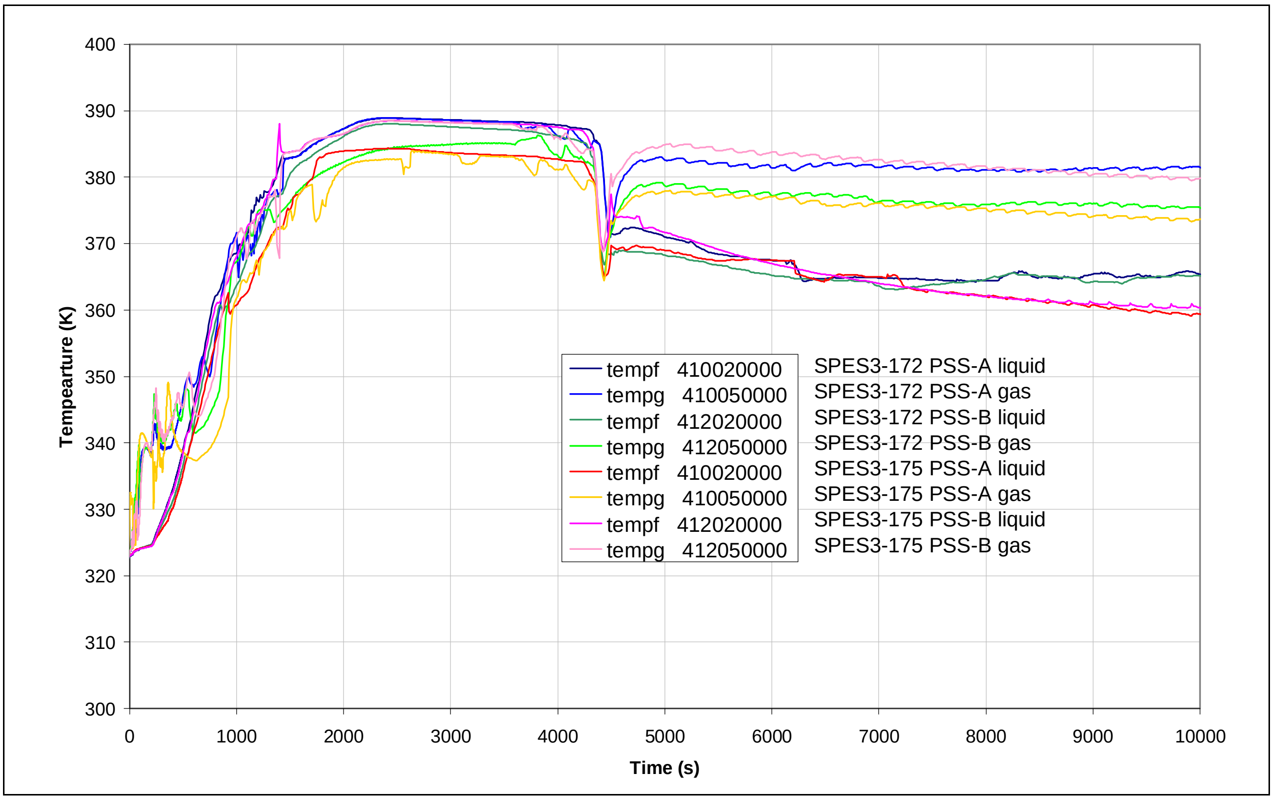


Fig.7. 30 - SPES3-172 and SPES3-175 PSS temperatures

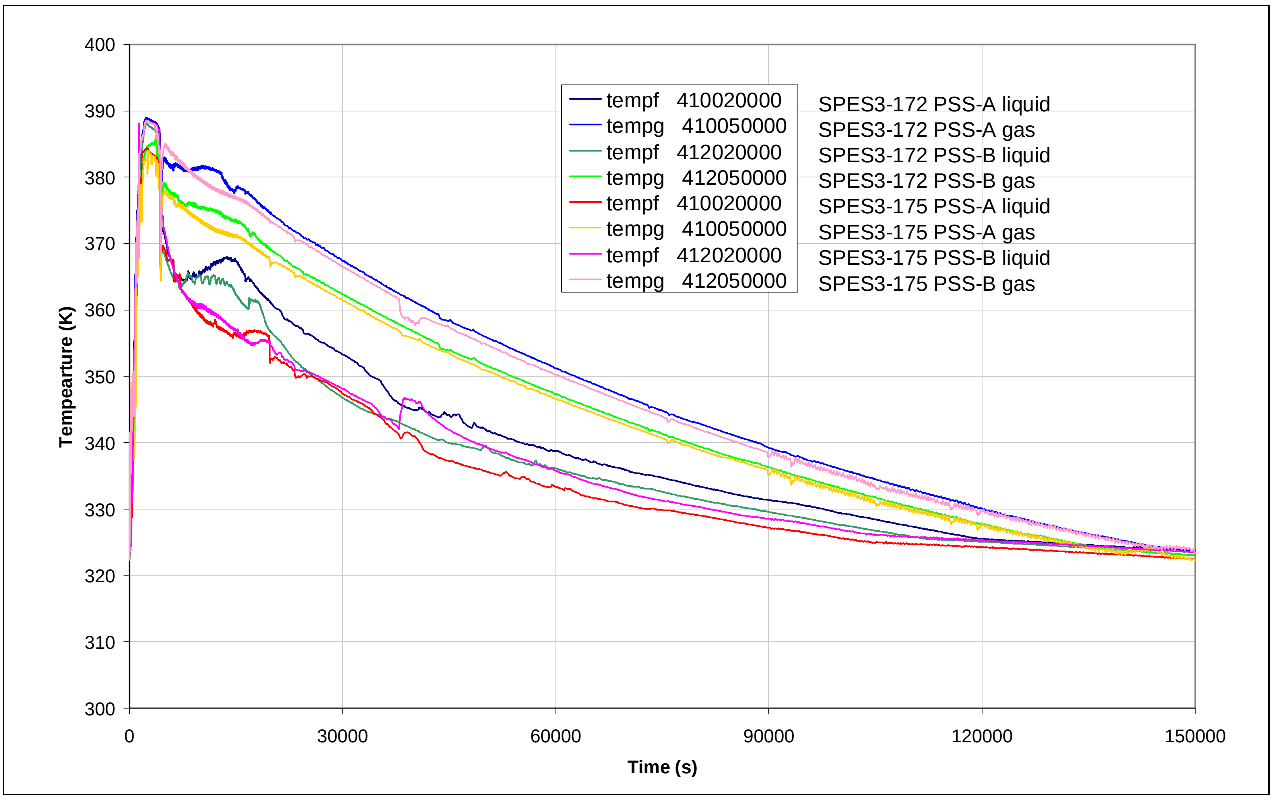


Fig.7. 31 - SPES3-172 and SPES3-175 Core power (window)

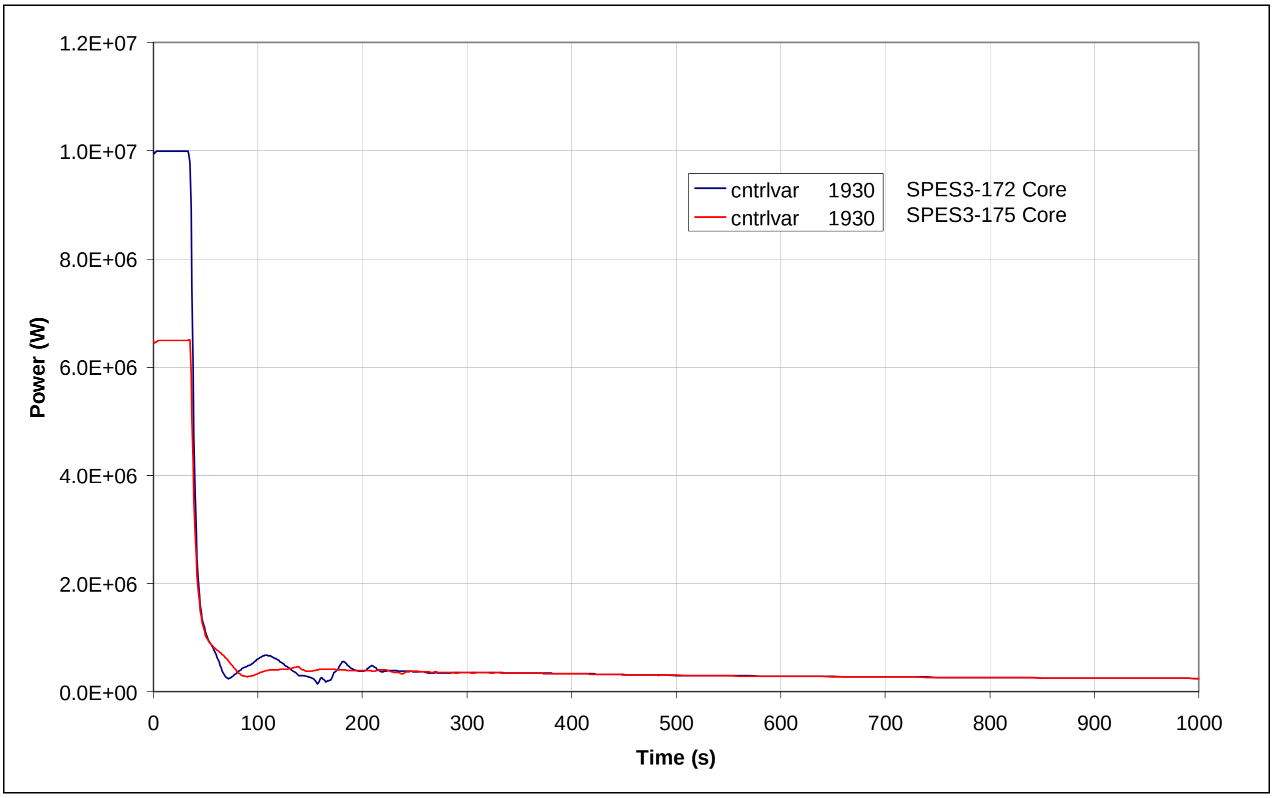


Fig.7. 32 - SPES3-172 and SPES3-175 Core power

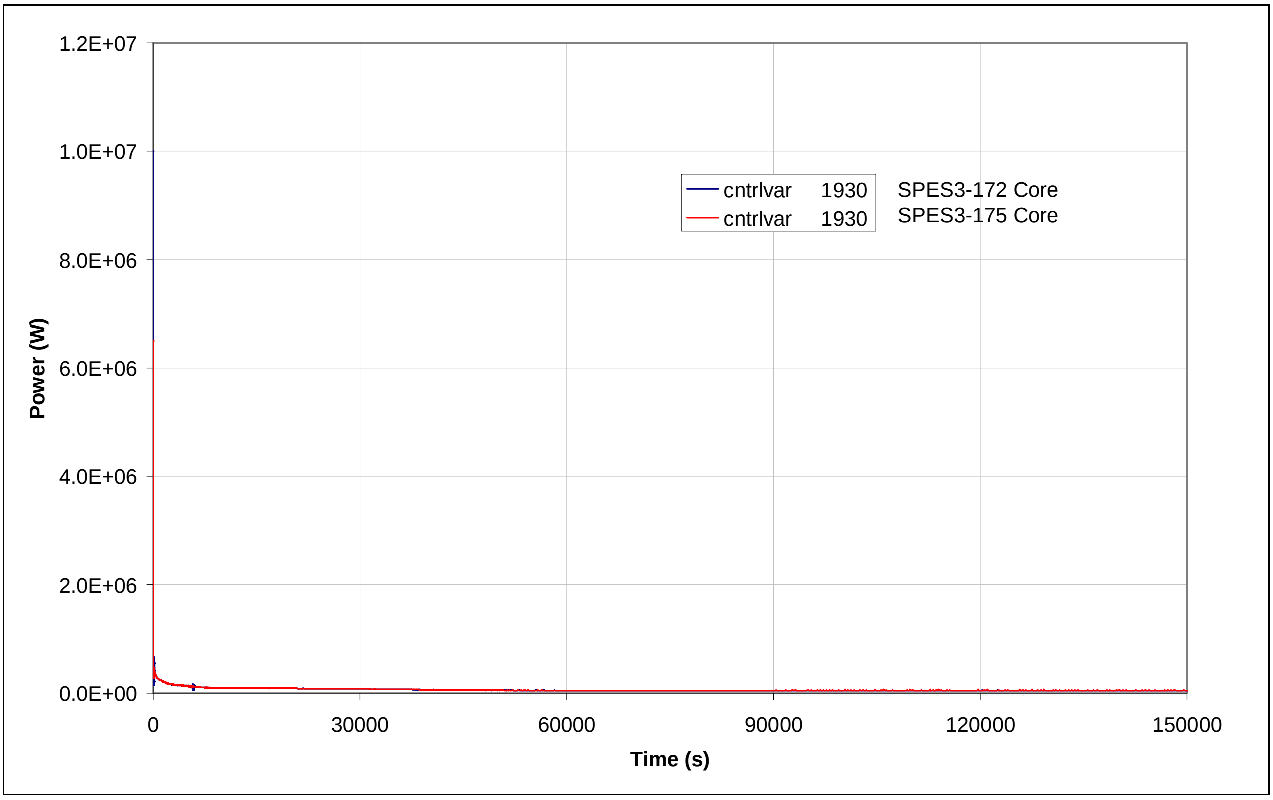


Fig.7. 33 - SPES3-172 and SPES3-175 SG power (window)

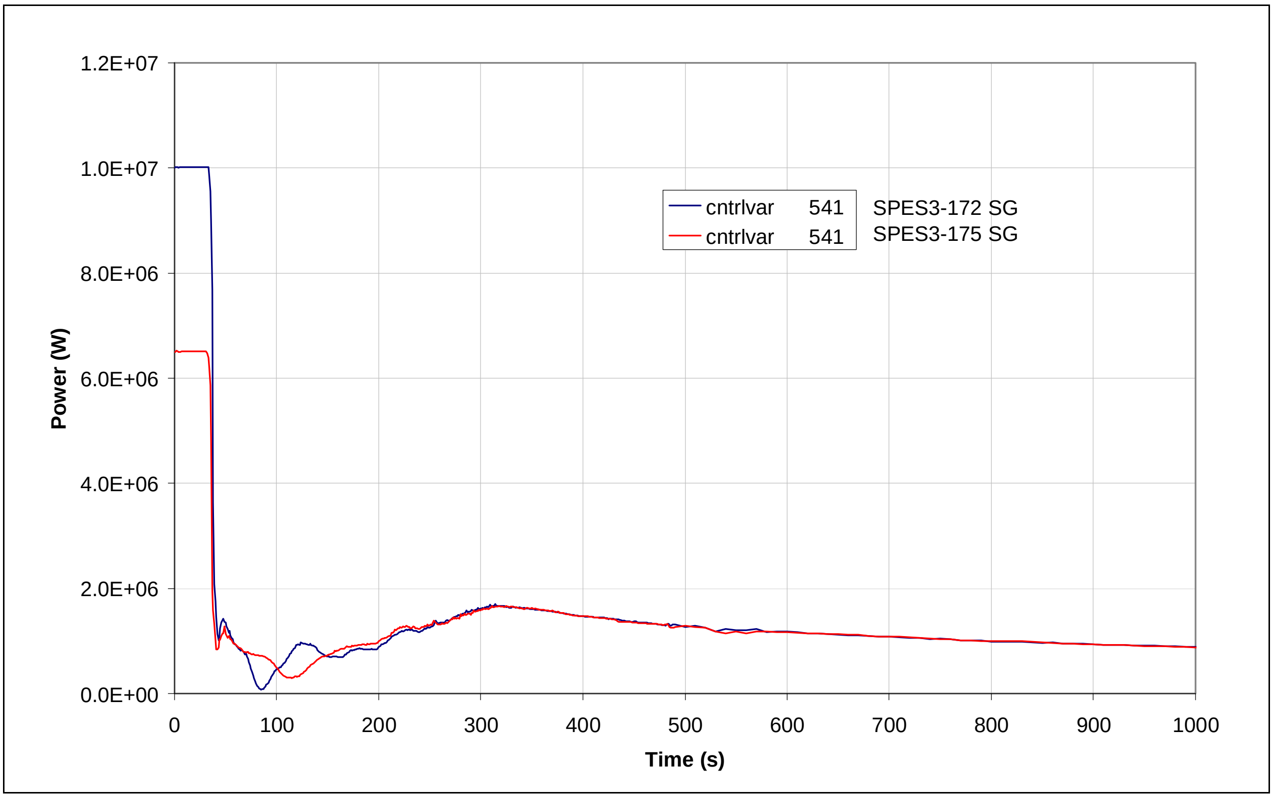


Fig.7. 34 - SPES3-172 and SPES3-175 SG power

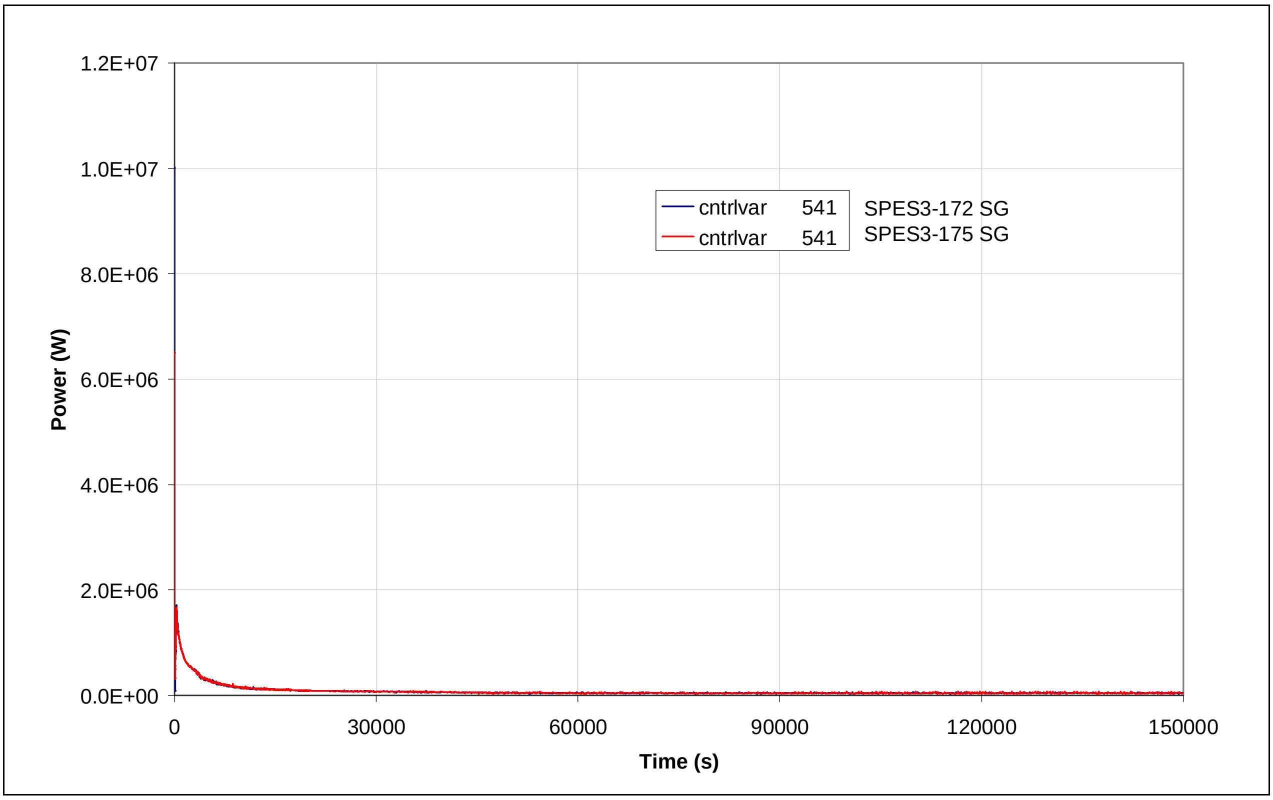


Fig.7. 35 - SPES3-172 and SPES3-175 SG ss mass flow (window)

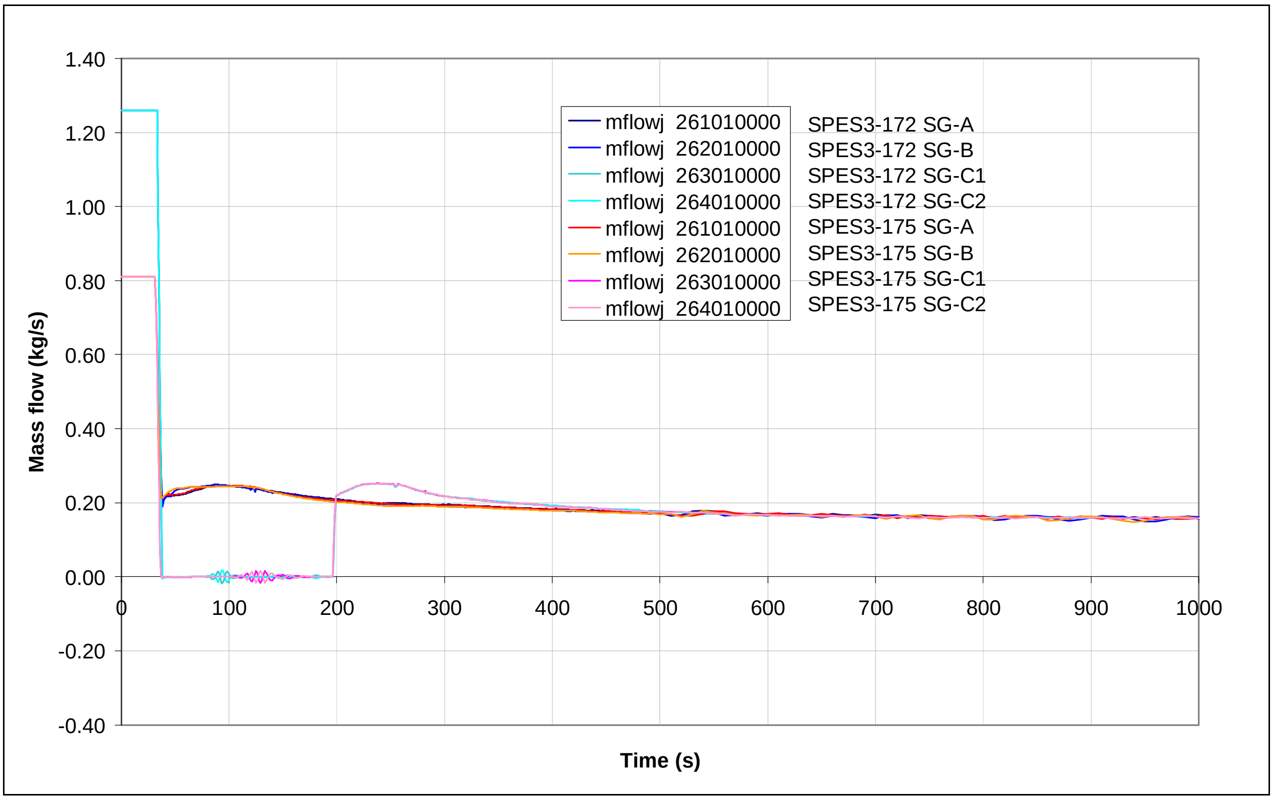


Fig.7. 36 - SPES3-172 and SPES3-175 SG ss mass flow

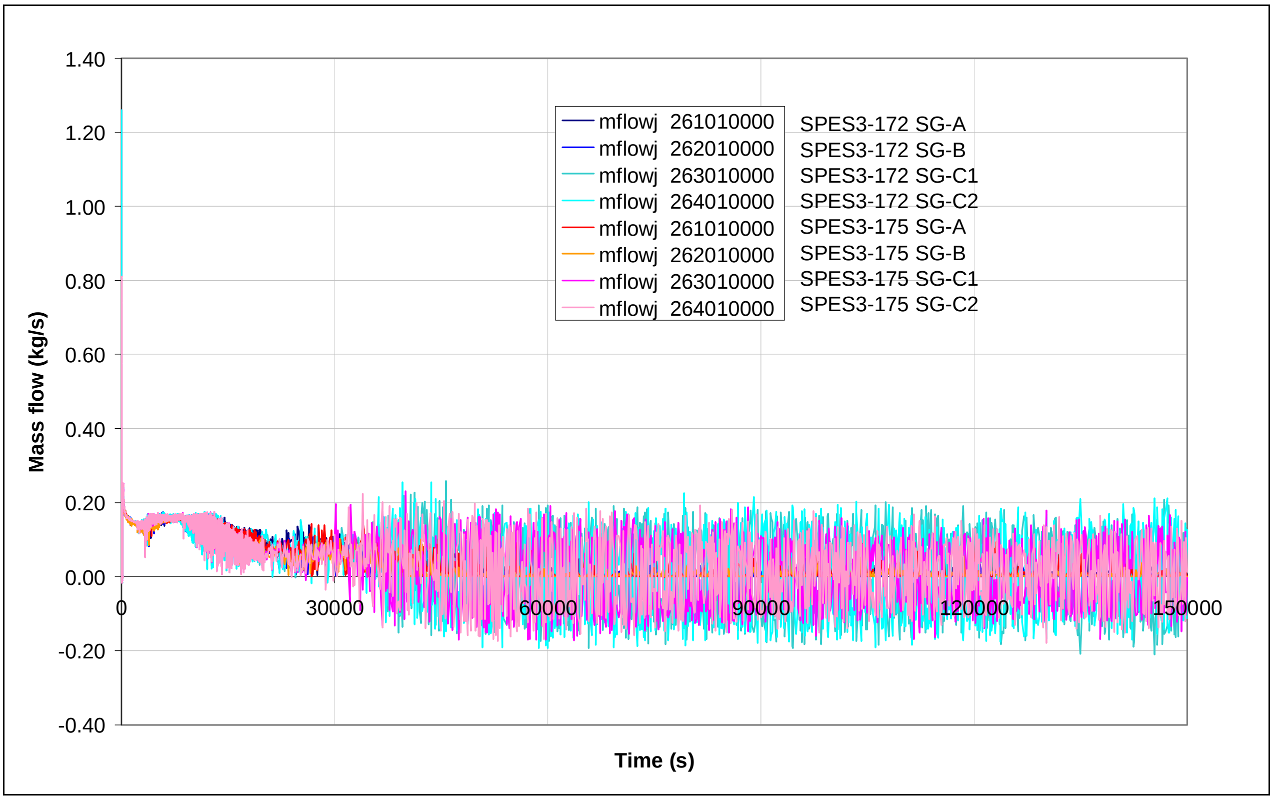


Fig.7. 37 - SPES3-172 and SPES3-175 EHRS cold leg mass flow (window)

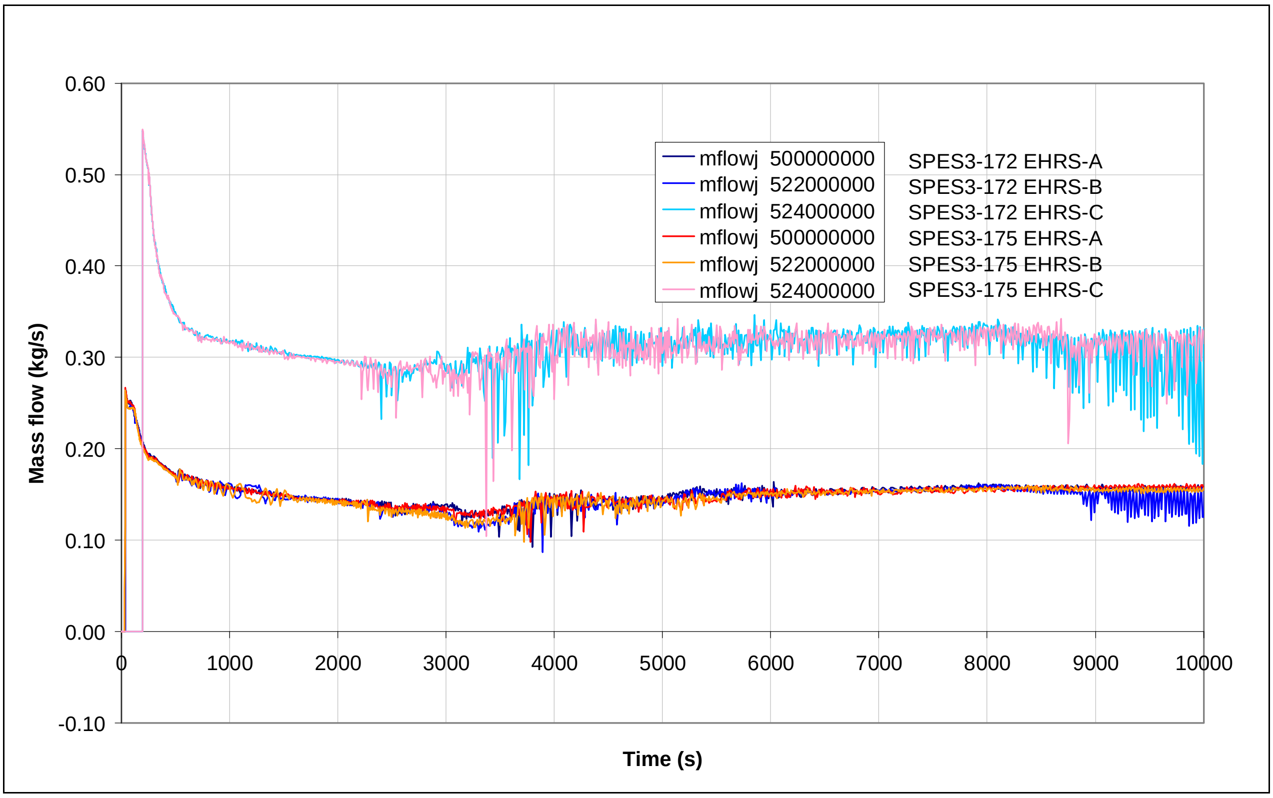


Fig.7. 38 - SPES3-172 and SPES3-175 EHRS cold leg mass flow

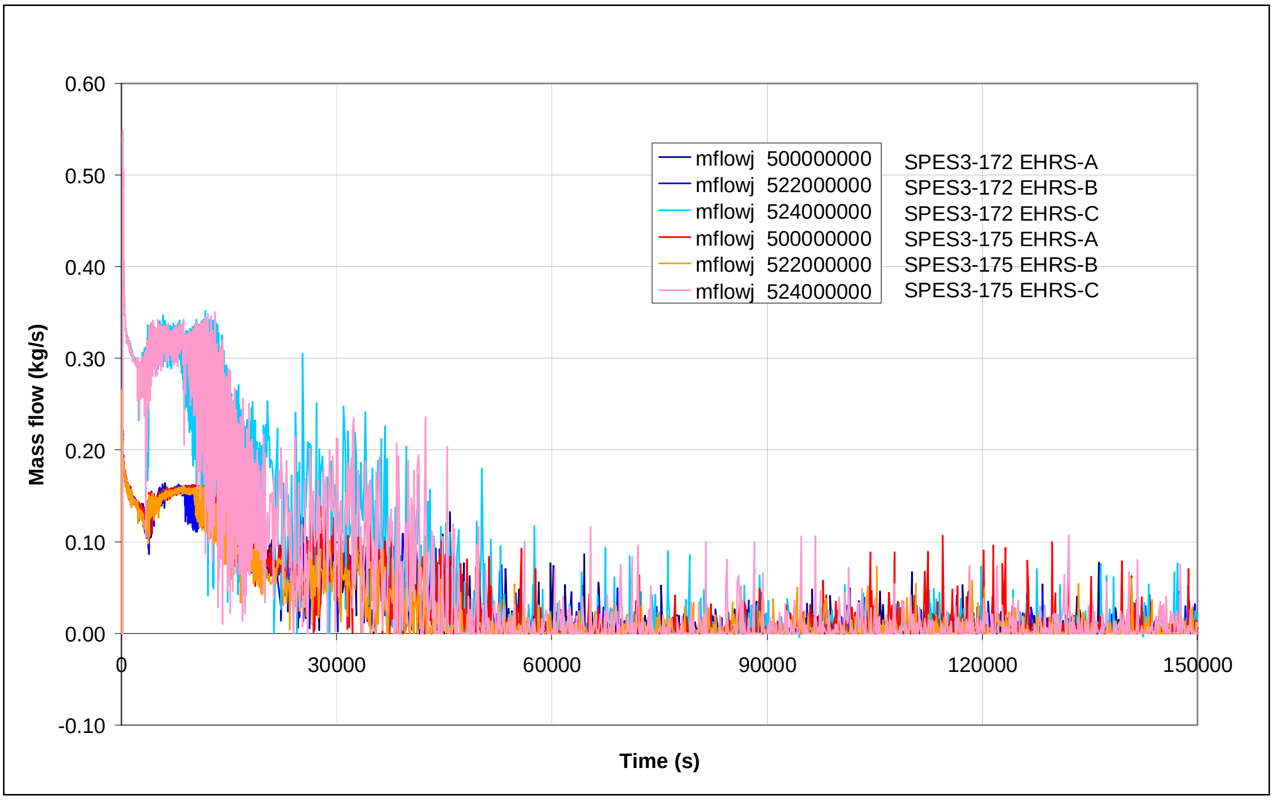


Fig.7. 39 - SPES3-172 and SPES3-175 EHRS power (window)

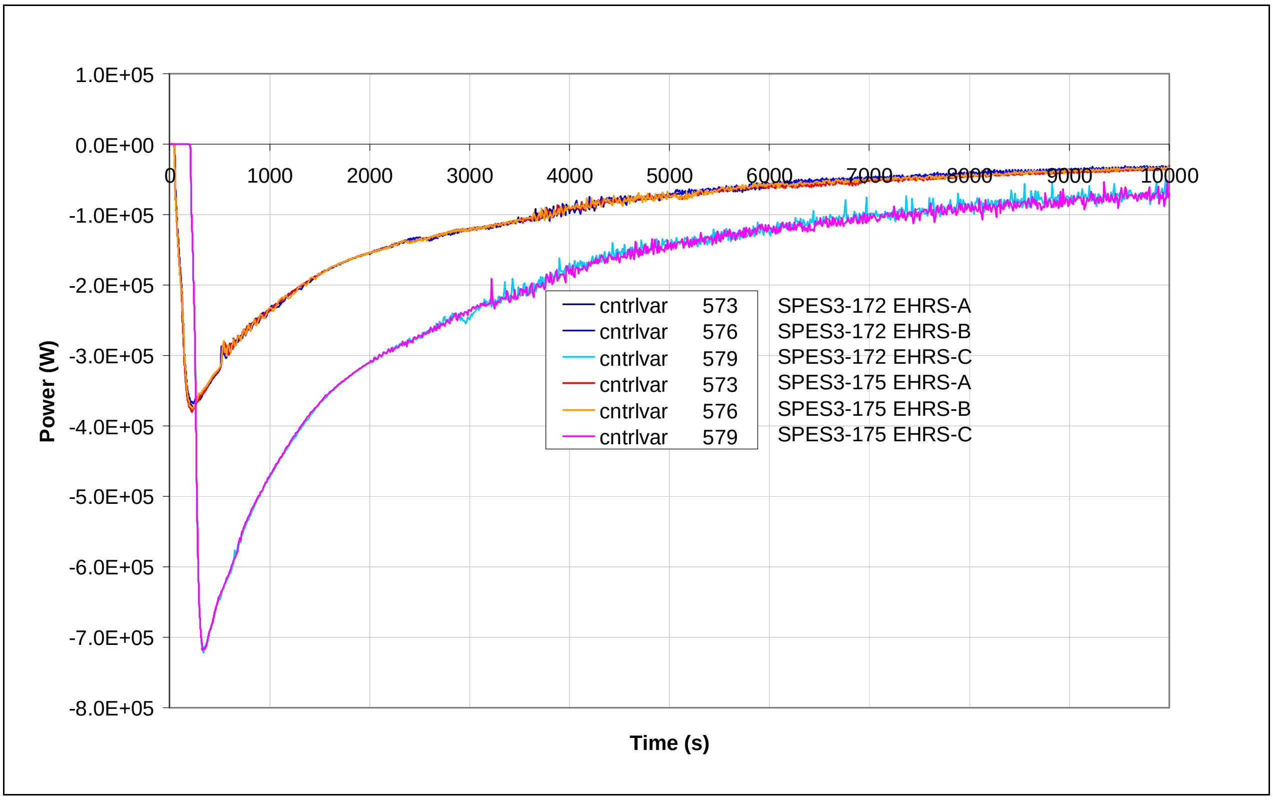


Fig.7. 40 - SPES3-172 and SPES3-175 EHRS power

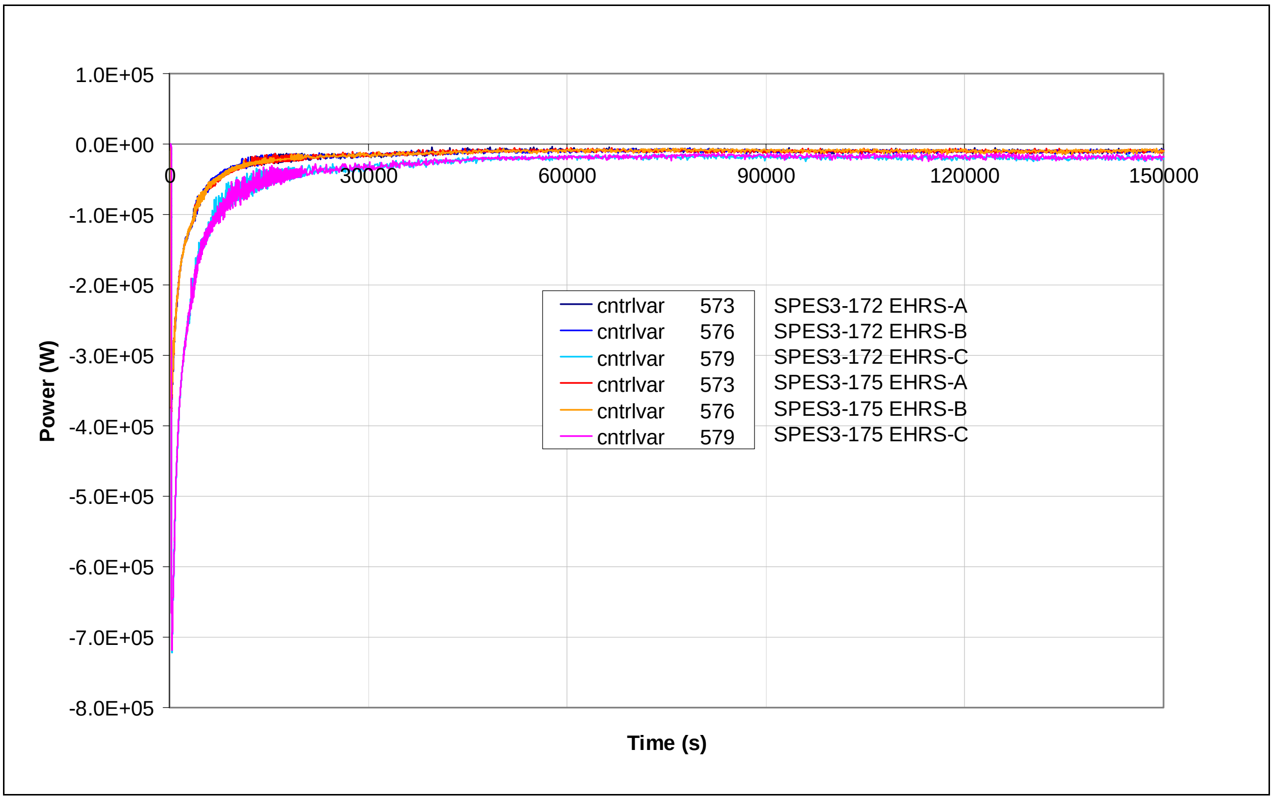


Fig.7. 41 - SPES3-172 and SPES3-175 SG ss outlet pressure (window)

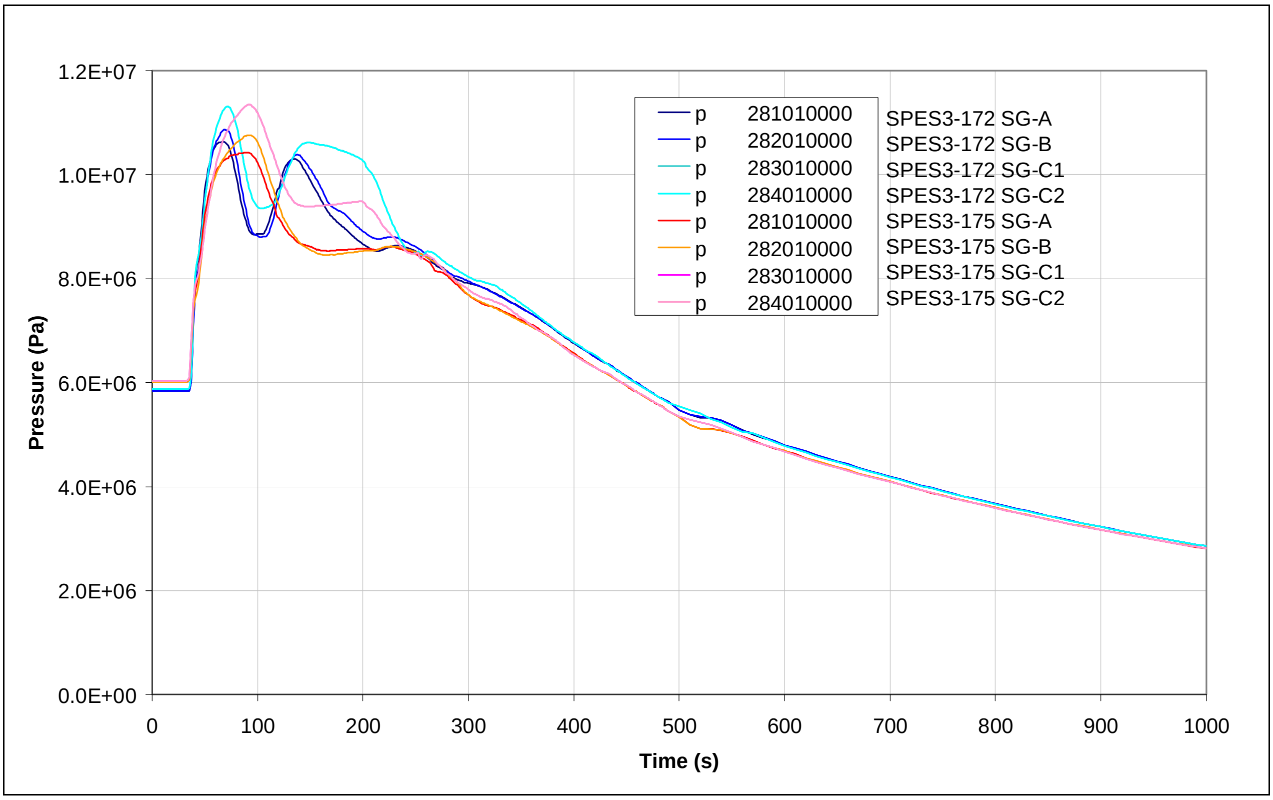


Fig.7. 42 - SPES3-172 and SPES3-175 SG ss outlet pressure

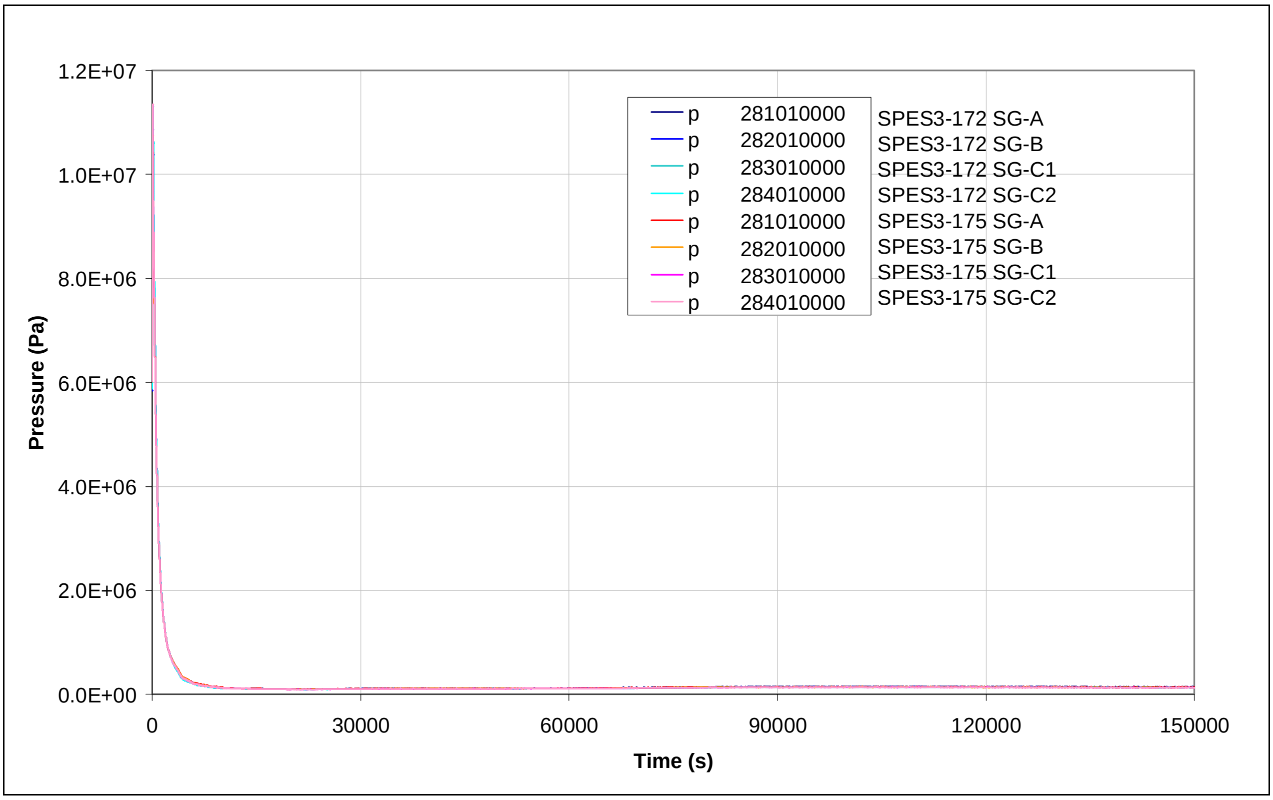


Fig.7. 43 - SPES3-172 and SPES3-175 SG-Ass collapsed level (window)

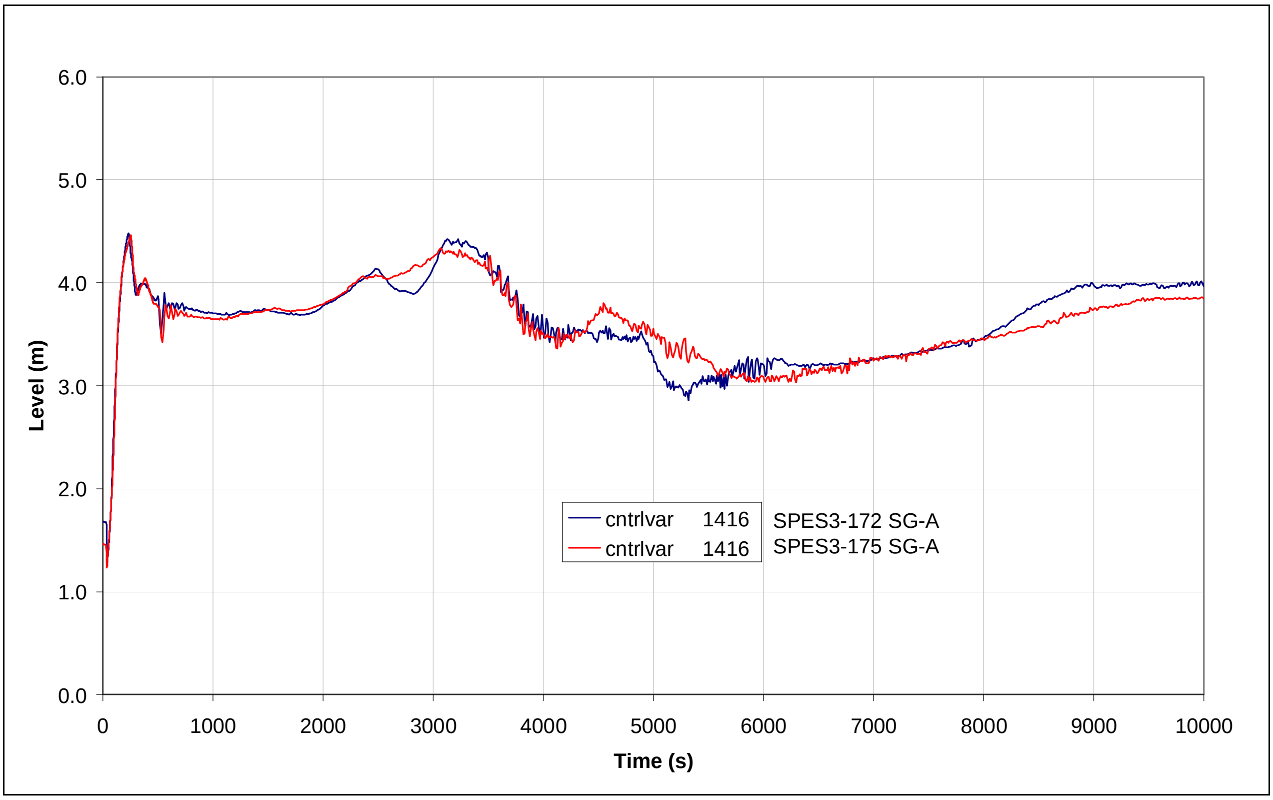


Fig.7. 44 - SPES3-172 and SPES3-175 SG-Ass collapsed level

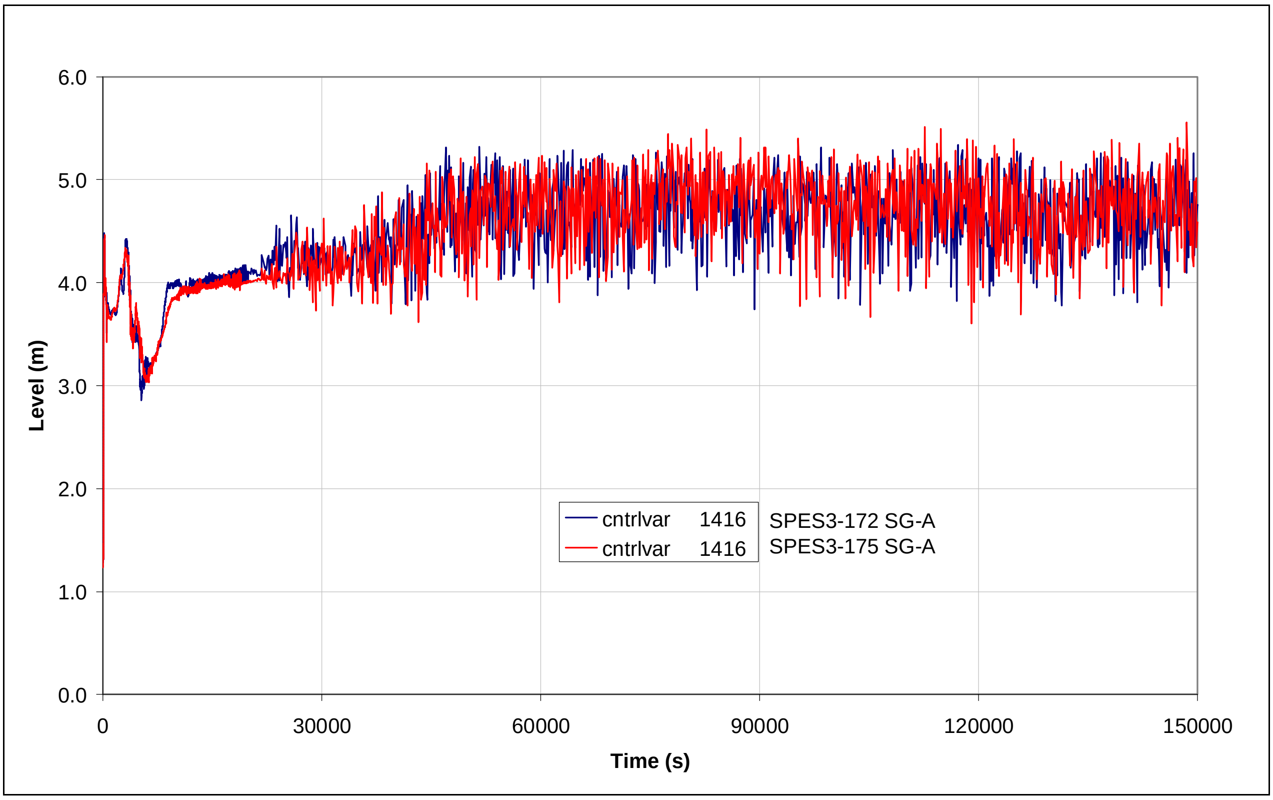


Fig.7. 45 - SPES3-172 and SPES3-175 PRZ level (window)

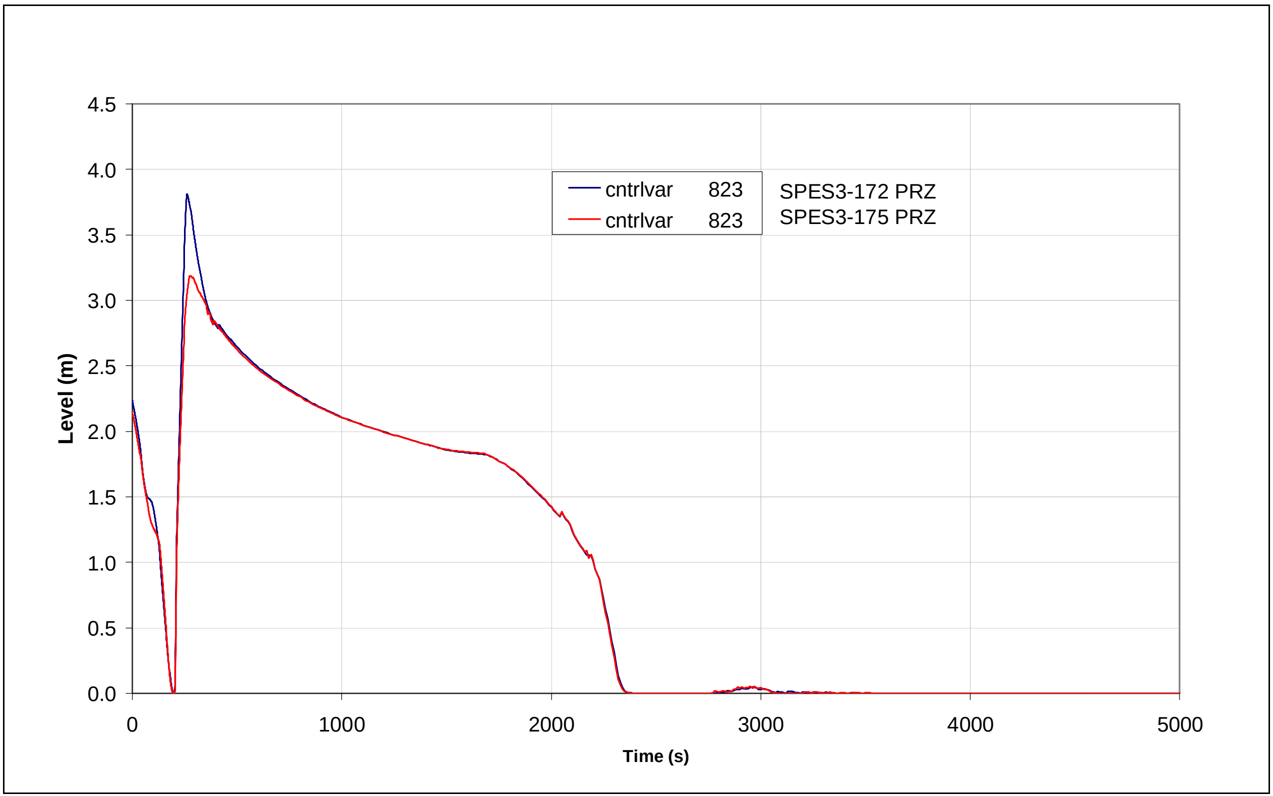


Fig.7. 46 - SPES3-172 and SPES3-175 Pump inlet liquid fraction (window)

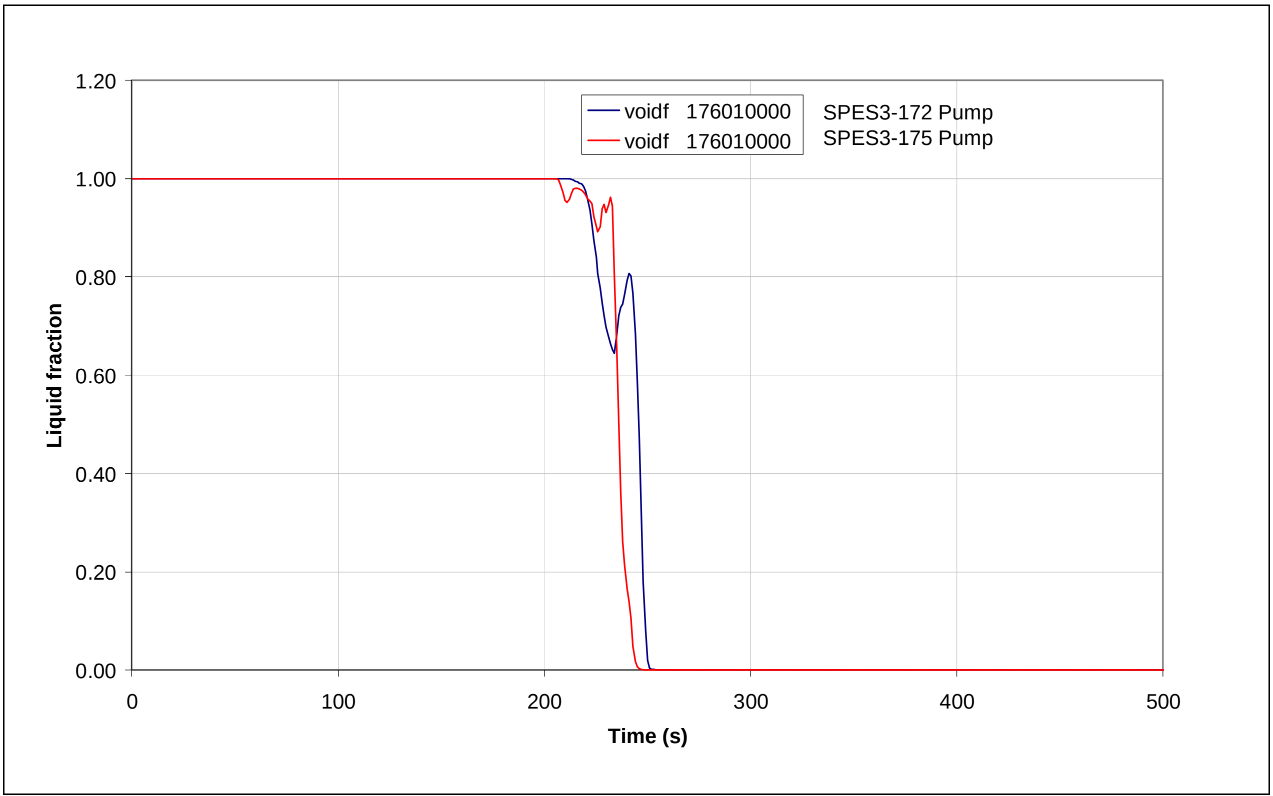


Fig.7. 47 - SPES3-172 and SPES3-175 Pump velocity (window)

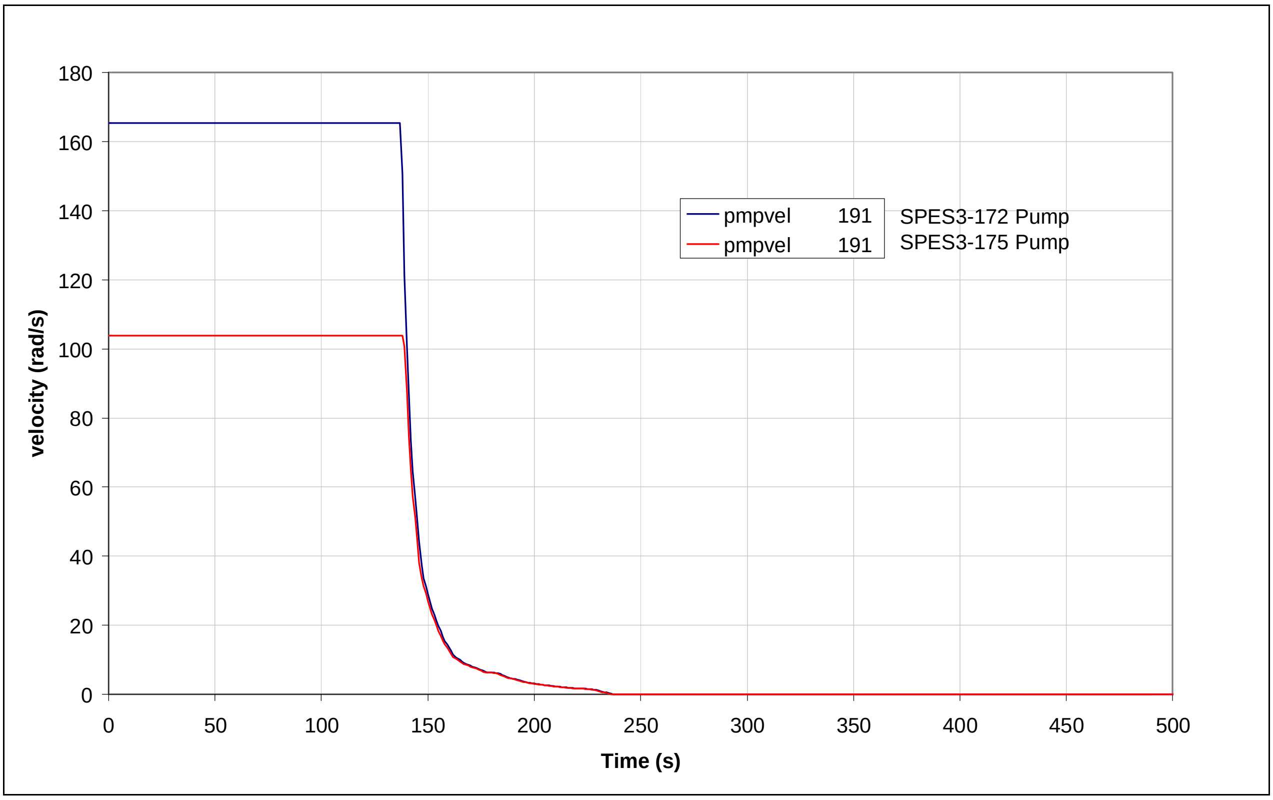


Fig.7. 48 - SPES3-172 and SPES3-175 Core inlet mass flow (window)

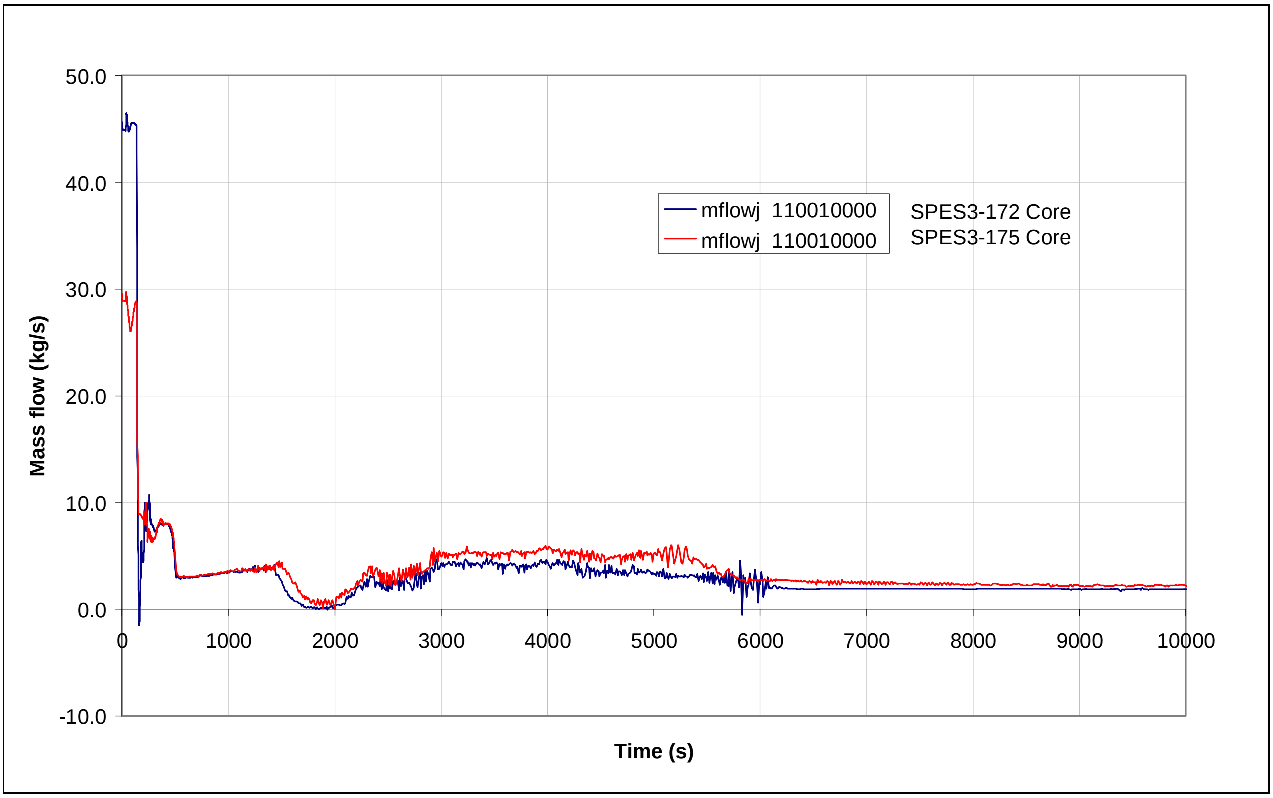


Fig.7. 49 - SPES3-172 and SPES3-175 Core inlet mass flow

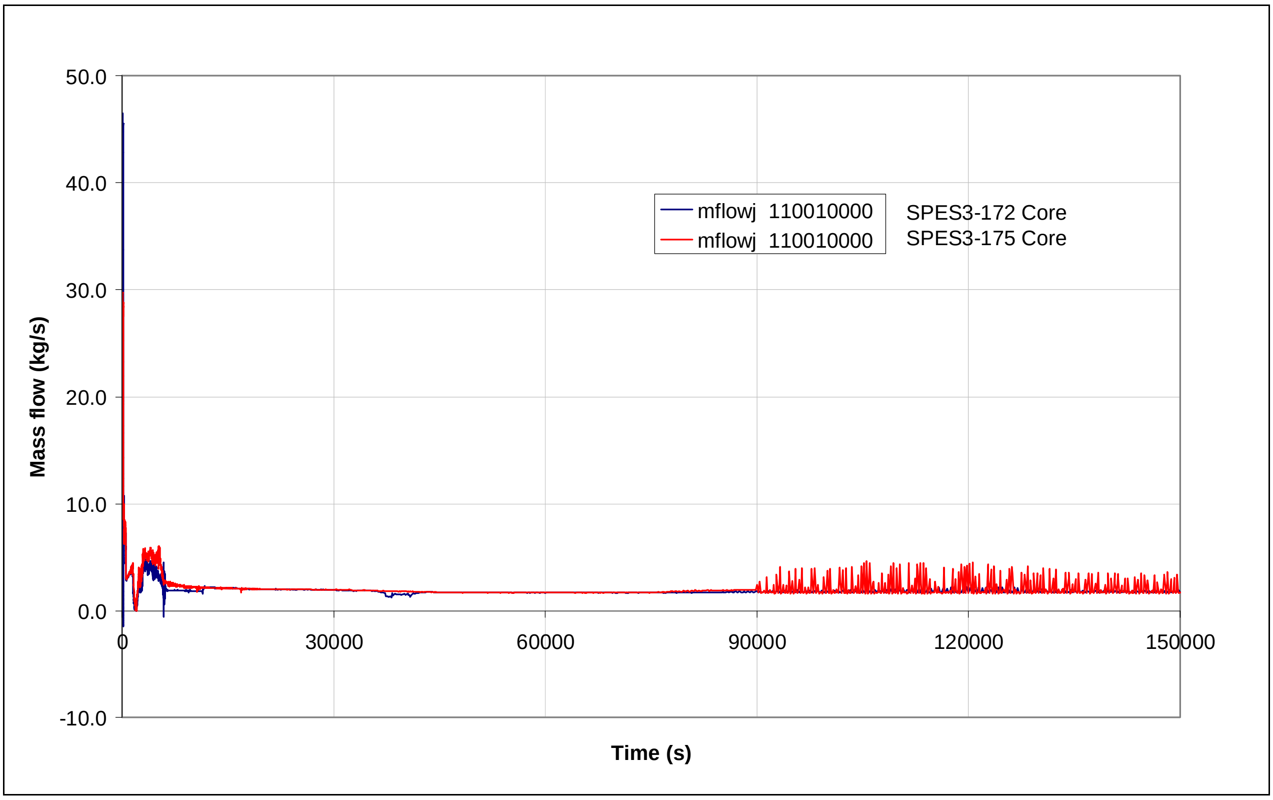


Fig.7. 50 - SPES3-172 and SPES3-175 RI-DC check valve mass flow (window)

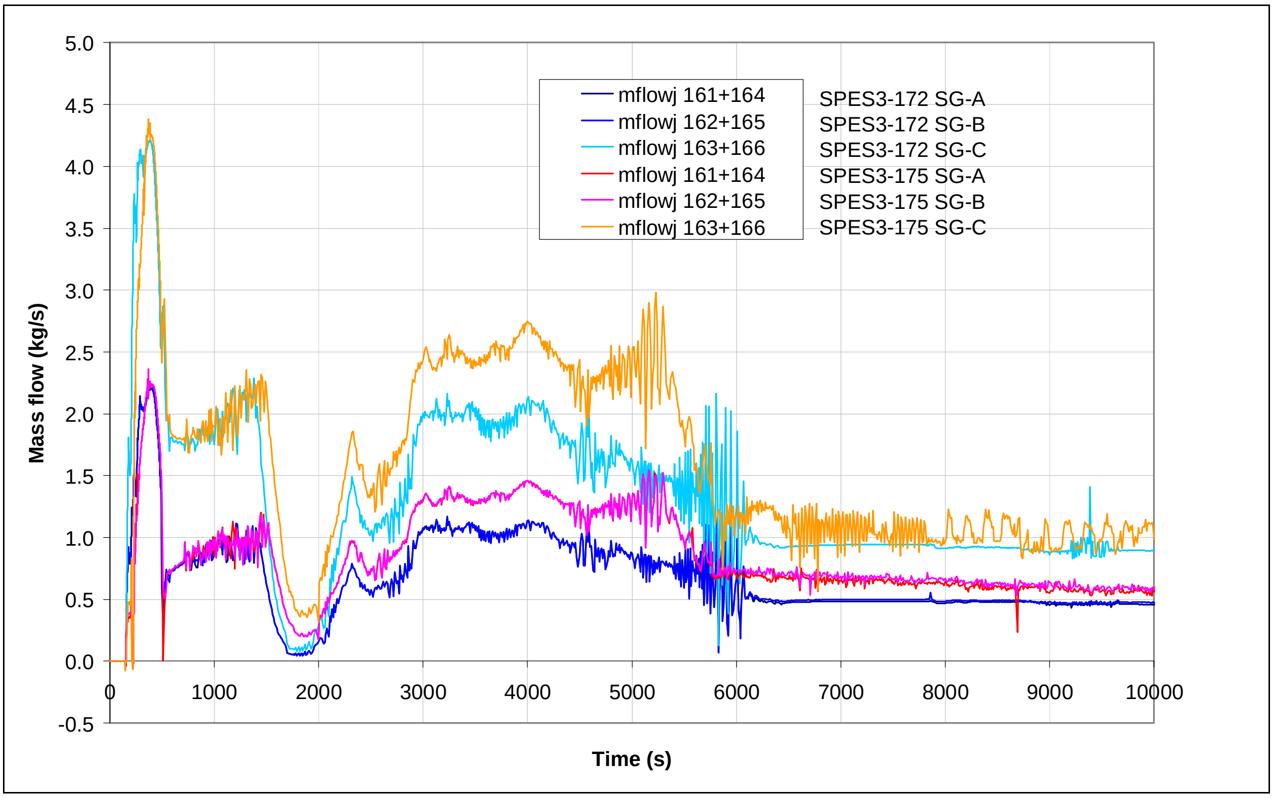


Fig.7. 51 - SPES3-172 and SPES3-175 RI-DC check valve mass flow

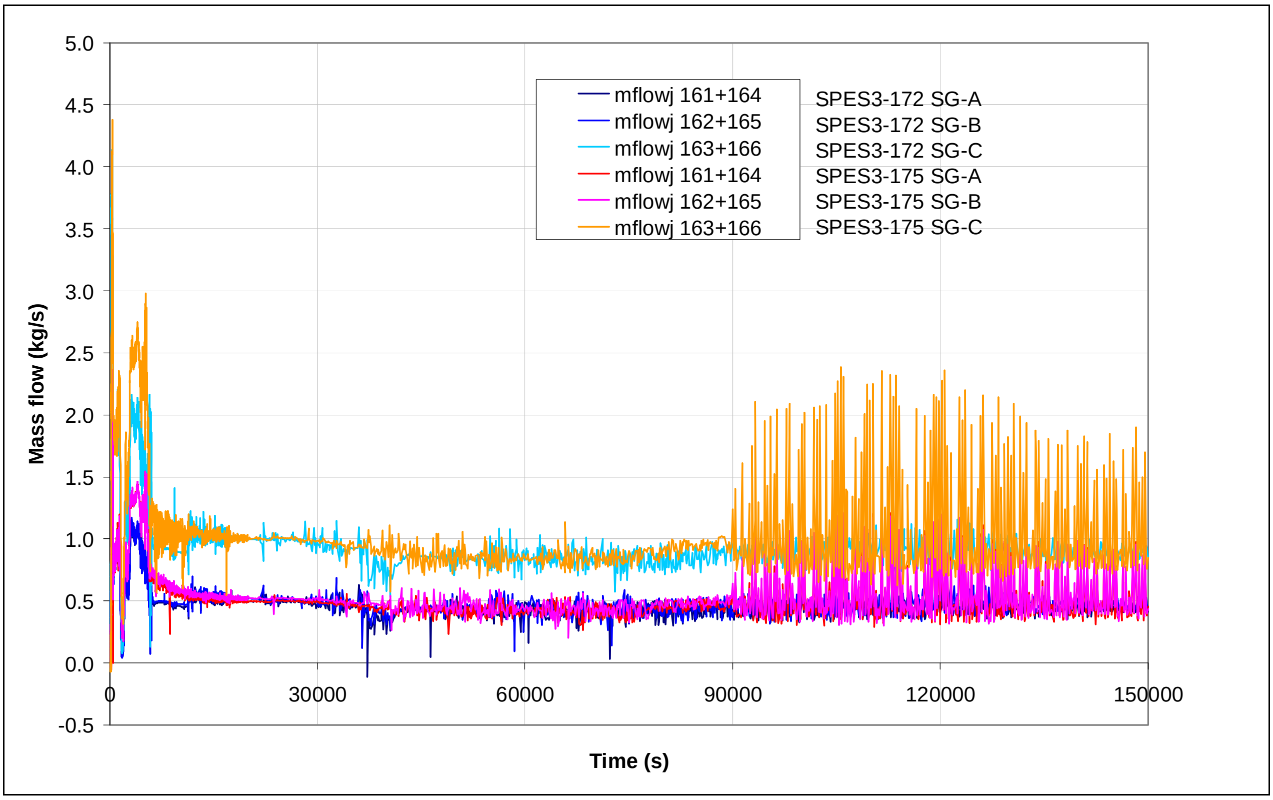


Fig.7. 52 - SPES3-172 and SPES3-175 RPV mass (window)

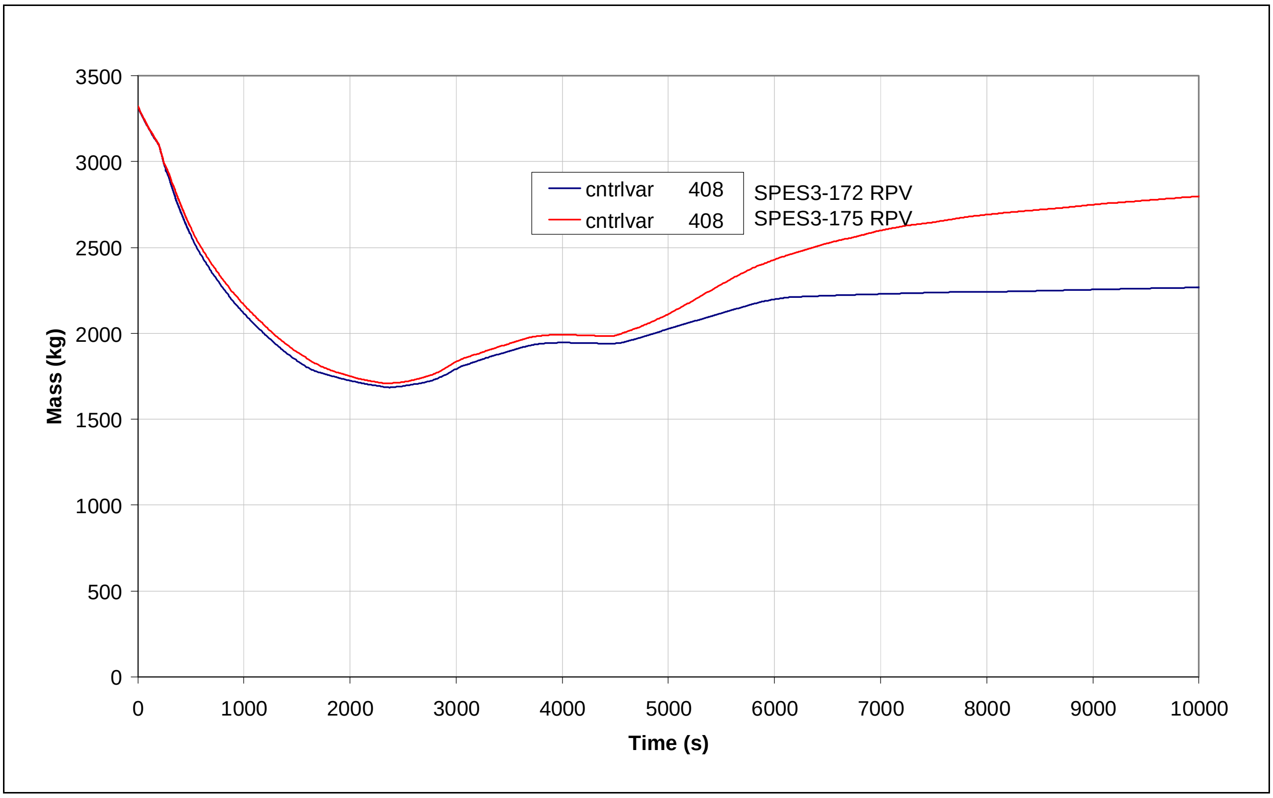


Fig.7. 53 - SPES3-172 and SPES3-175 RPV mass

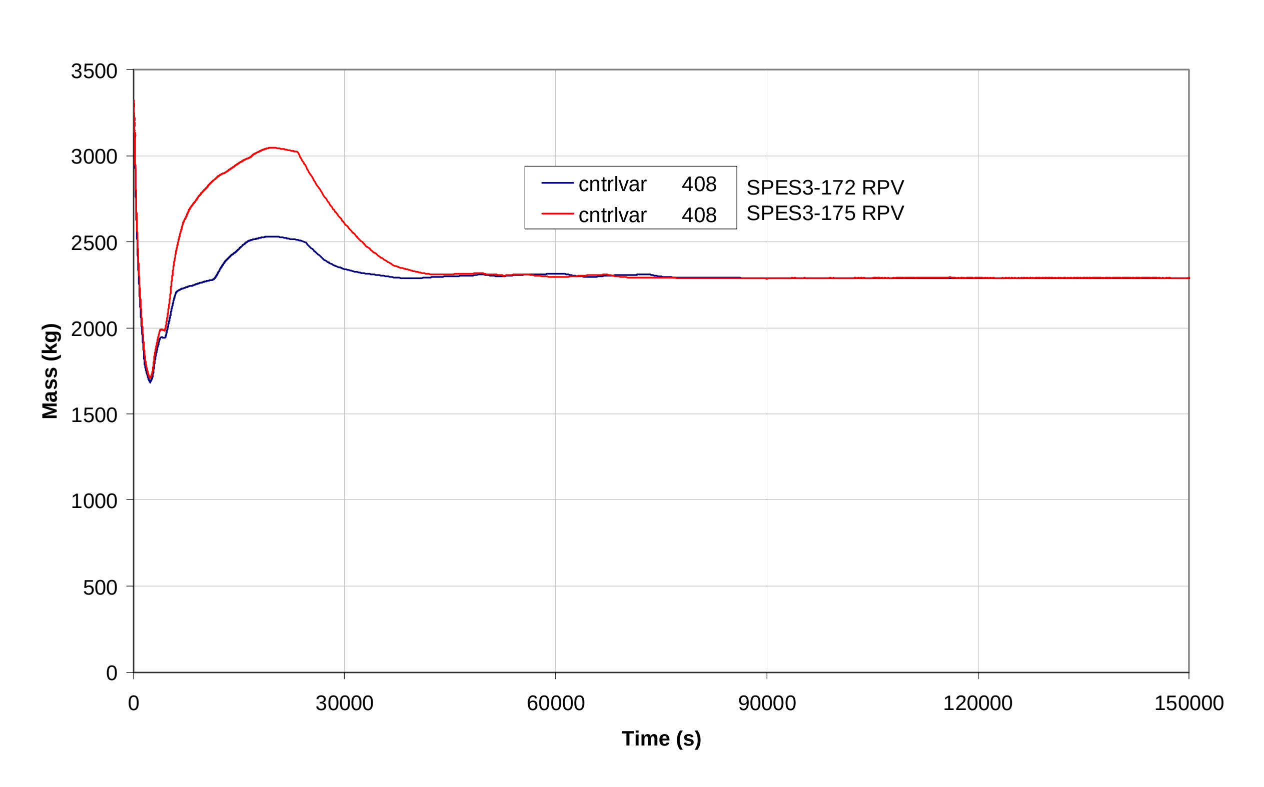


Fig.7. 54 - SPES3-172 and SPES3-175 Core liquid fraction (window)

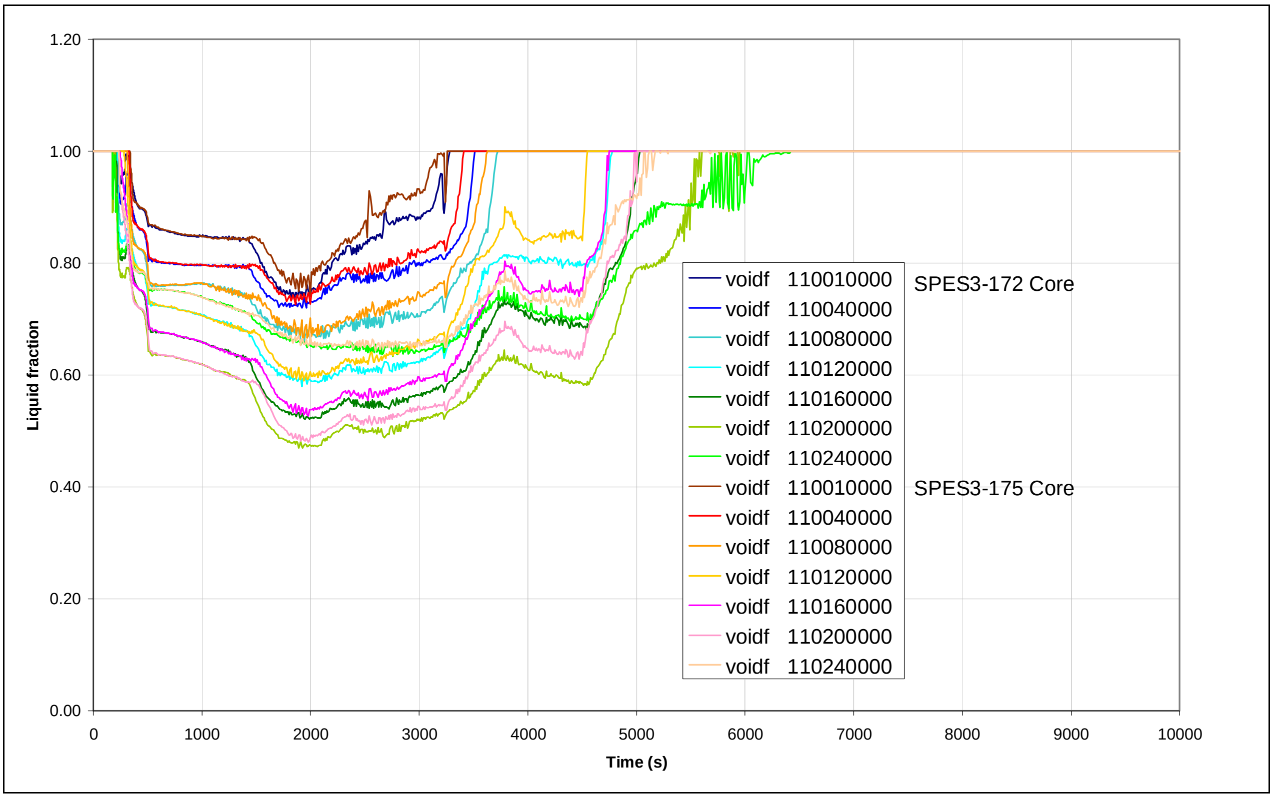


Fig.7. 55 - SPES3-172 and SPES3-175 ADS Stage-I integral flow

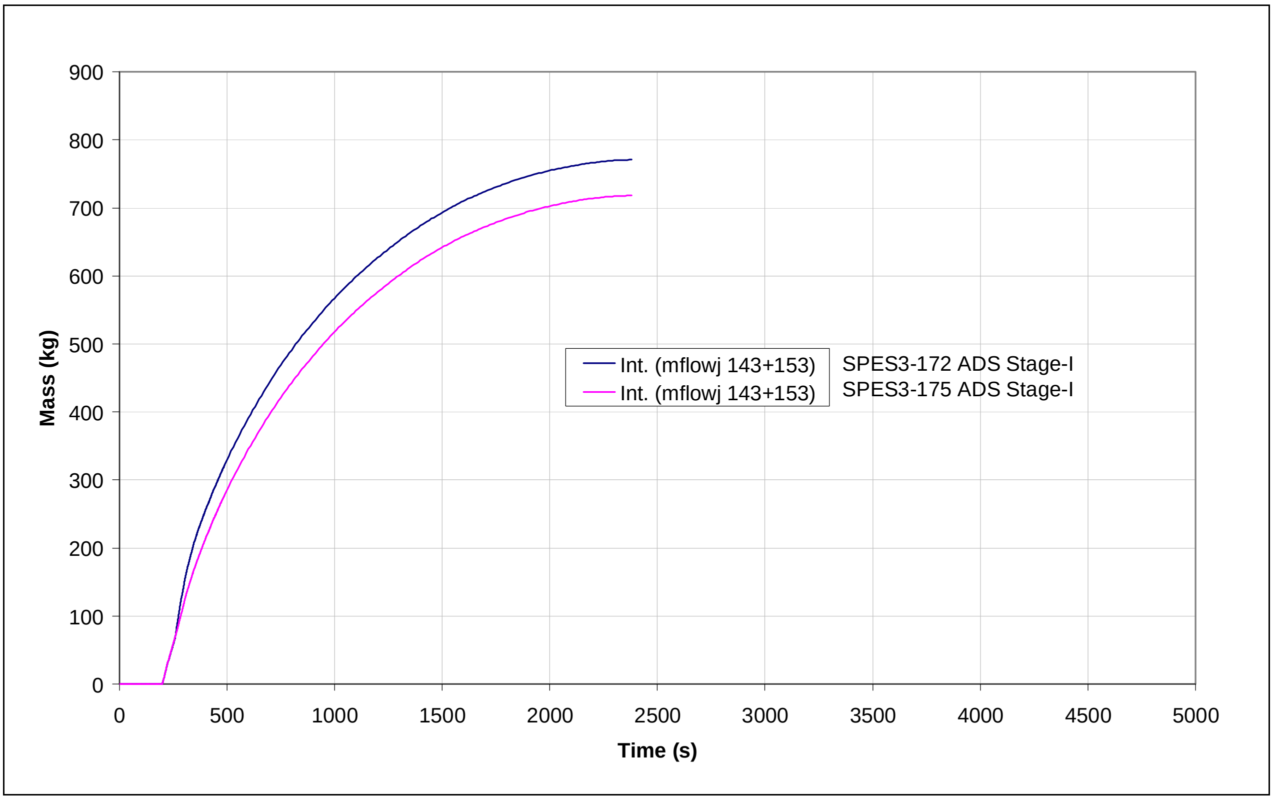


Fig.7. 56 - SPES3-172 and SPES3-175 RC to DVI mass flow IL (window)

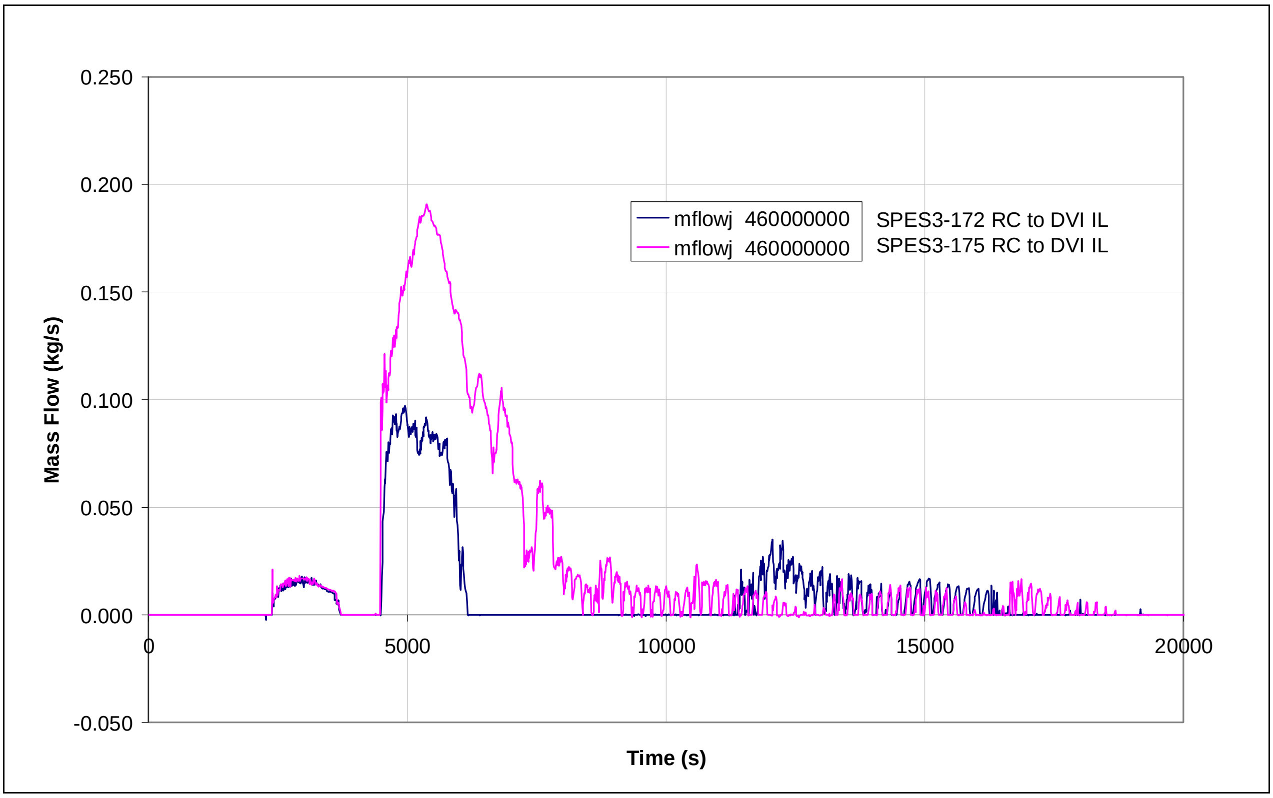


Fig.7. 57 - SPES3-172 and SPES3-175 RC to DVI mass flow IL

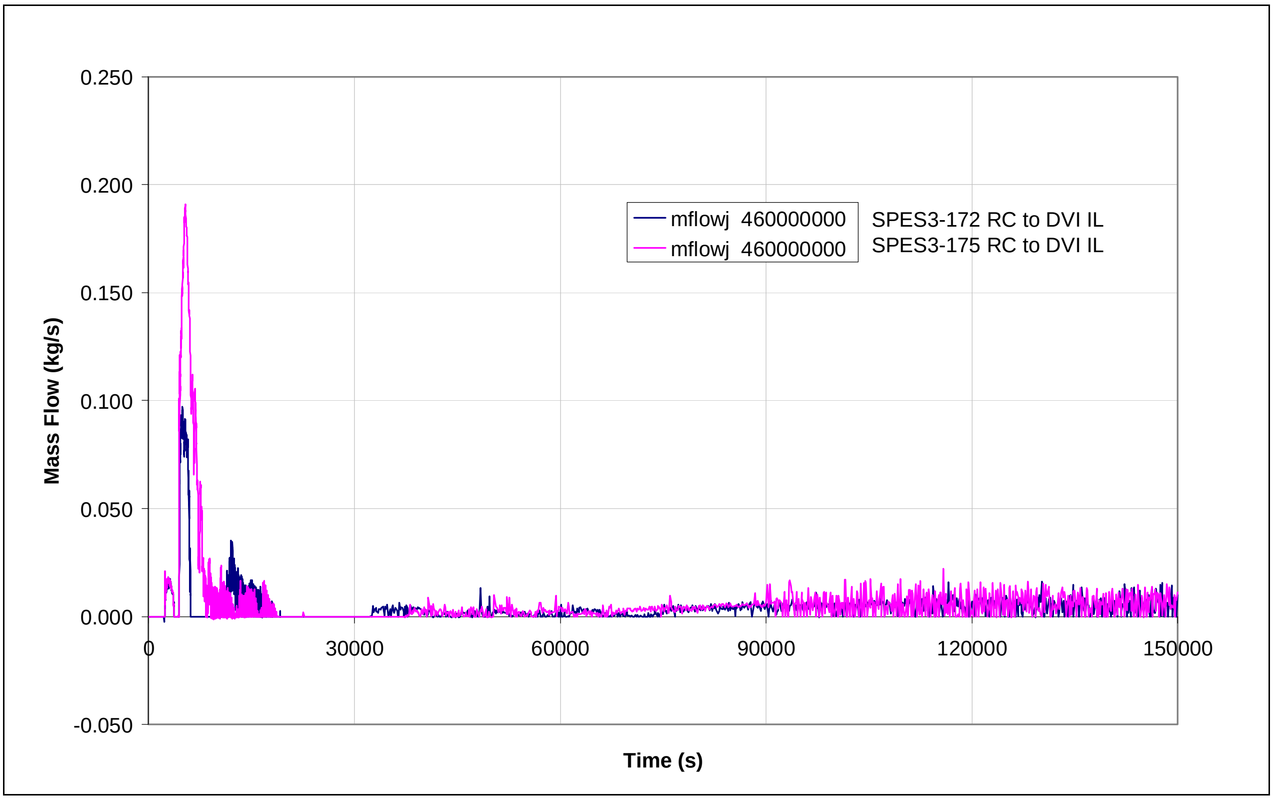


Fig.7. 58 - SPES3-172 and SPES3-175 EBT level (window)

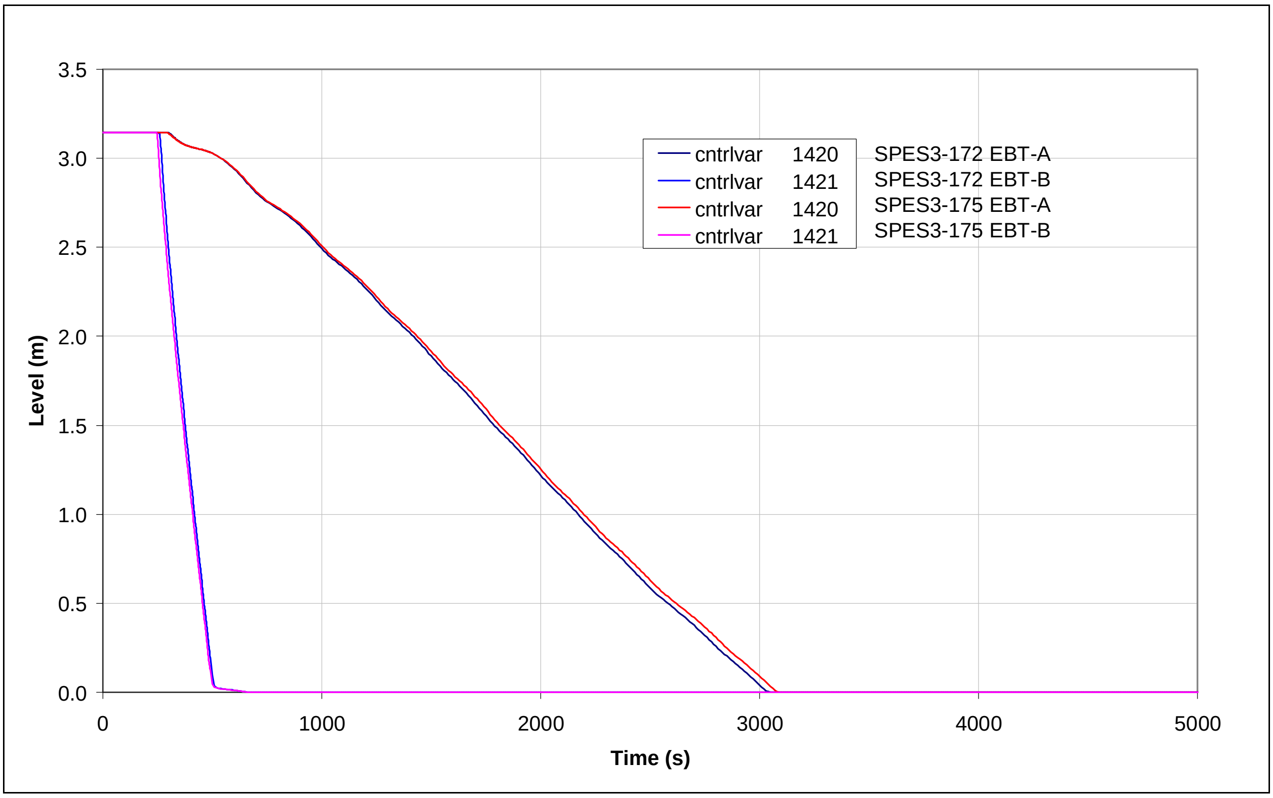


Fig.7. 59 - SPES3-172 and SPES3-175 EBT to RPV balance line mass flow (window)

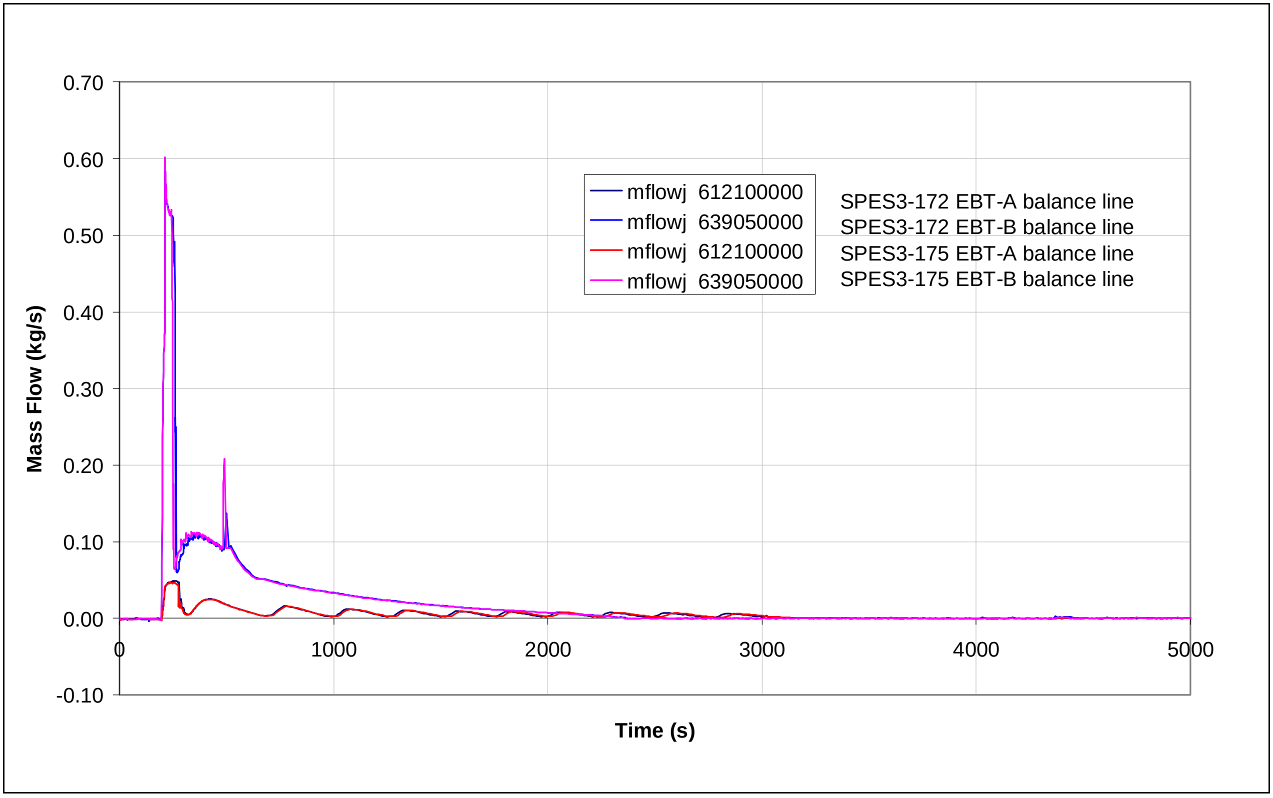


Fig.7. 60 - SPES3-172 and SPES3-175 Core inlet and outlet fluid temperature (window)

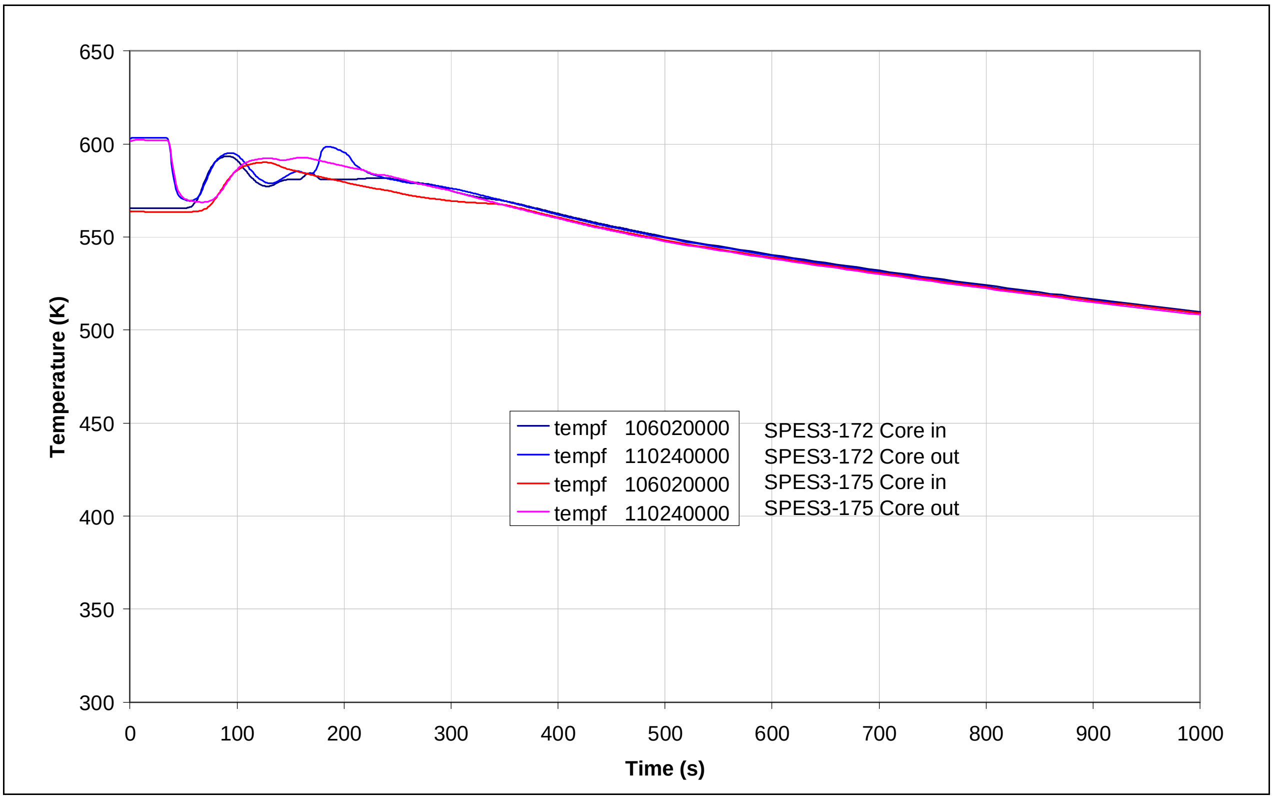


Fig.7. 61 - SPES3-172 and SPES3-175 Core inlet and outlet fluid temperature

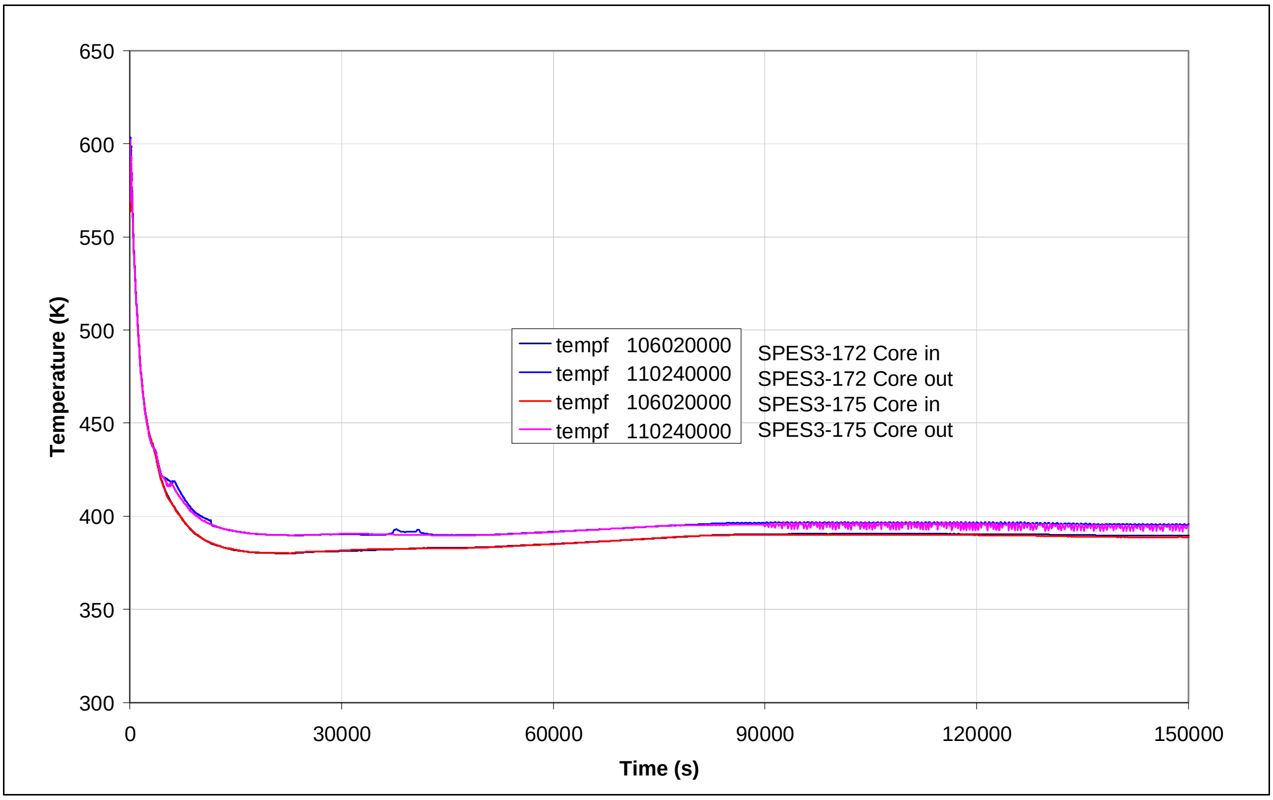


Fig.7. 62 - SPES3-172 and SPES3-175 Core heater rod surface temperature –normal rod (window)

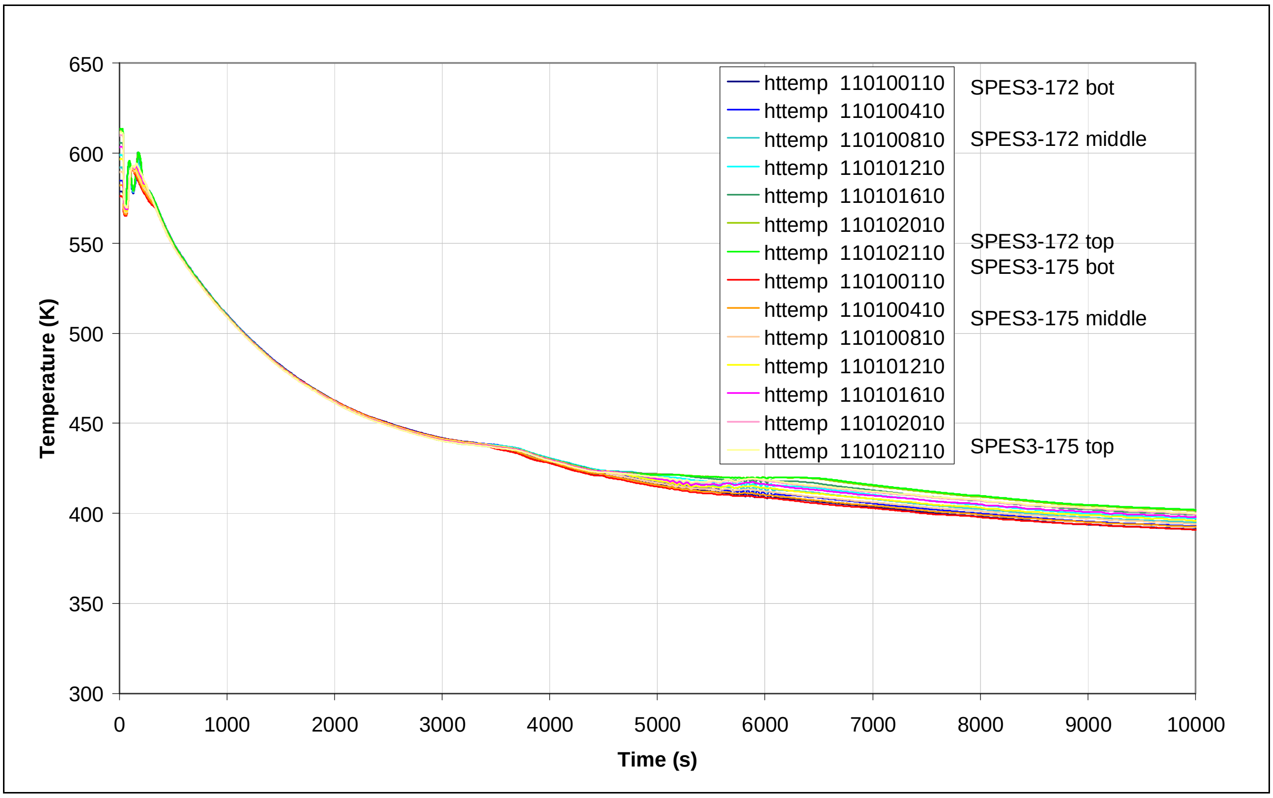


Fig.7. 63 - SPES3-172 and SPES3-175 Core heater rod surface temperature –normal rod

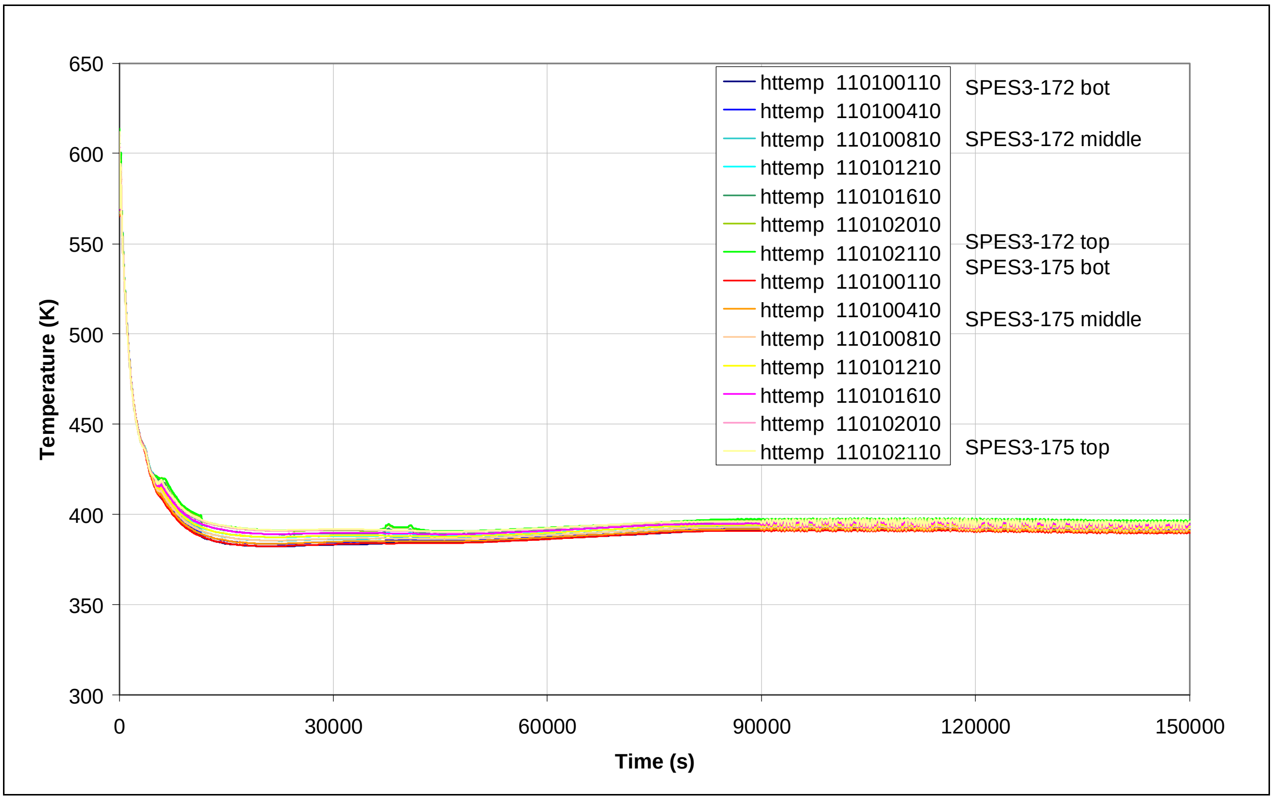


Fig.7. 64 - SPES3-172 and SPES3-175 Core heater rod surface temperature –hot rod (window)

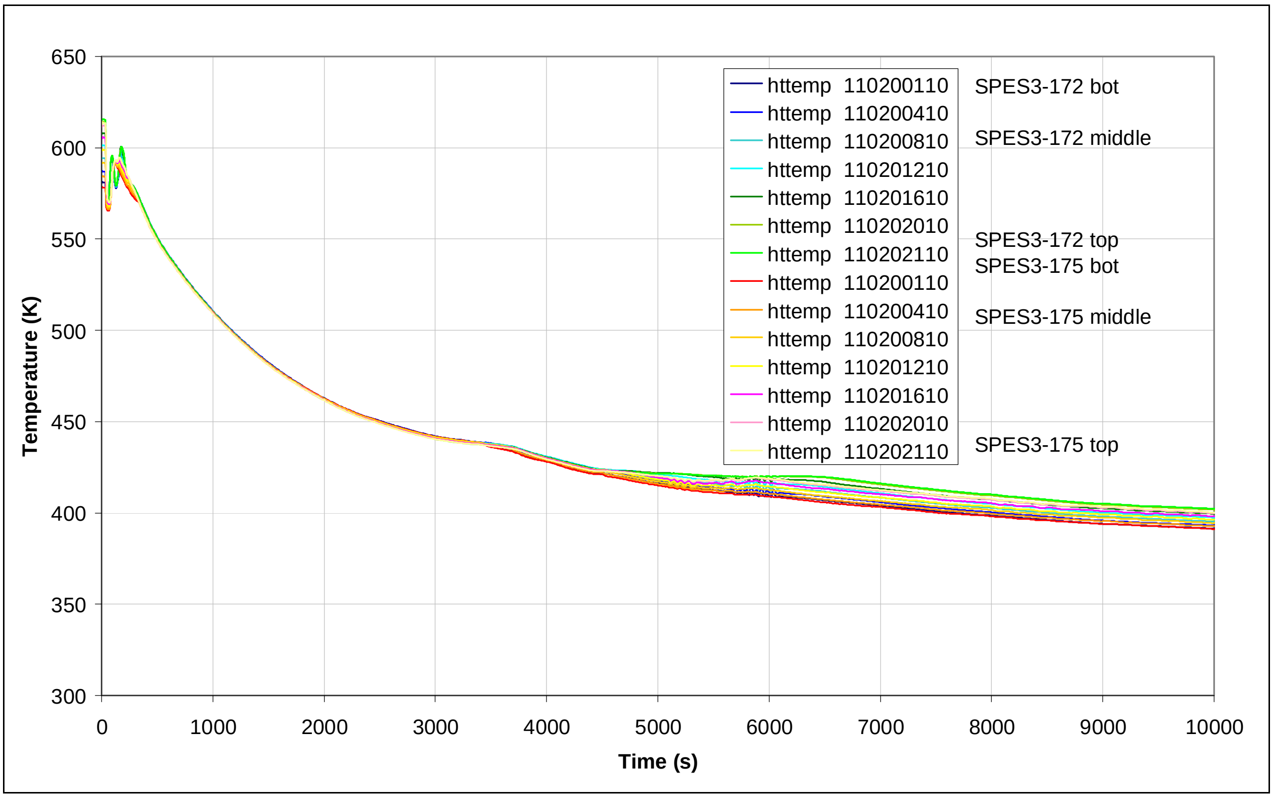


Fig.7. 65 - SPES3-172 and SPES3-175 Core heater rod surface temperature –hot rod

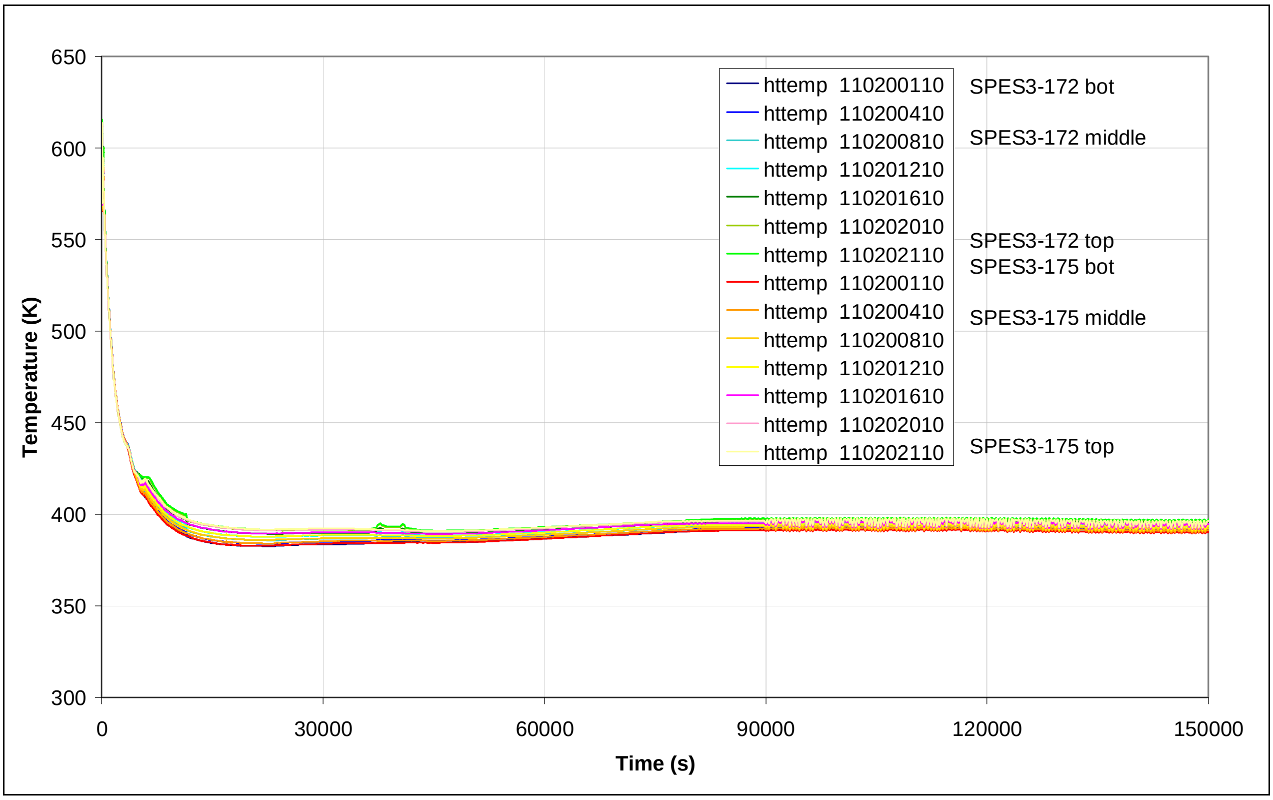


Fig.7. 66 - SPES3-172 and SPES3-175 LGMS level

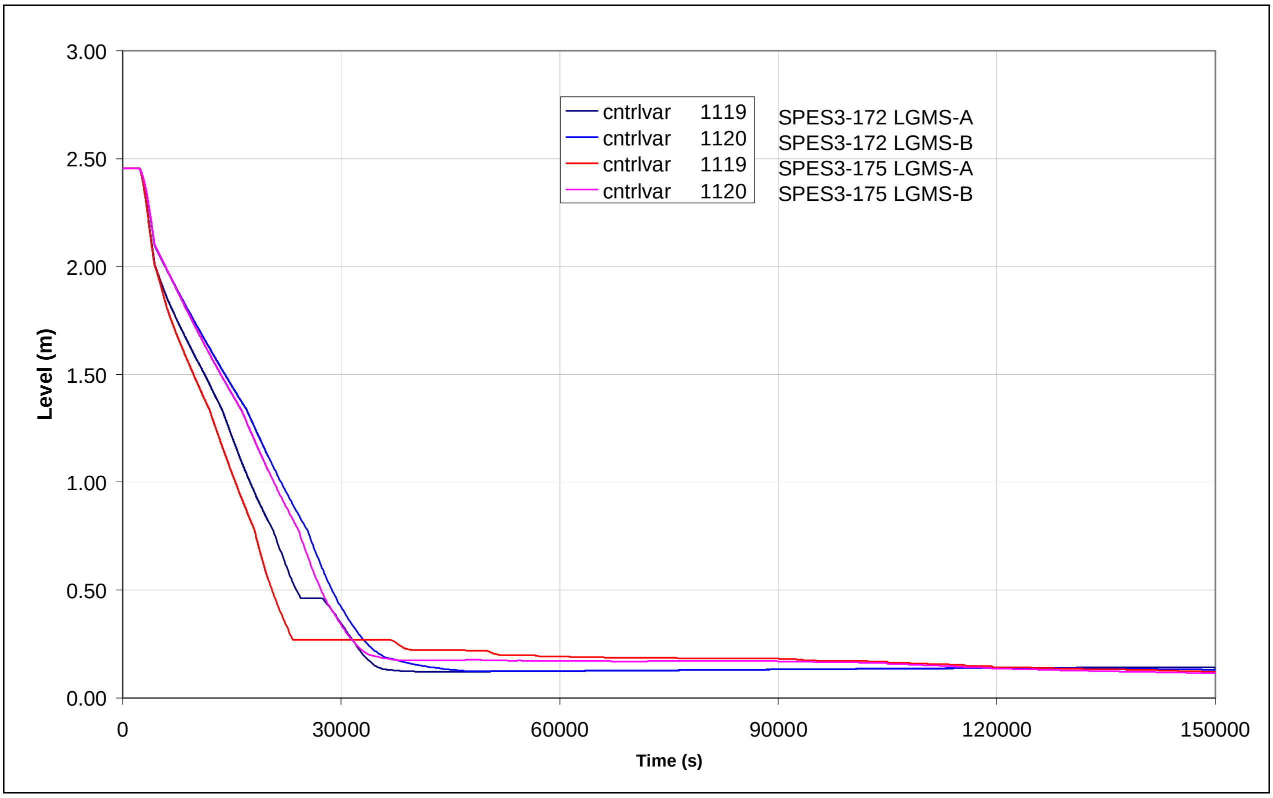


Fig.7. 67 - SPES3-172 and SPES3-175 DW level

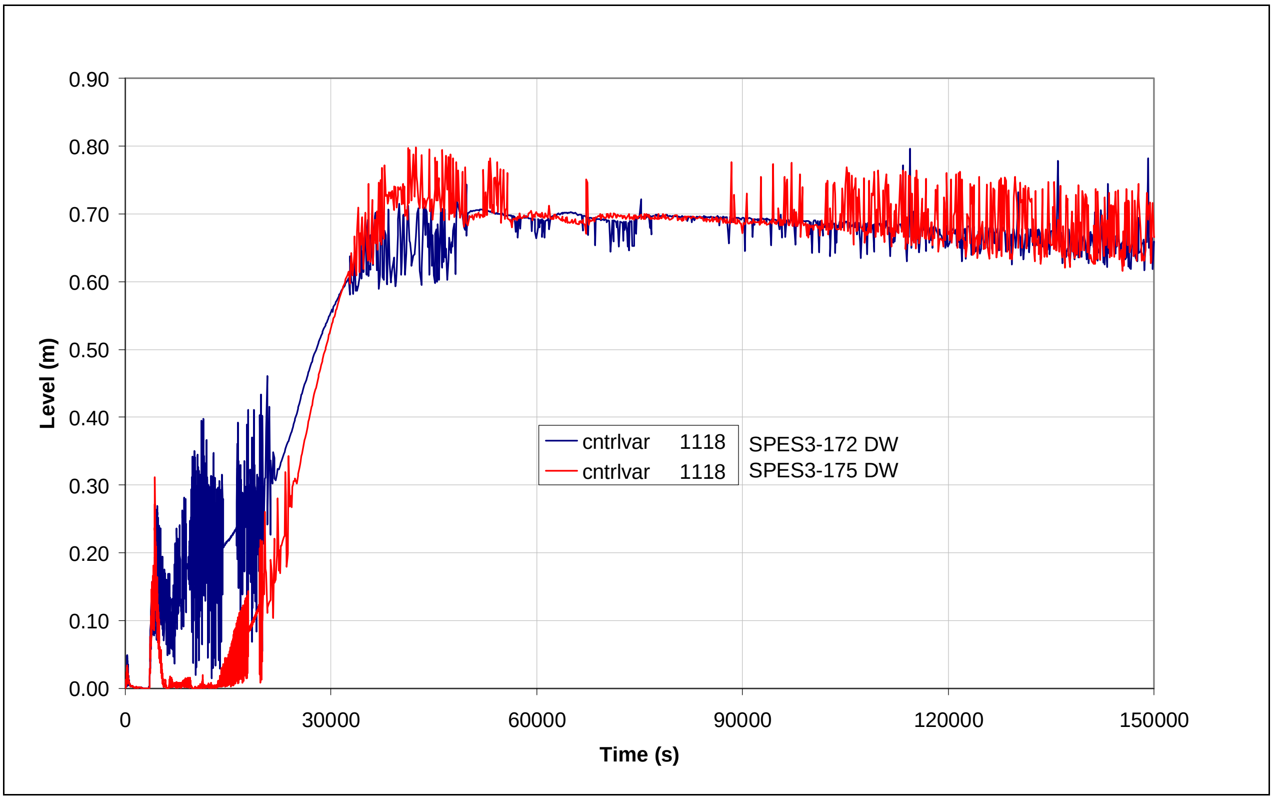


Fig.7. 68 - SPES3-172 and SPES3-175 DVI mass flow (window)

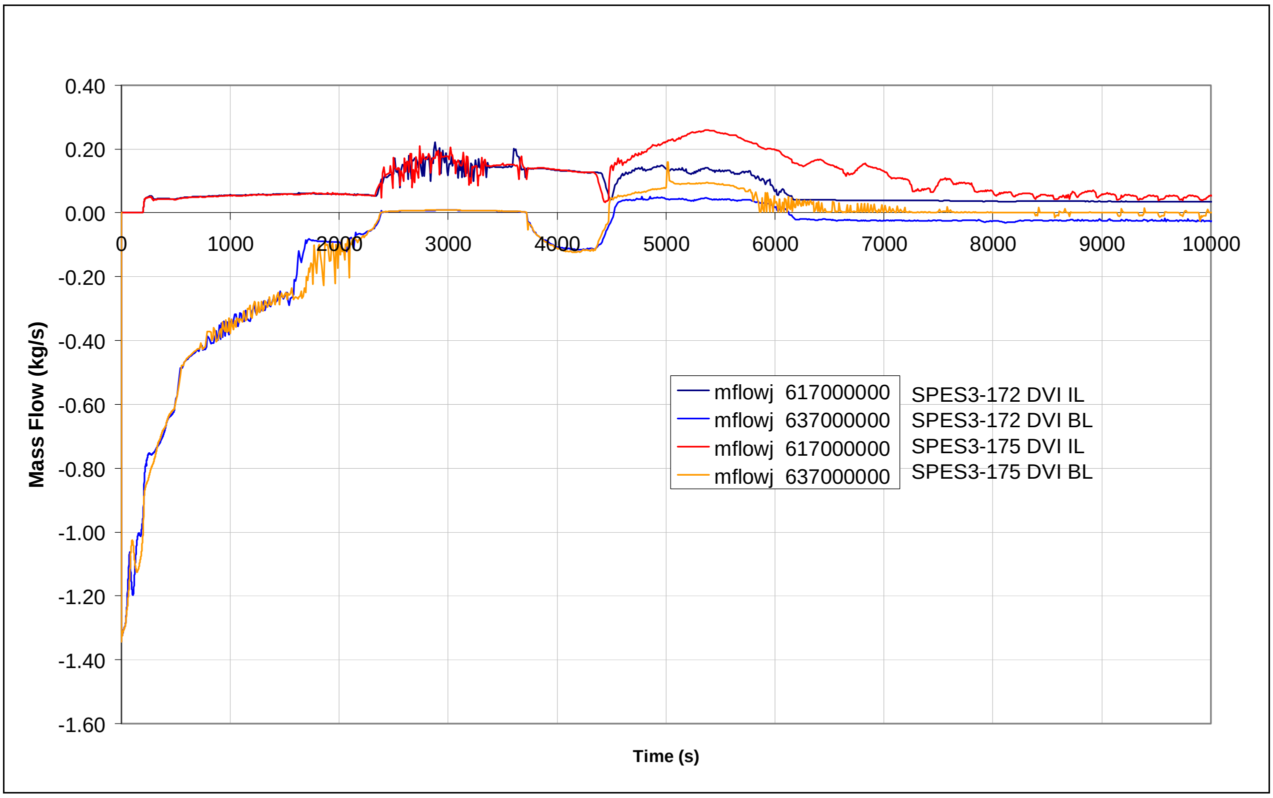


Fig.7. 69 - SPES3-172 and SPES3-175 DVI mass flow

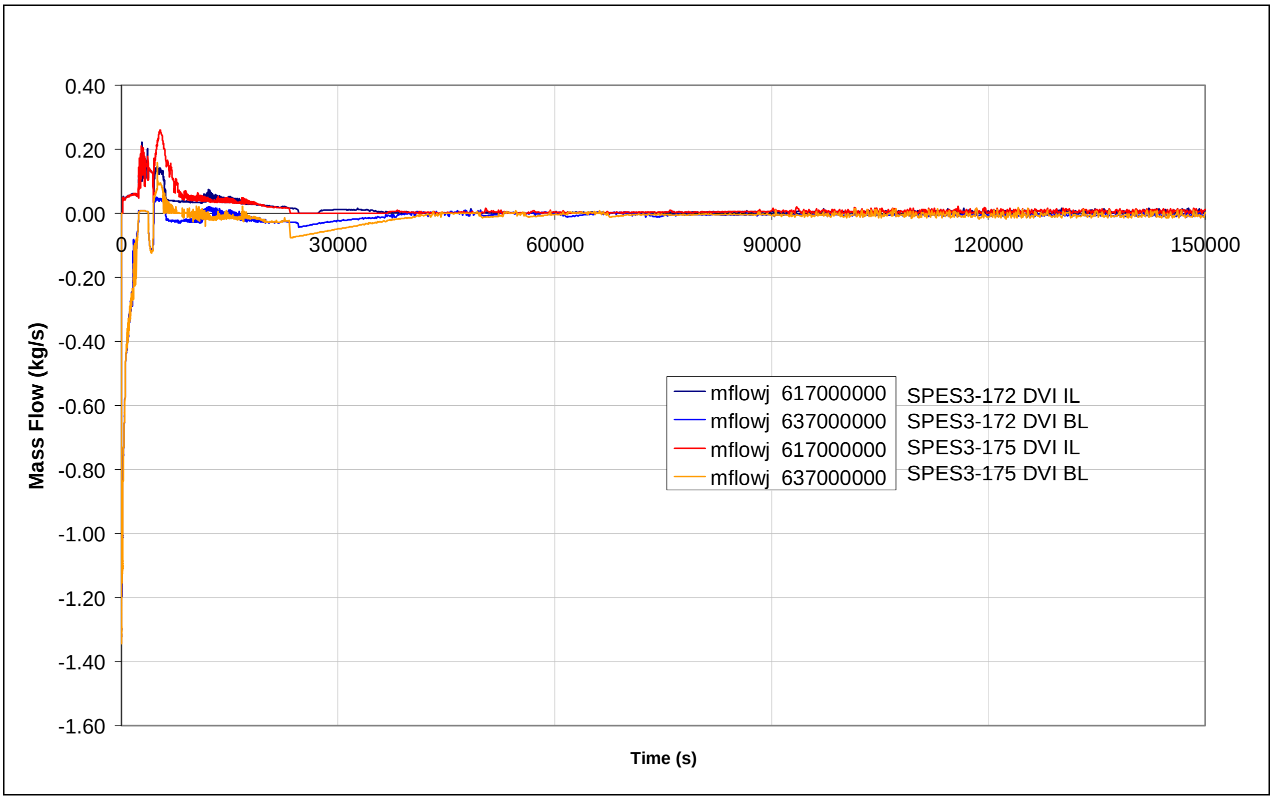


Fig.7. 70 - SPES3-172 and SPES3-175 QT level

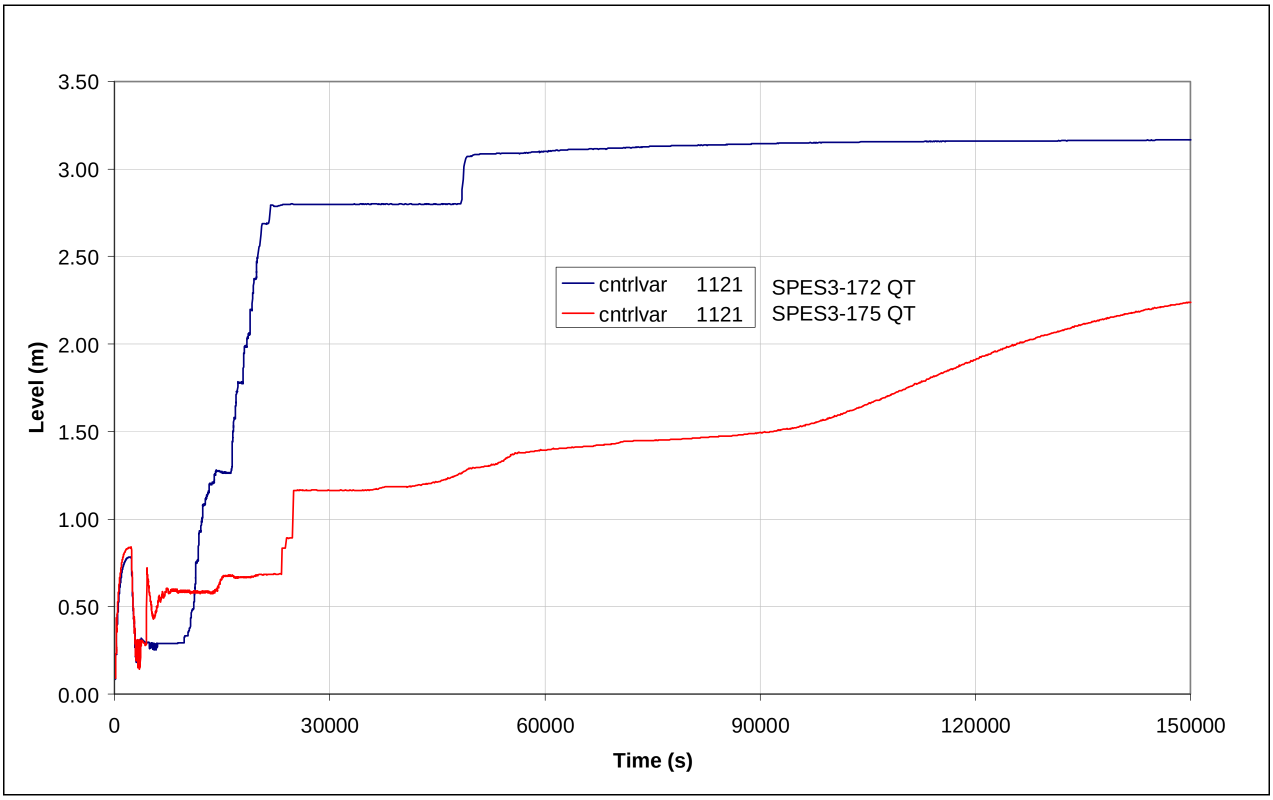


Fig.7. 71 - SPES3-172 and SPES3-175 LGMS mass (window)

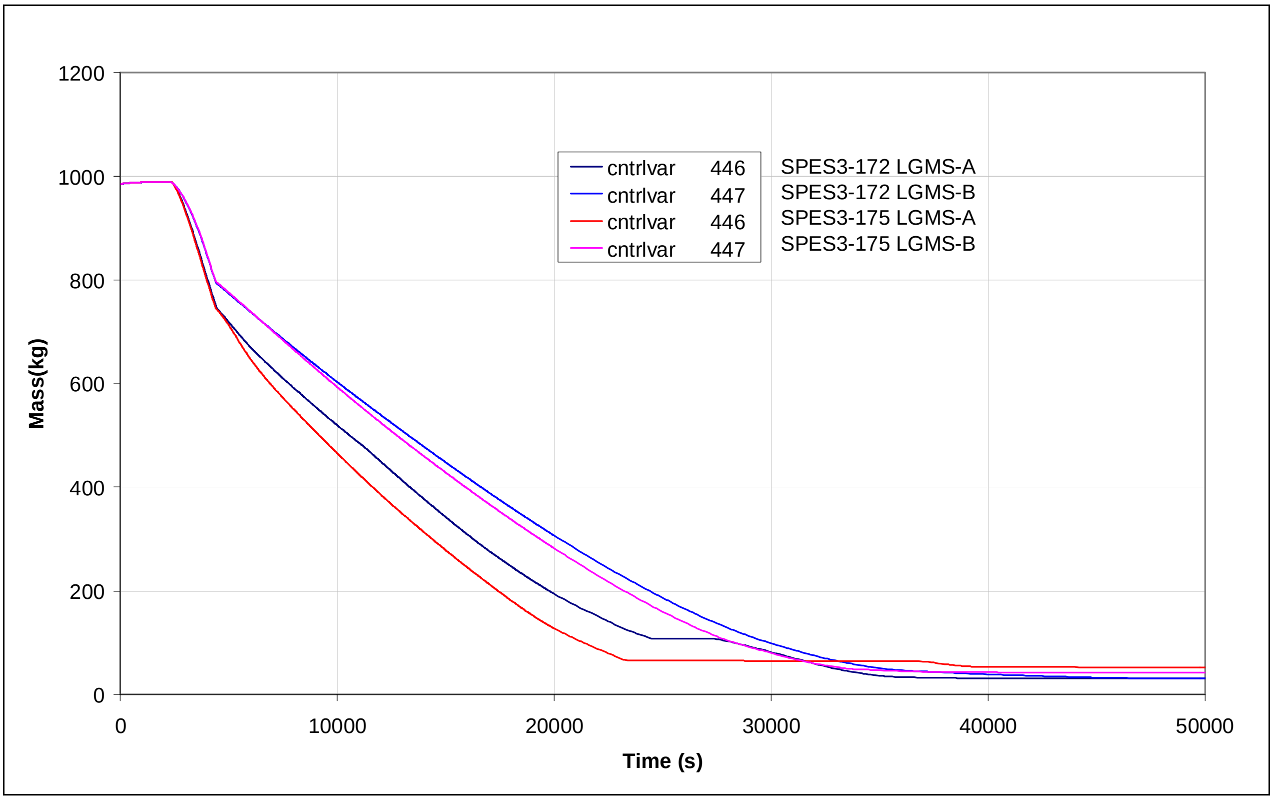


Fig.7. 72 - SPES3-172 and SPES3-175 ADS Stage-II mass flow (window)

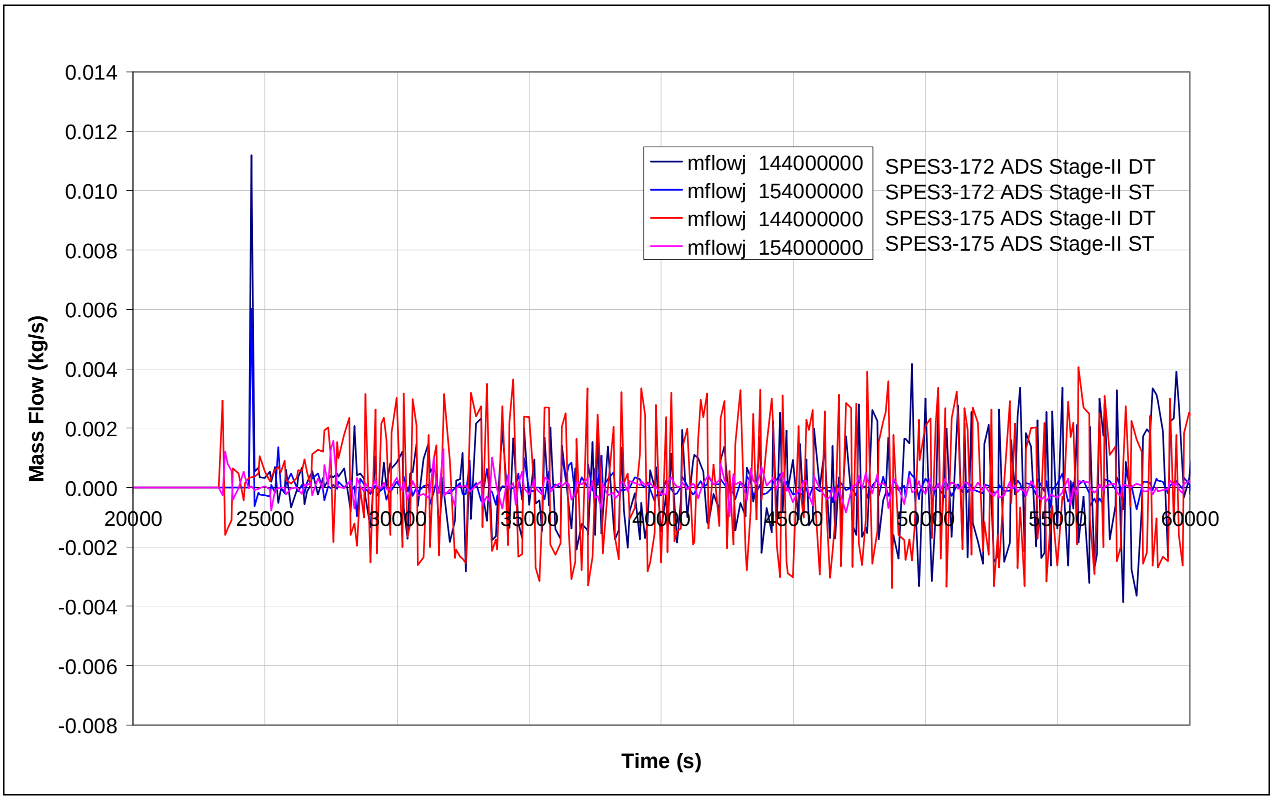


Fig.7. 73 - SPES3-172 and SPES3-175 ADS Stage-II mass flow

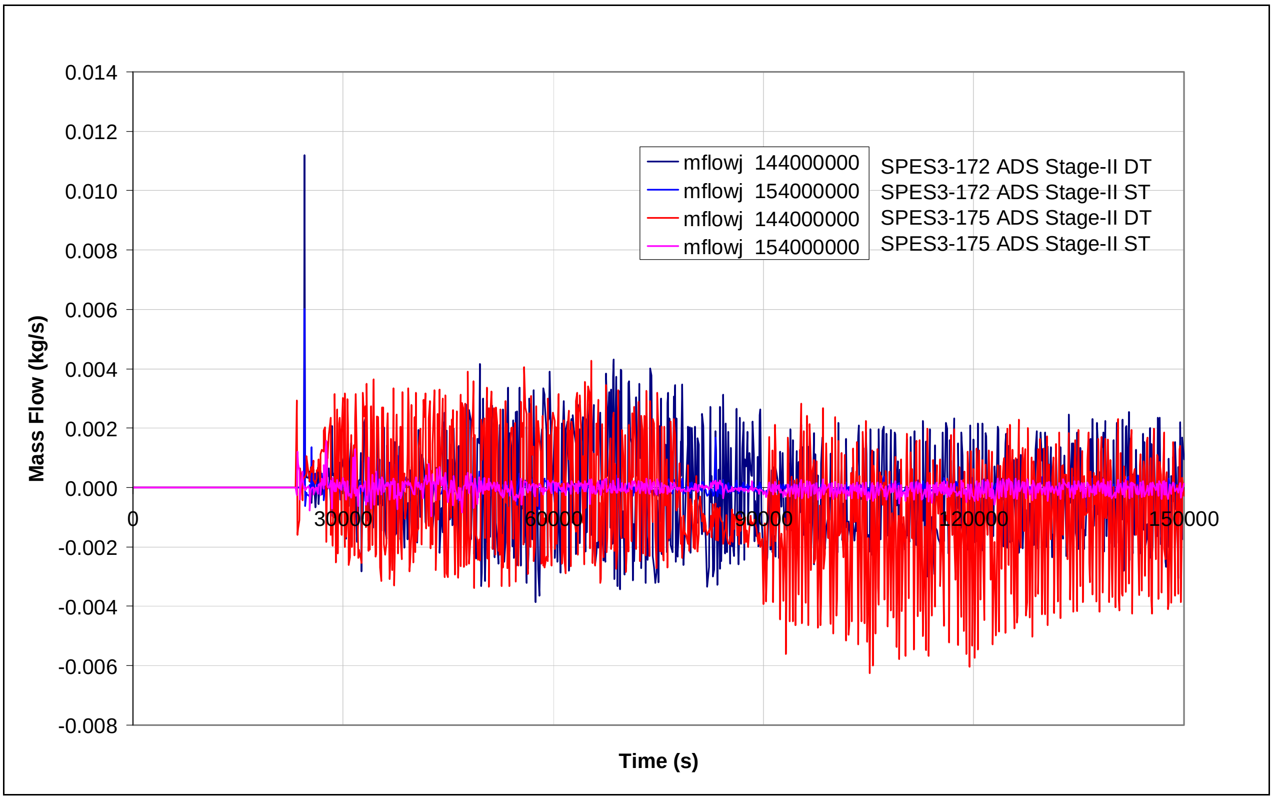


Fig.7. 74 - SPES3-172 and SPES3-175 RWST temperature

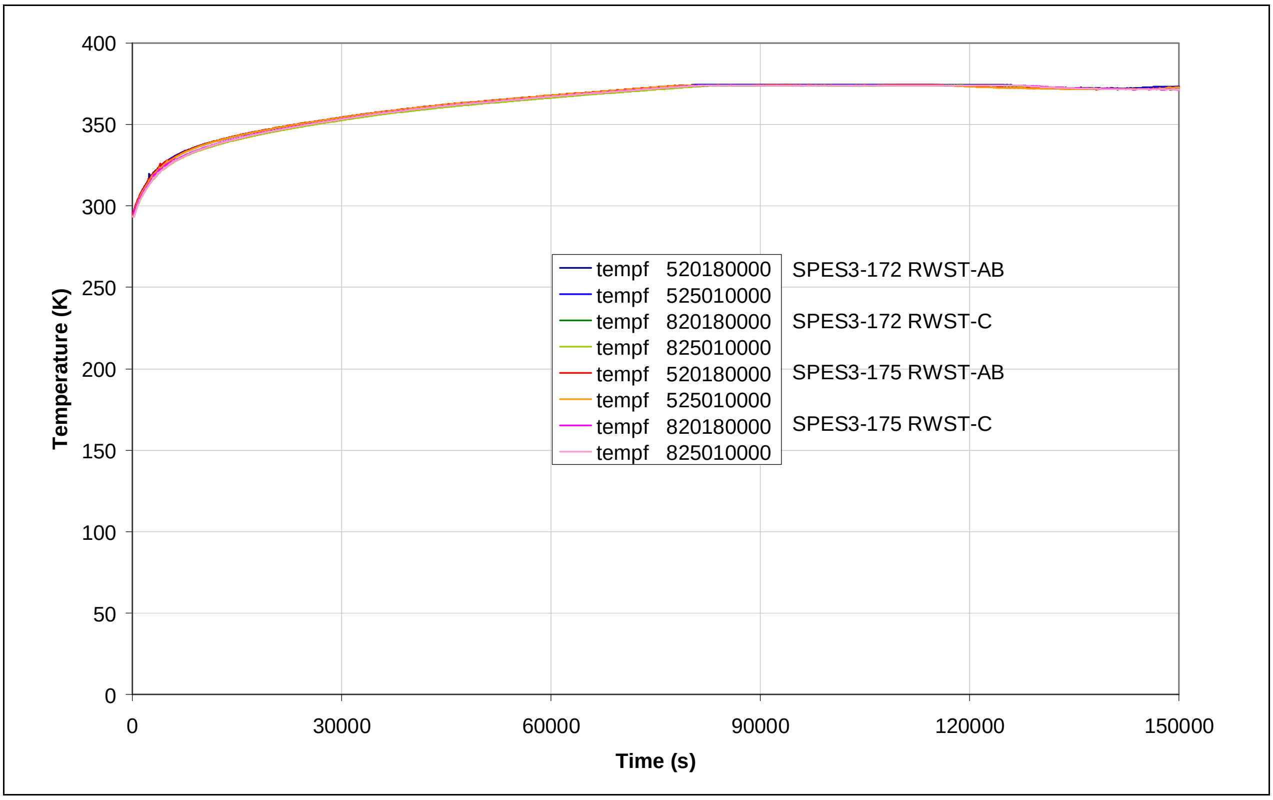


Fig.7. 75 - SPES3-172 and SPES3-175 RWST mass

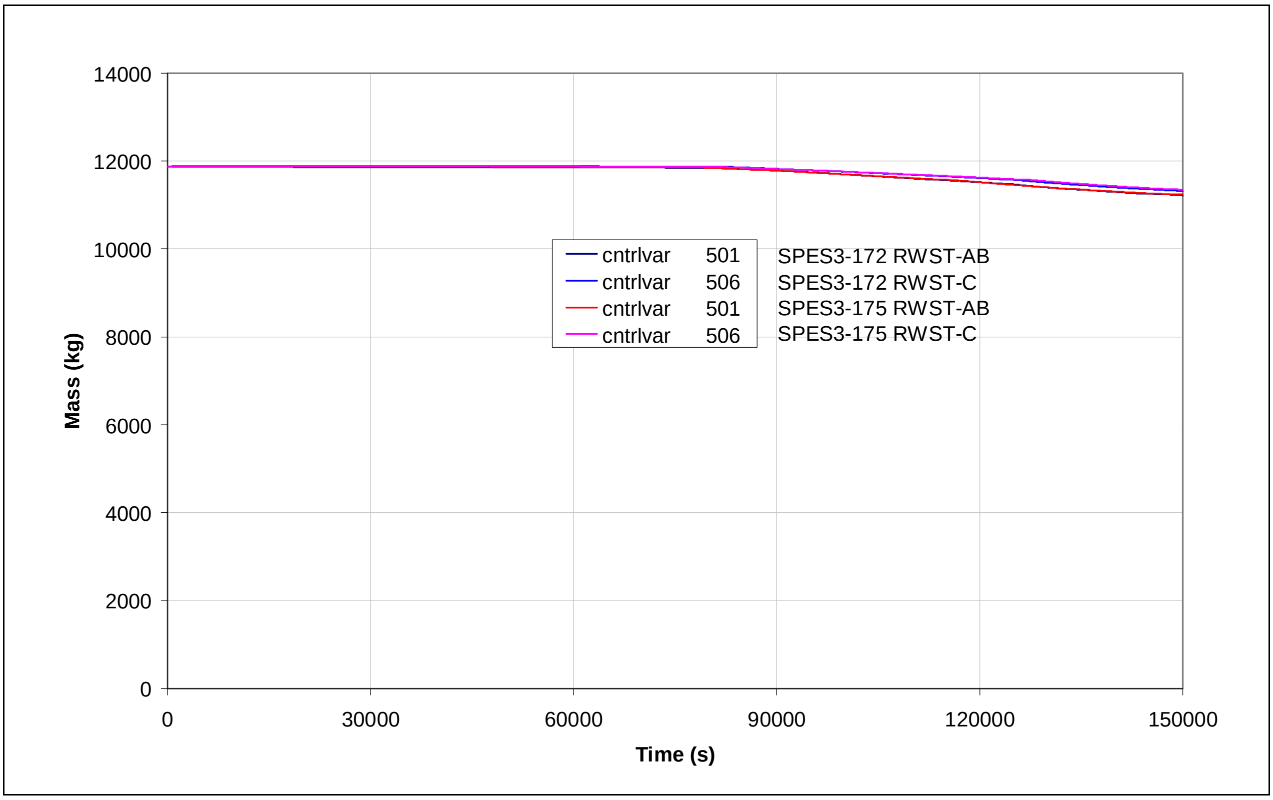
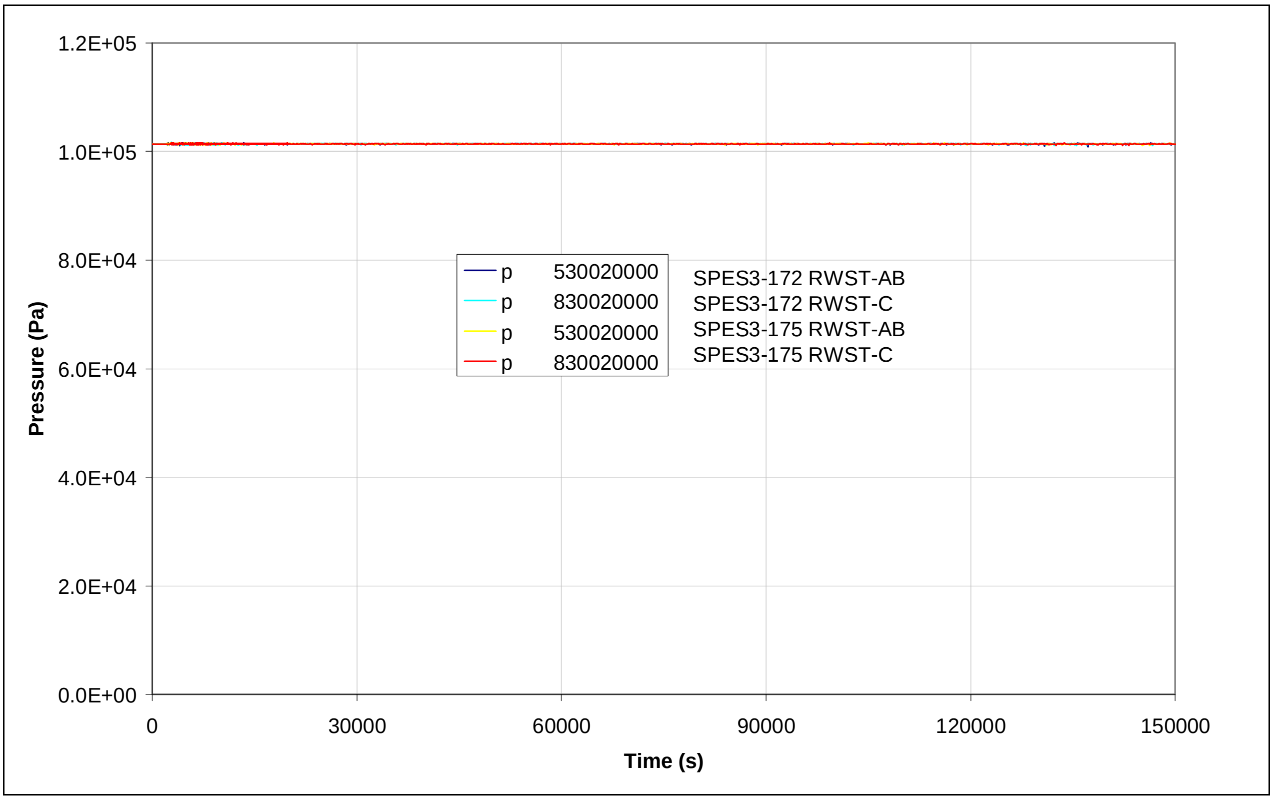


Fig.7. 76 - SPES3-172 and SPES3-175 RWST pressure



8. BDBE DVI LINE DEG BREAK FROM 100% AND 65% POWER: SPES3-173 AND SPES3-176

The same BDBE DVI line DEG break transient was simulated starting from steady conditions reached at 100% and 65% power (Chapter 6.) and the results compared to verify similarity of quantities.

As come-out of the sensitivity analysis on the BDBE DVI line DEG break transient (Chapter 5.), the signal combination to trigger the PCC is based on 0.9 MPa DW pressure AND LM-signal delayed of 1800 s.

Instead, the ADS Stage-II intervention, was anticipated to the LM-signal, as for ADS Stage-I, accordingly to the accident management procedure reported in [22] [23] (triggering signal no more based on low LGMS mass signal).

Case SPES3-173 is the full power transient, starting from steady conditions as reported in Tab.6. 1.

Case SPES3-176 is the reduced power transient, starting from steady conditions as reported in Tab.6. 2.

In the reduced power transient, the core power decay curve and the pump coastdown curve, initially at reduced rate, reach the corresponding decay curves, from full power, as described in Chapter 7., for the DBE DVI line transient.

The list of the main events occurring during the transients, with timing and quantities, is reported in Tab.8. 1 for both full and reduced power cases.

8.1 SPES3-173 and SPES3-176 transient phases and description

The first 10 s of SPES3 data (-10 s to 0 s) are steady state conditions.

All times of the events are given with respect to the break time, assumed as time 0 s.

Break

Break line mass flow, RPV side (SPLIT) and containment side (DEG), is shown in Fig.8. 1, Fig.8. 2 and Fig.8. 3. The peak of 1.33 kg/s is observed, RPV side, in both cases, at 2 s.

Mass flow, containment side, is first related to safety injection of EBT in the broken loop (~250 s) and later to LGMS injection (~1000 s), Fig.8. 4, Fig.8. 5, Fig.8. 6.

Reverse flow from containment (RC) to RPV is observed through the SPLIT line, after the ADS Stage-I and ADS Stage-II are opened with RPV depressurization below the containment value (~3500 s), Fig.8. 7, Fig.8. 8, Fig.8. 9, Fig.8. 10, Fig.8. 11, Fig.8. 12, Fig.8. 13, Fig.8. 14.

Blowdown, RPV depressurization, containment pressurization

The blowdown phase depressurises the RPV with mass and energy transfer to containment.

PRZ pressures is shown in Fig.8. 15, Fig.8. 16, Fig.8. 17.

While PRZ depressurises, containment pressure increases as shown in Fig.8. 14, Fig.8. 18, Fig.8. 19. The increase in pressurization rate, around 250 s, is due to ADS Stage-I and Stage-II intervention that discharges mass and energy into the DW, Fig.8. 7, Fig.8. 9. Around 900 s, PRZ and DW pressure are coupled and both increase up to reach the containment peak of 1.59 MPa at 2055 s.

After the peak, pressure decreases thanks to PCC intervention (~2050 s) which removes power from containment and brings pressure to oscillate between 0.8 and 0.9 MPa set points, Fig.8. 25, Fig.8. 26.

Around 1850 s, RPV is sufficiently depressurized to allow LGMS injection through the intact DVI line for RPV water inventory restoring, Fig.8. 5.

Around 2150 s, water back-flow from PSS to DW occurs that contributes to increase the amount of water available for RC to RPV injection, Fig.8. 22, Fig.8. 23.

Steam dumping into PSS

Containment space (DW and RC) pressurization causes transfer of steam-gas mixture from DW to PSS through the PSS vent lines, starting at 16 s and lasting up to PCC intervention and consequent DW depressurization, Fig.8. 22.

Within 500 s, almost all DW non-condensable gas is transferred to the PSS, as shown in Fig.8. 24, Fig.8. 25. Steam is dumped underwater through the PSS sparger and air pressurizes the PSS and LGMS gas space, Fig.8. 26, Fig.8. 27, Fig.8. 28, Fig.8. 29. After PSS to DW injection start, PSS and LGMS pressure follows the DW depressurization until the PSS sparger is uncovered and consequent DW, PSS and LGMS pressure equalization, Fig.8. 30, Fig.8. 31. Water level in the PSS vent pipes and extension is shown in Fig.8. 32, Fig.8. 33. It reaches the top only when PSS pressure is sufficiently high to overcome the PSS vent pipe gravity head and push water upwards into the DW, Fig.8. 32, Fig.8. 33. The PSS and DW volumes remain separated from the pressure point of view until the PSS sparger uncovers (0.75 m from PSS bottom), then they are coupled and follow the oscillations determined by PCC, Fig.8. 34, Fig.8. 35, Fig.8. 30, Fig.8. 31.

Soon after PSS sparger uncovering and water injection stop, PSS level slowly increases due to cyclic DW to PSS mass transfer in accordance to period of higher DW pressure, determined by the PCC operation mode. Around 40000 s, non-symmetric behaviour of PSS-A and B is observed with greater level and mass increase in PSS-B, probably related to slightly different pressure drops in the two PSS vent pipes, Fig.8. 35, Fig.8. 36. Level oscillations observed in the RC, Fig.8. 37, Fig.8. 38 and DW Fig.8. 39, push DW steam toward the PSS vent lines, with an oscillatory mode. Around 40000 s, fast DW level increase is observed, Fig.8. 39, corresponding to PSS level step increase. As DW level increases, water is transferred into the QT up to complete fill-up, Fig.8. 40. The phenomenon of slow water accumulation into the PSS, makes it no more available to be injected into the RPV and it may be critical if amount of water above the core is little. Both in SPES3-173 and SPES3-176 cases, sufficient amount of water is available in the primary circuit to keep the core cooled.

PSS water temperature increases thanks to the mass transfer from DW, Fig.8. 22, Fig.8. 41, Fig.8. 42. Both the liquid and gas temperatures are reported in Fig.8. 41 and Fig.8. 42 and they are very similar. Water temperature remains below saturation (maximum temperature reached at the pressure peak of 1.57 MPa is around 450 K (Tsat 473 K)), but without great margin for steam condensation. This causes the containment pressurization up to 1.59 MPa. After the end of injection toward the DW, residual PSS water is close to saturation (temperature at the minimum pressure of 0.8 MPa is around 430 K (Tsat 443.6 K)).

S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure

The high containment pressure set-point (1.7e5 Pa) is reached at 32.78 s in SPES3-173 and at 31.58 in SPES3-176. It triggers the S-signal.

The S-signal (Safeguard) starts the reactor SCRAM and isolates the three secondary loops. EHRS-A and B actuation is assumed to fail.

Power released to fluid in the core is shown in Fig.8. 43, Fig.8. 44, Fig.8. 45. Steady state power of the cases are 10 MW for SPES3-173 and 6.5 MW for SPES3-176. After the scram signal, the reduced power curve continues at 6.5 MW for 3.35 s, until it intersects the nominal decay power curve. After the reactor isolation, no power is removed through the SGs toward the EHRSs, as failed, Fig.8. 46, Fig.8. 47.

The MFIV and MSIV of the secondary loops are contemporarily closed in 5 s and the secondary loop mass flows set to zero, Fig.8. 48.

Secondary side pressures are shown in Fig.8. 49, Fig.8. 50. After isolation, pressure increases up to 11.3 MPa in SPES3-173 and to 11.5 MPa in SPES3-176, due to heat transfer from primary side and tube water evaporation. Such water evaporation causes tube level decrease, as shown in Fig.8. 51 and Fig.8. 52.

Pump coastdown and primary circulation through RI-DC check valves

PRZ level is shown in Fig.8. 53. The early phase of level decrease, until the ADS Stage-I and Stage-II intervention (~250 s), is due to loss of mass from the break. Level increase, after the ADS actuation, is due to water swelling and suction toward the QT (Stage-I) and the DW (Stage-II), Fig.8. 7, Fig.8. 8. Due to loss of mass from the break and ADS, the pump uncovers soon, Fig.8. 55.

The pump coastdown is triggered with 15 s delay on the Low PRZ level signal, Fig.8. 54. Pump speed, in SPES3-176 steady state, is scaled on power to maintain the nominal inlet-outlet core ΔT. After the pump coastdown signal, speed is kept constant for 2 s, up to intersect the nominal pump velocity decay curve. After that, speed is reduced accordingly in SPES3-173 and SPES3-176 cases. Soon after the pump suction is uncovered, Fig.8. 55, RPV natural circulation through the pump interrupts.

Core inlet flow is shown in Fig.8. 56 and Fig.8. 57. Natural circulation lasts until the RI to DC check valves are covered (~500 s), Fig.8. 58. After about 10000 s, when RPV mass inventory is restored from the RC, through the intact loop RC to DVI line, circulation in the check valves is present again with oscillations related to PCC operation, Fig.8. 59, Fig.8. 60.

LM-Signal: ADS Stage-I, ADS Stage-II and EBT actuation, EHRS-C actuation failure, PCC actuation counter start.

The LM-Signal (LOCA mitigation) occurs at about 250 s, when the low PRZ pressure set-point (11.72e6 Pa) is reached, Fig.8. 15.

EHRS-C actuation on LM-signal is assumed to fail. Failure of EHRS-C starts the counter for PCC actuation with 1800 s delay on LM-signal. Such delay is assumed as time required to fill the containment refuelling cavity, heat sink for PCC.

The LM-signal triggers the ADS Stage-I and the EBT actuation valves.

The ADS Stage-I and Stage-II trains are actuated contemporarily and the valves are fully open in 10 s. ADS Stage-I mass flows are shown in Fig.8. 7 and Fig.8. 8. ADS Stage-II mass flows are shown in Fig.8. 9, Fig.8. 10, Fig.8. 11. Mass flow peak of about 2.5 kg/s and 1.25 kg/s are observed in the ADS Stage-I DT and ST, respectively, while flow peak of about 10 kg/s and 5 kg/s are observed in the ADS Stage-II DT and ST. Initially, steam is discharged toward the QT and the DW. Soon after the ADS opening, PRZ water is sucked upwards and PRZ level increases with great liquid fraction at the ADS nozzles, Fig.8. 53. The contemporary ADS Stage-I and II opening causes great mass and energy transfer from primary to containment that leads to strong DW pressurization, up to about 1.59 MPa at 2050 s, Fig.8. 18. Such DW pressurization, overcomes the SPES3 containment design pressure of 1.5 MPa and it will be necessary to adjust the test procedures, for this specific transient, in order to conduct the tests and contemporarily protect the plant.

The LM-signal triggers the EBT valves that are fully open in 15 s. EBT injection mass flows are shown in Fig.8. 4. The EBT injection into the broken DVI line is initially about 14 times grater than injection into the intact one, due to the presence of the break. EBT masses and levels are shown in Fig.8. 61 and Fig.8. 62, respectively.

Soon after the EBT actuation, liquid circulation from the RPV toward the EBT starts at the EBT balance connection to RPV, then, after such connection is uncovered, steam replaces water contained in the EBT top lines and tanks, Fig.8. 63. The broken loop EBT is empty around 700 s while the intact loop EBT is empty at about 2800 s, Fig.8. 62.

EBT actuation is responsible for mass flow through the break line, containment side, starting around 250 s, Fig.8. 1.

RPV saturation

Fast RPV depressurization and loss of mass from the break, Fig.8. 1, Fig.8. 15, rapidly cause flashing of the primary circuit and void begins at the core outlet at 265 s in SPES3-173 and 282 s in SPES3-176, Fig.8. 64, Fig.8. 65. At high level in the core, liquid fractions are reached down to 0.4. After about 2800 s, water enters the RPV through the intact loop RC to DVI line, Fig.8. 66, and break line, RPV side, Fig.8. 67, Fig.8. 68, RPV mass begins to be restored, Fig.8. 60, core circulation restarts through the RI-DC check valves, Fig.8. 58, Fig.8. 59, and this guarantees to keep core cooled and heater rod clad temperature at limited values.

Inlet and outlet core temperatures are shown in Fig.8. 69 and Fig.8. 70. Limited temperature excursion (~25 °C) is observed due to the break and ADS opening th at cause fast system depressurization, flashing and cooling capability reduction.

Core heater rod surface temperatures are shown in Fig.8. 72, Fig.8. 73 and Fig.8. 74, Fig.8. 75, for the normal and hot rods, respectively. As for core fluid temperatures, they show little excursions in the early phases of the transient. After that, liquid in the core is sufficient to maintain it cooled.

RC to DVI line mass flow is shown in Fig.8. 66. Water injection into the RPV occurs only through the intact loop. Thanks to rapid RPV depressurization by the ADS, water injection starts soon after the RC is full (~2700 s). It’s oscillatory trend is linked to cyclic actuation of PCC.

DVI line mass flows at the RPV connections are shown in Fig.8. 67 and Fig.8. 68 for the intact and broken loop. Water flow into the RPV, through the intact loop, is due to the EBT and LGMS injection. Negative values of broken loop mass flow, represent water lost from the break; positive values represent back-flow from containment to RPV, driven by primary to containment differential pressure.

Mass flow entering the RPV through the break line is of the same order of magnitude of that entering the RPV through the RC to DVI line and core rewetting occurs for both contributions, Fig.8. 67, Fig.8. 68, Fig.8. 66.

PCC actuation

The containment pressure peak of 1.59 MPa occurs at about 2050 s, Fig.8. 18.

Pressure is rapidly dumped thanks to PCC intervention at 2053.85 s in SPES3-173 and 2043.63 s in SPES3-176 (i.e. 1800 s delayed on the LM-signal), Fig.8. 20, Fig.8. 21. After that, pressure is maintained between 0.8 MPa and 0.9 MPa, according to PCC actuation logic, Fig.8. 18, Fig.8. 19.

PCC tube mass flow is shown in Fig.8. 75. The tubes discharge into and are fed by the PCC tank that operates as steam condenser and water supply. PCC tank level is controlled by a PI (proportional-integral) control system, 0.7 m level set-point, that injects cold water into the feed line from an auxiliary circuit, Fig.8. 76. PCC inlet and outlet temperatures are shown in Fig.8. 77. Water enters slightly subcooled and exits saturated with a liquid fraction at the outlet of about 0.2, Fig.8. 78, Fig.8. 79.

Low DP RPV-Containment signal, LGMS and RC to DVI valve actuation

The “Low DP RPV-Containment” signal set point of 50 kPa is reached at about 870 s.

The combination of LM-signal AND Low DP RV-Containment signal actuates the LGMSs and opens the valves on the lines connecting RC to DVIs.

The LGMS isolation valves are fully open in 2 s as well as the RC to DVI line isolation valves.

LGMS injection into the IL DVI line starts around 1850 s and it is due both to gravity and air pressurization at the top, through the PSS to LGMS balance lines (pressurized during the RPV blowdown into RC and DW). After PCC intervention and containment and RPV fast depressurization (after coupling around 2050 s), injection mass flow increases until PSS sparger is uncovered and LGMS, PSS and DW pressure are equalized. After that, gravity drives water injection. LGMS injection mass flow is shown in Fig.8. 5, Fig.8. 6. LGMS level and mass are reported in Fig.8. 80 and Fig.8. 81, respectively. LGMS injection into the RPV, through the IL DVI line occurs when DVI pressure is lower than LGMS pressure, accordingly to PCC operation, and this explains the oscillatory trend of injection, Fig.8. 82, Fig.8. 83, Fig.8. 5, Fig.8. 6.

PSS water flow to DW, RC flooding, Containment and RPV pressure equalization, reverse flow from containment to RPV

At 2830 s, PSS pressure overcomes the hydrostatic head of water in the PSS vent lines and water is pushed toward the DW through the vent line extensions, Fig.8. 22, Fig.8. 23. Strong DW and consequently PSS pressurization, after the PCC intervention, causes continuous and strong water injection from PSS to DW, Fig.8. 22.

RC level, initially increased for the break and ADS mass flow collection, rapidly increases in correspondence of PSS to DW injection up to the complete fill-up at 2710 s (11 m level from bottom), Fig.8. 37, Fig.8. 38.

The QT, initially empty, is partially filled-up by ADS Stage-I discharge, Fig.8. 40. Later fill-up around 23000 s in SPES3-173 and 16100 in SPES3-176 is related to rapid increase of DW level, mostly due to LGMS water injection, after RC fill-up, Fig.8. 39, Fig.8. 81.

After the RC to DVI line valves are opened, (~875 s) and RC level is above the DVI line elevation, water back-flow from RC to RPV is allowed after the systems pressure equalization and when RPV pressure is lower than containment one, Fig.8. 66, Fig.8. 67, Fig.8. 68. Being the break line at the DVI line elevation, water back-flow from RC to RPV is allowed through it as well, Fig.8. 2.

Long term conditions

In the long term of the transient, system pressure is maintained between 0.8 and 0.9 MPa by PCC.

Core power, average value between 100000 and 150000 s, is about 46.3 kW in SPES3-173 and SPES3-176.

PCC removed power, average value between 100000 and 150000 s, is about 54.2 kW and this contributes to slowly cool-down the system.

8.2 Case conclusions

The comparison between the full power (SPES3-173) and reduce power (SPES3-176) cases showed a great similarity of the results with very similar phenomena and event timing.

On the basis of the results obtained by the analysis of SPES3-160 case, similar to SPES3-173 and SPES3-176, but with ADS Stage-II actuated on low (20%) LGMS mass, the present cases, with ADS Stage-II anticipated actuation on LM-signal, show that the system can cope with the BDBE DVI line DEG break transient and maintain the plant in safe conditions.

The combination of signals that triggers the ADS Stage-II together with ADS-Stage-I, on LM-signal, and the PCC with 1800 s delay on LM-signal, with DW pressure greater than 0.9 MPa, seems the best to recover the studied BDBE.

According to the calculated DW pressure peak value (15.9 MPa), criticalities can arise for the SPES3 facility containment designed at 1.5 MPa. Proper test procedures will be need to execute a BDBE DVI line DEG break test contemporarily representative of the IRIS one and not impairing the facility integrity. Little delay on ADS Stage-II actuation could be sufficient to solve the problem.

Tab.8. 1 – SPES3-173 and SPES3-176 list of the main events

	BDBE DVI-B line DEG break (2-inch equivalent)	**SPES3-173**		**SPES3-176**		
N.	**Phases and events**	**Time (s)**	**Quantity**	**Time (s)**	**Quantity**	**Notes**
Break						
1	Break initiation	0				break valves stroke 2 s
2	Break flow peak (Containment side)	1	0.688 kg/s	1	0.688 kg/s	Break flow = 0 kg/s at 11 s
3	Break flow peak (RPV side)	2	1.33 kg/s	2	1.33 kg/s	
Blowdown, RPV depressurization, containment pressurization, steam dumping into PSS						
4	Steam-air mixture begins to flow from DW to PSS	16		16, 17		SPES3-176 PSS-B, PSS-A
S-Signal: Reactor scram, secondary loop isolation. EHRS-A and B actuation failure						
5	**High Containment pressure signal**	32.78	1.7e5 Pa	31.58	1.7e5 Pa	**S-signal. Set-point for safety analyses**
6	SCRAM begins	32.78		31.58		
7	MFIV-A,B,C closure start	32.78		31.58		MFIV-A,B,C stroke 5 s
8	MSIV-A-B-C closure start	33.78		31.58		MSIV-A,B,C stroke 5 s.
9	EHRS-A and B actuation failure (EHRS 1 and 3 in IRIS)	32.78		31.58		EHRS-A,B IV stroke 2 s.
10	**High SG pressure signal**	46.28	9e6 Pa	48.69	9e6 Pa	
11	SG-A high pressure reached	46.28		48.69		
12	SG-B high pressure reached	47.73		50.61		
13	SG-C high pressure reached	47.28		50.36		
14	Secondary loop pressure peak	69 69 70	111e5 Pa 113e5 Pa 113e5 Pa	87 86 90	111e5 Pa 115e5 Pa 114e5 Pa	SG-A SG-B SG-C
Pump coastdown and primary circulation through RI-DC check valves						
15	**Low PRZ water level signal**	136.90	1.189 m	144	1.189 m	
16	RCP coastdown starts	151.90		159		Low PRZ level signal + 15 s delay
17	Natural circulation begins through shroud valves	173; 174		178,179,180		SPES3-173 A,C; B SPES3-176 C, B, A
18	Flashing begins at core outlet	255		248		voidf 110 (core) < 1
LM-Signal: ADS Stage-I, ADS Stage-II and EBT actuation, EHRS-C actuation failure. PCC actuation counter start. RPV saturation. Reverse flow from containment to RPV						
19	**Low PRZ pressure signal**	253.85	11.72e6 Pa	243.63	11.72e6 Pa	**LM-Signal** (High P cont + Low P PRZ)
20	EHRS-C actuation failure (EHRS 2 and 4 in IRIS)	253.85		243.63		
21	ADS Stage-I opening start (3 trains)	253.85		243.63		ADS valve stroke 10 s
22	ADS Stage-I first peak flow (3 trains)	279	3.77 kg/s	266	3.76 kg/s	SPES3-173 ST 1.27 kg/s; DT 2.50 kg/s SPES3-176 ST 1.24 kg/s; DT 2.52 kg/s Due to liquid fraction
23	ADS Stage-I second peak flow (3 trains)	344	1.61 kg/s	345	1.58 kg/s	SPES3-173 ST 0.46 kg/s; DT 1.15 kg/s SPES3-176 ST 0.46 kg/s; DT 1.12 kg/s Due to liquid fraction.
24	ADS Stage-II start opening	253.85		243.63		LGMS-A AND LGMS-B low mass ADS Stage-II valve stroke 10 s.
25	ADS Stage-II first peak flow (3 trains)	291	14.26 kg/s	272	15.88 kg/s	SPES3-173 ST 4.74 kg/s; DT 9.52 kg/s SPES3-176 ST 5.18 kg/s; DT 10.07 kg/s Due to liquid fraction
26	ADS Stage-II second peak flow (3 trains)	344, 359	6.16 kg/s	345, 366	5.83 kg/s	SPES3-173 ST 1.71 kg/s; DT 4.45 kg/s SPES3-176 ST 1.59 kg/s; DT 4.24 kg/s Due to liquid fraction.
27	EBT-A and B valve opening start	253.85		243.63		EBT valve stroke 15 s
28	Core in saturation conditions	265		282		
29	Break flow peak (Containment side)	269		263		Due to EBT intervention
30	High containment pressure signal	294.15	0.9 MPa	285.22	0.9 MPa	
31	EBT-RV connections uncovered	379, 316		263, 302		EBT-B, EBT-A
32	Natural circulation interrupted at SGs top	434		446		Pump inlet uncovered (voidf 176-01 ~0)
33	EBT-B empty (broken loop)	700		650		550 s almost empty (760 s completely empty)
Low DP RPV-Containment signal, PSS water flow to DW, RC flooding, LGMS and RC to DVI valve actuation						
34	**Low DP RV-Containment**	874.21	50e3 Pa	876.24	50e3 Pa	
35	LGMSA/B valve opening start	874.21		876.24		LM + low DP RV-cont. LGMS valve stroke 2 s.
36	RC to DVI line valve opening	874.21		876.24		RC to DVI valve stroke 2 s.
37	LGMS-B starts to inject into RC through DVI broken loop	1020		1030		
38	LGMS-A starts to inject into RV through DVI intact loop	1850		1850		
39	PCC actuation	2053.85		2043.63		LM-signal + 1800 s + P cont > 0.9 MPa
40	Containment pressure peak	2055	15.9e5 Pa	2055	15.9e5 Pa	
41	DW pressure lower than PSS pressure	2080		2060		
42	Water starts to flow from PSS to DW	2160		2150		cyclic injection until 4320 s
43	RC level at DVI elevation	2540		2540		
44	EBT-A empty (intact loop)	2810		2810		
45	RC full of water	2710		2710		
46	Water starts to flow from RC to DVI-A	2830		2830		
47	Containment and RV pressure equalization	2050		2060		
48	QT fill-up starts from DW connection	23190		16010		
49	LGMS-B empty (broken loop)	33490		33490		
50	LGMS-A empty (intact loop)	27240		27240		
Long Term conditions						
51	Containment and RPV pressure		0.8–0.9 MPa		0.8–0.9 MPa	PCC controlled
52	Core power		46.32 kW		46.27 kW	Average between 100000 s and 150000 s
53	PCC removed power		54.15 kW		54.30 kW	Average between 100000 s and 150000 s

Fig.8. 1 – SPES3-173 and SPES3-176 DVI line break flow (window)

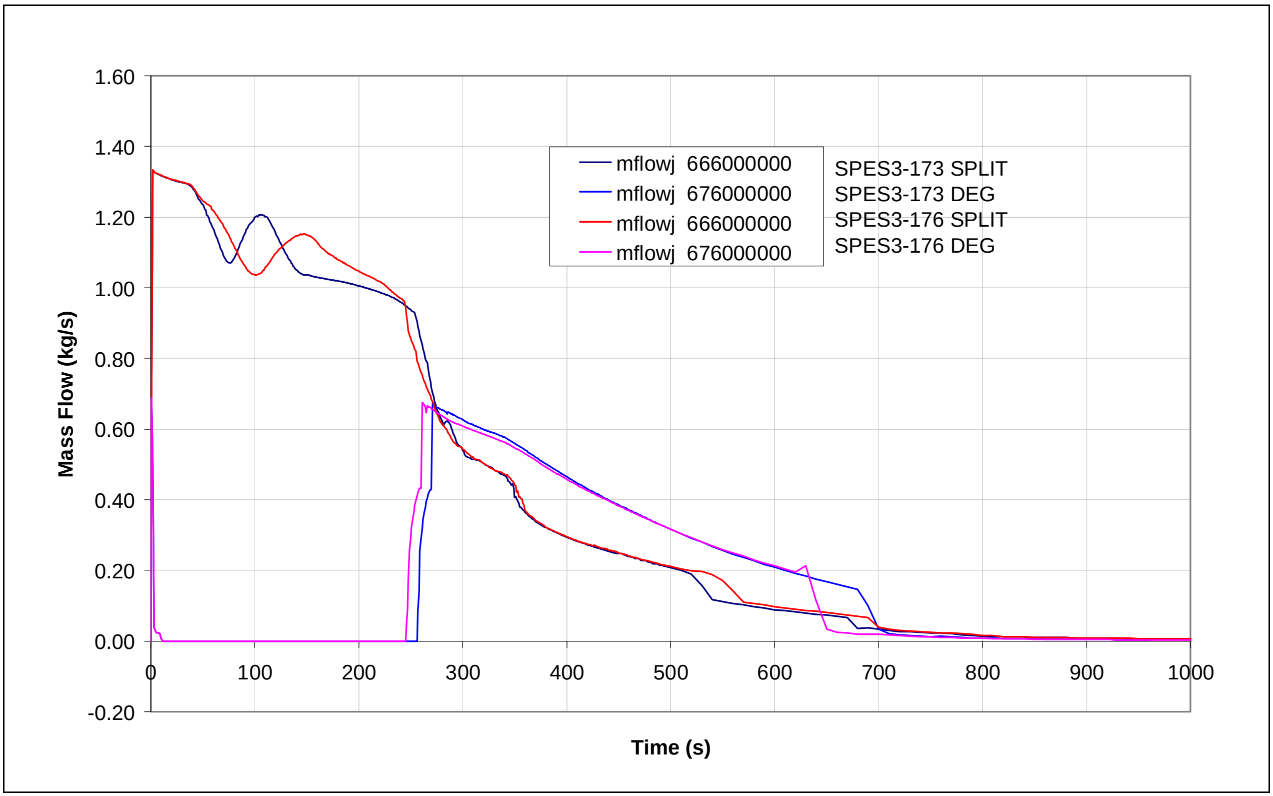


Fig.8. 2 – SPES3-173 and SPES3-176 DVI line break flow (window)

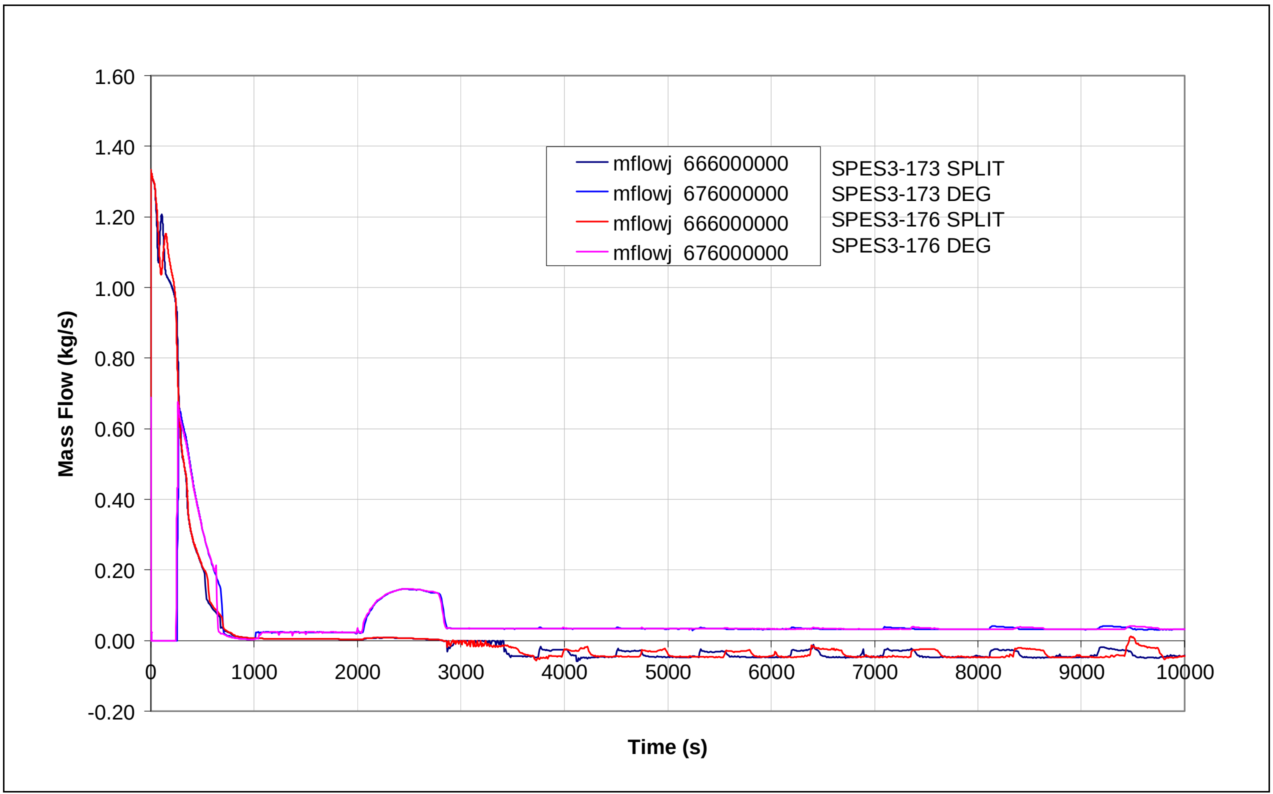


Fig.8. 3 – SPES3-173 and SPES3-176 DVI line break flow

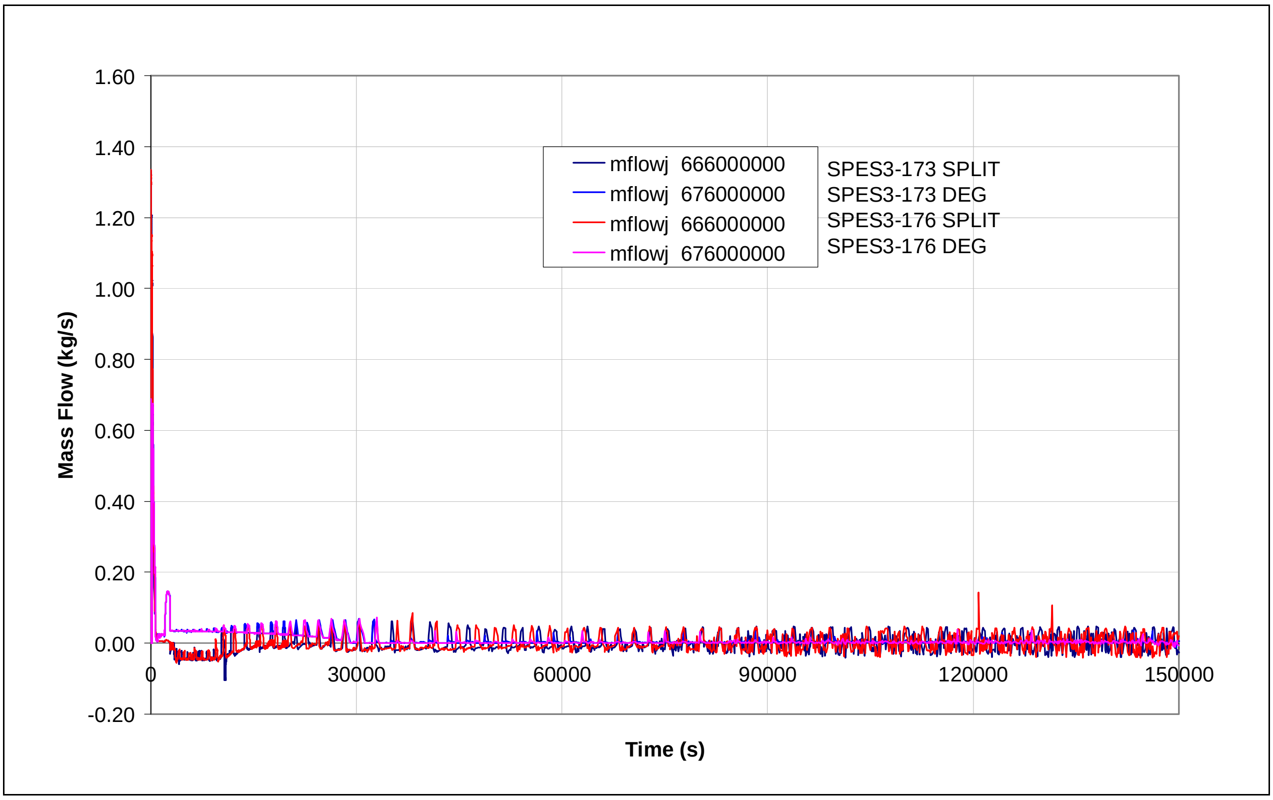


Fig.8. 4 – SPES3-173 and SPES3-176 EBT injection mass flow (window)

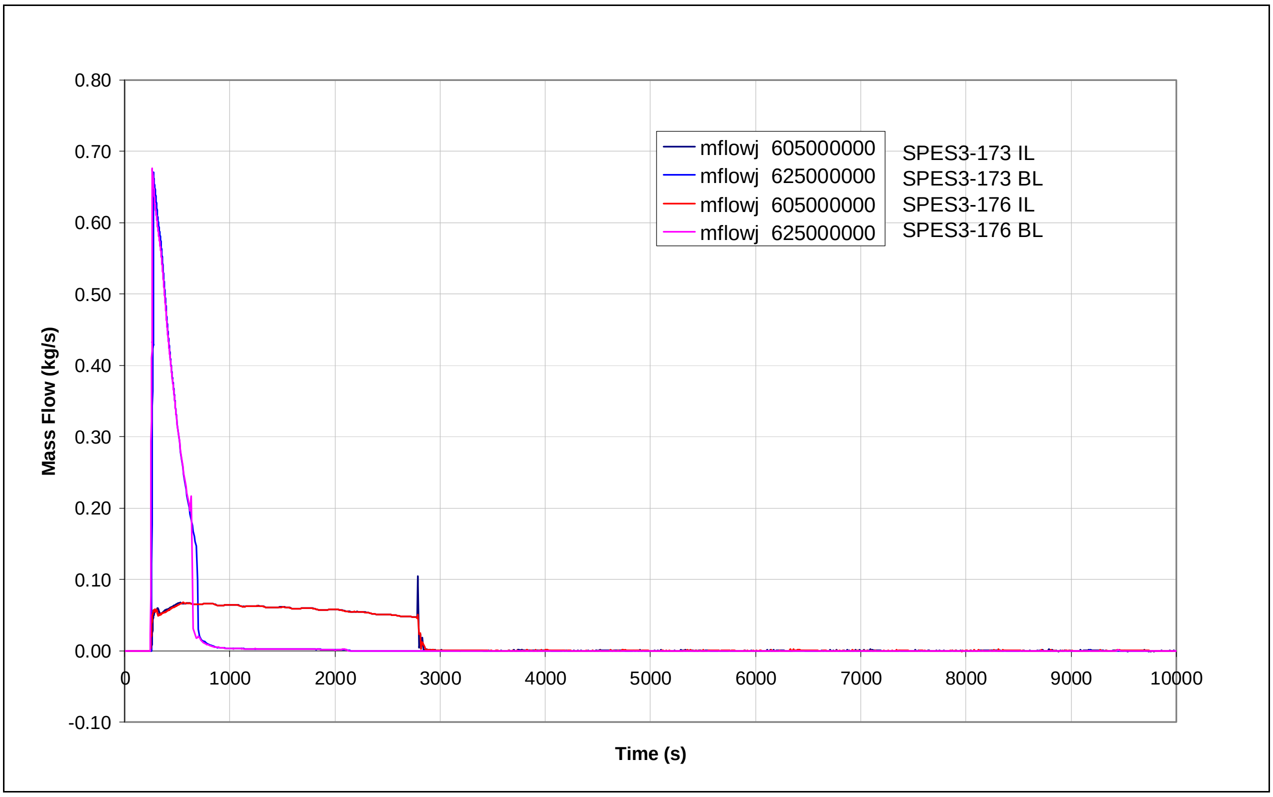


Fig.8. 5 – SPES3-173 and SPES3-176 LGMS injection mass flow (window)

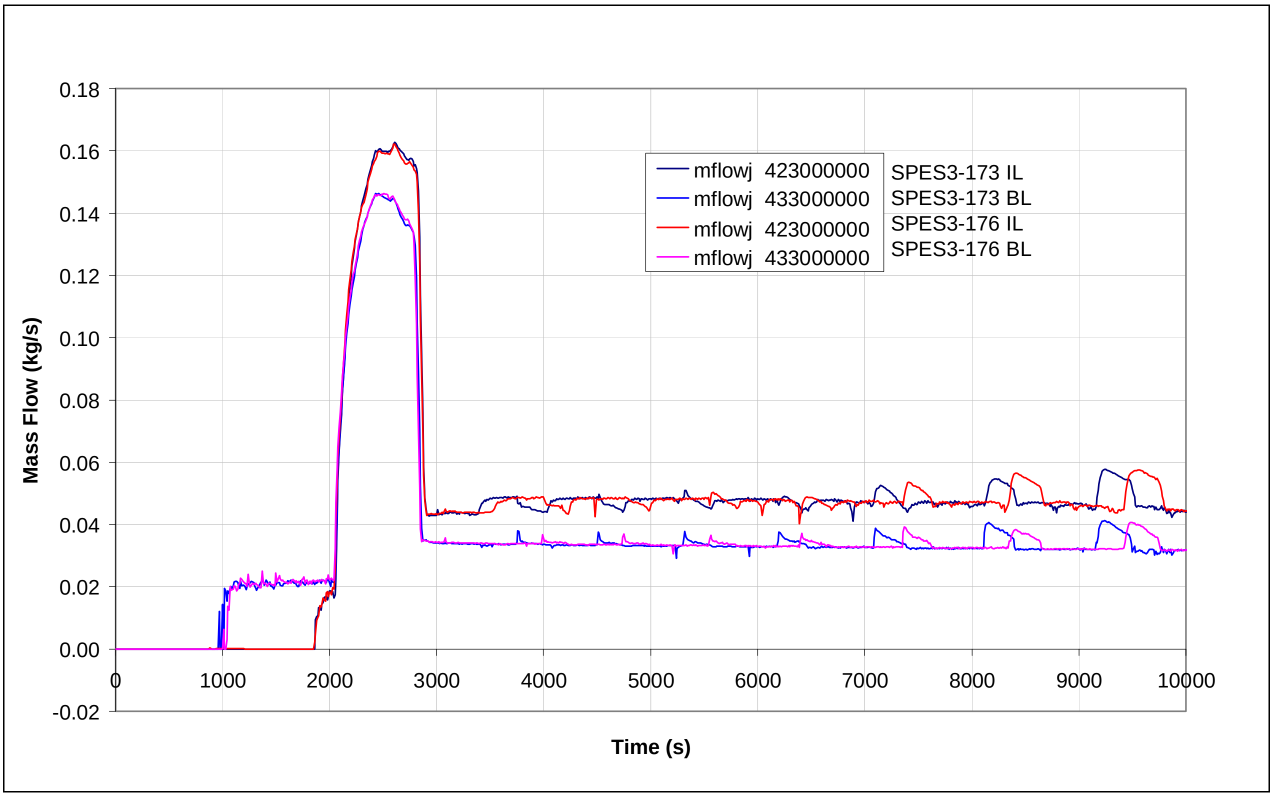


Fig.8. 6 – SPES3-173 and SPES3-176 LGMS injection mass flow

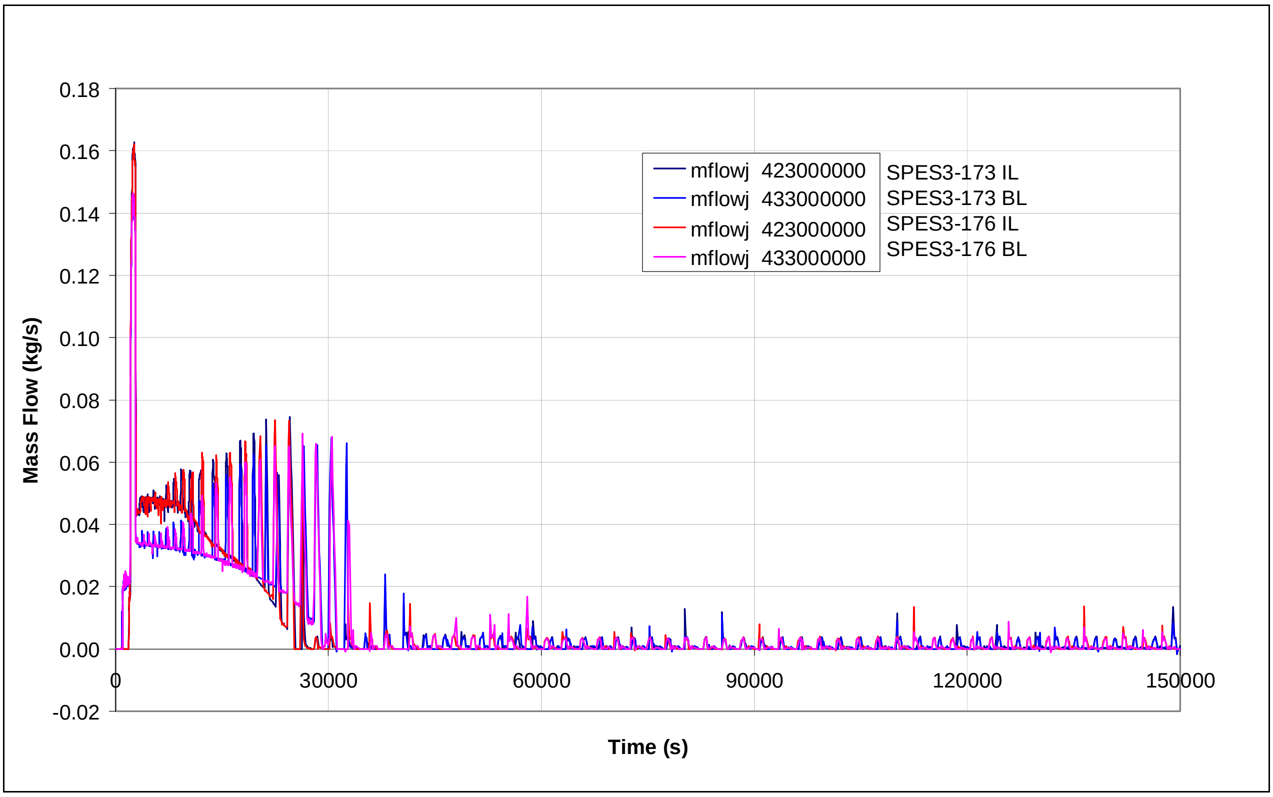


Fig.8. 7 – SPES3-173 and SPES3-176 ADS Stage-I mass flow (window)

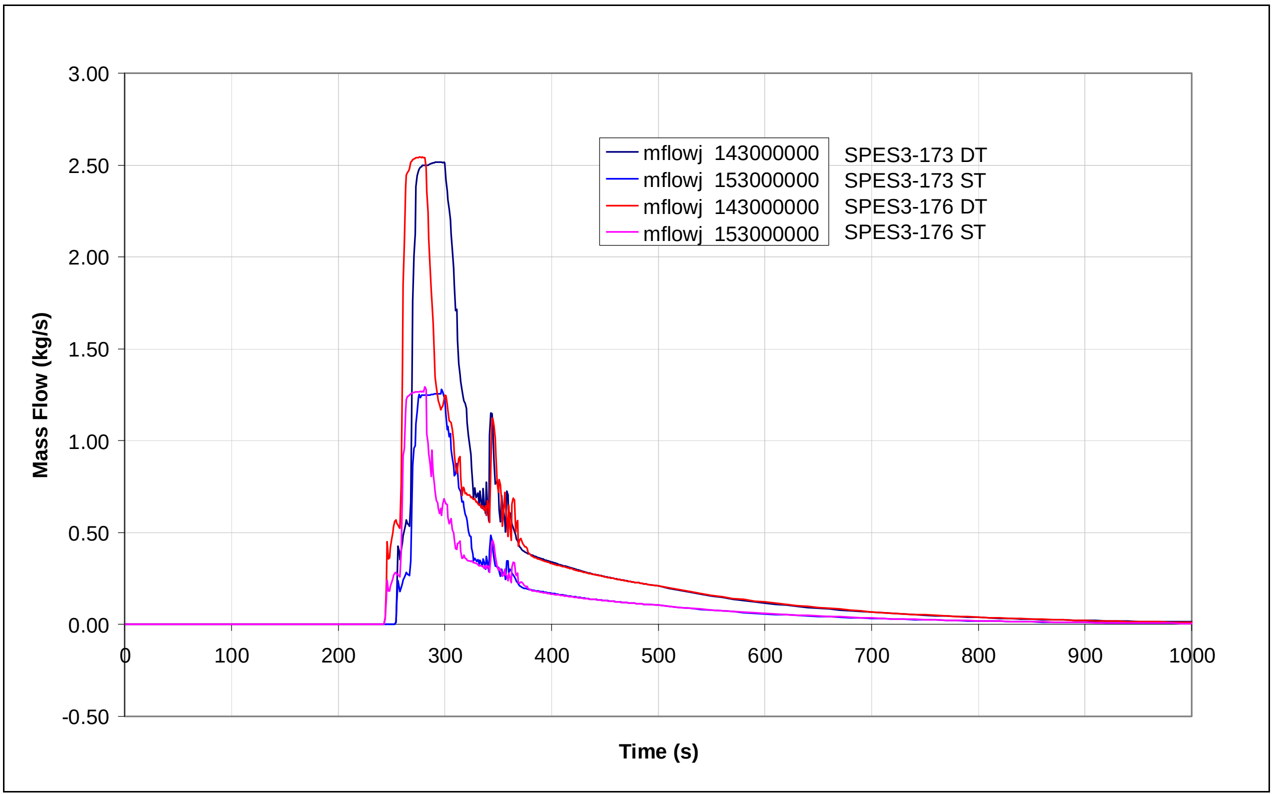


Fig.8. 8 – SPES3-173 and SPES3-176 ADS Stage-I mass flow (window)

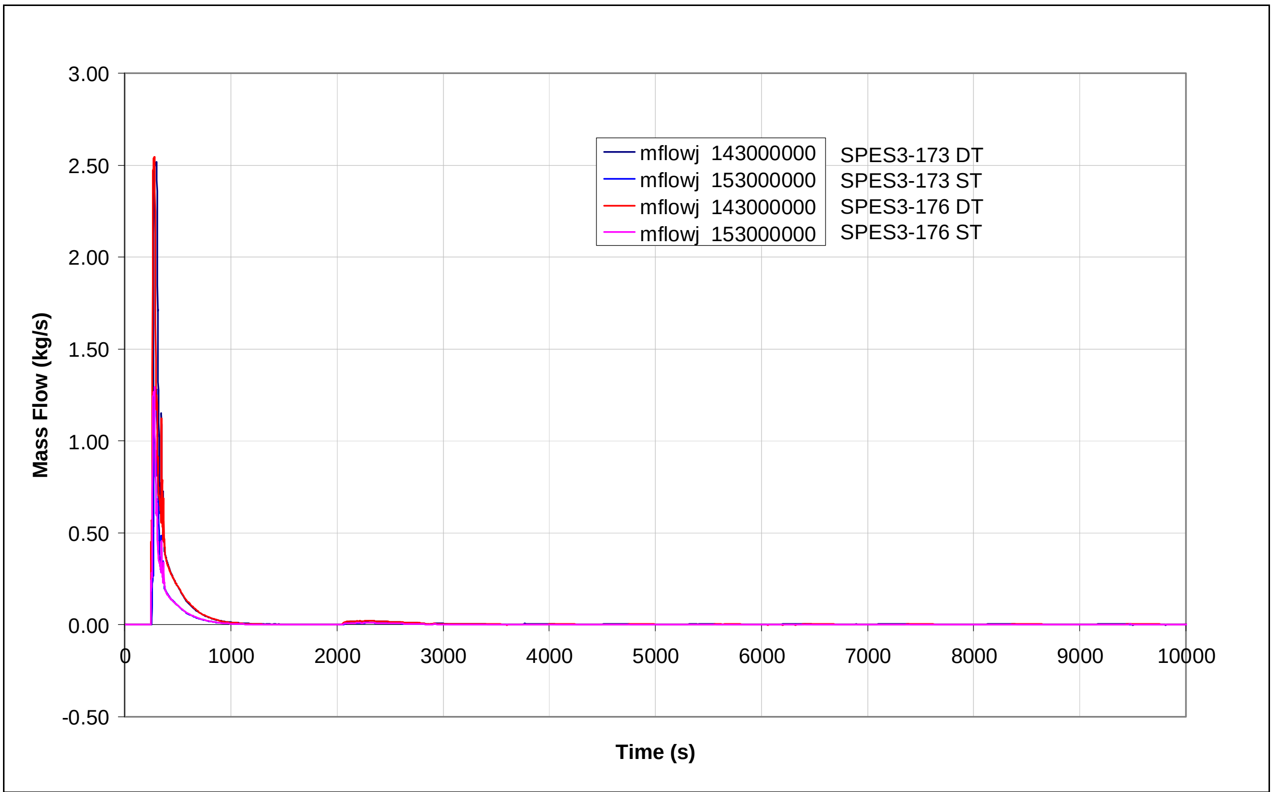


Fig.8. 9 – SPES3-173 and SPES3-176 ADS Stage-II mass flow (window)

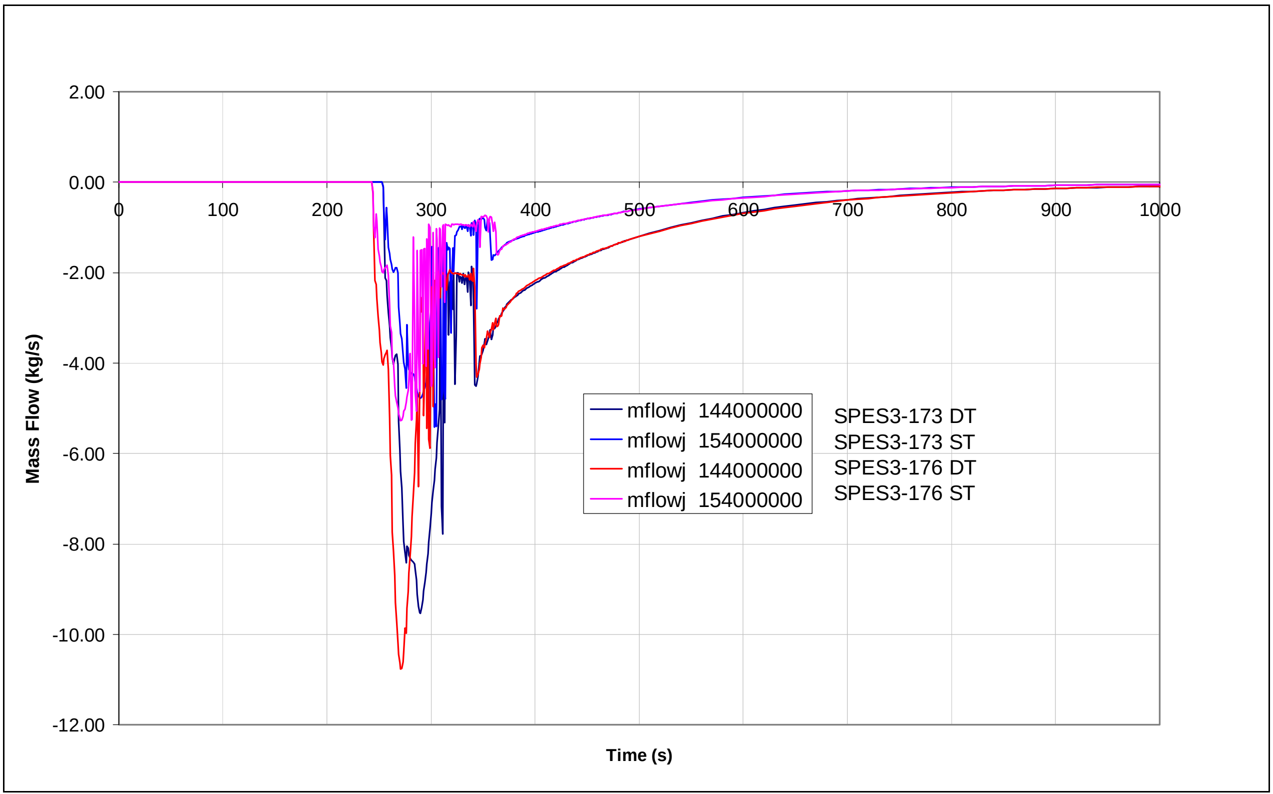


Fig.8. 10 – SPES3-173 and SPES3-176 ADS Stage-II mass flow (window)

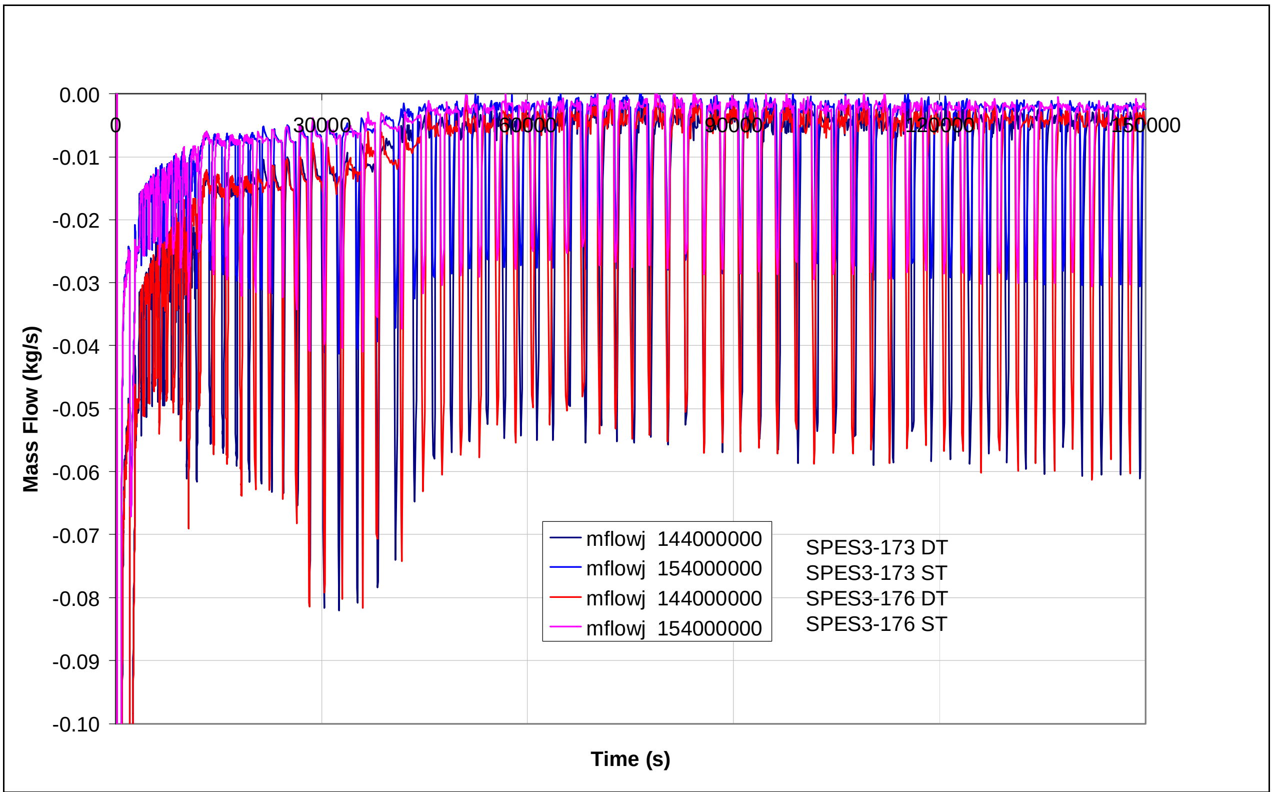


Fig.8. 11 – SPES3-173 and SPES3-176 ADS Stage-II mass flow

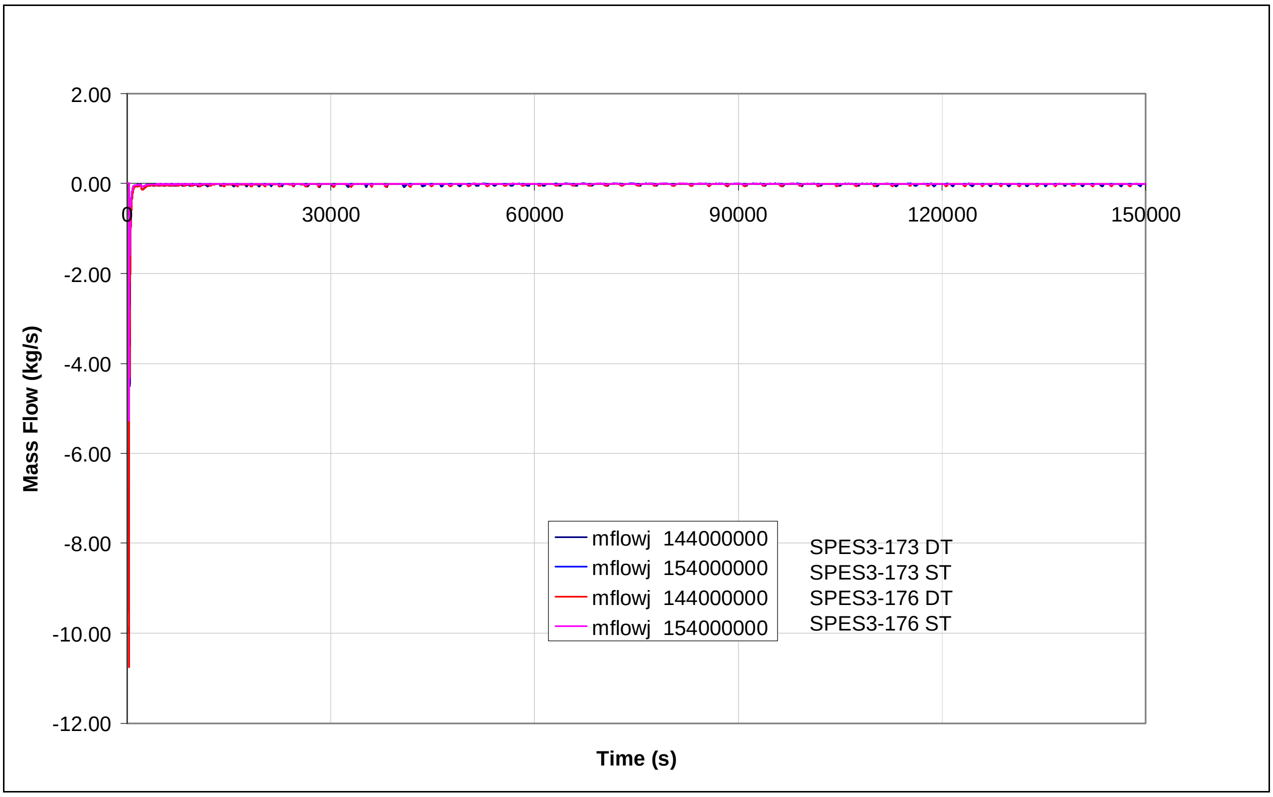


Fig.8. 12 – SPES3-173 and SPES3-176 PRZ and DW pressures (window)

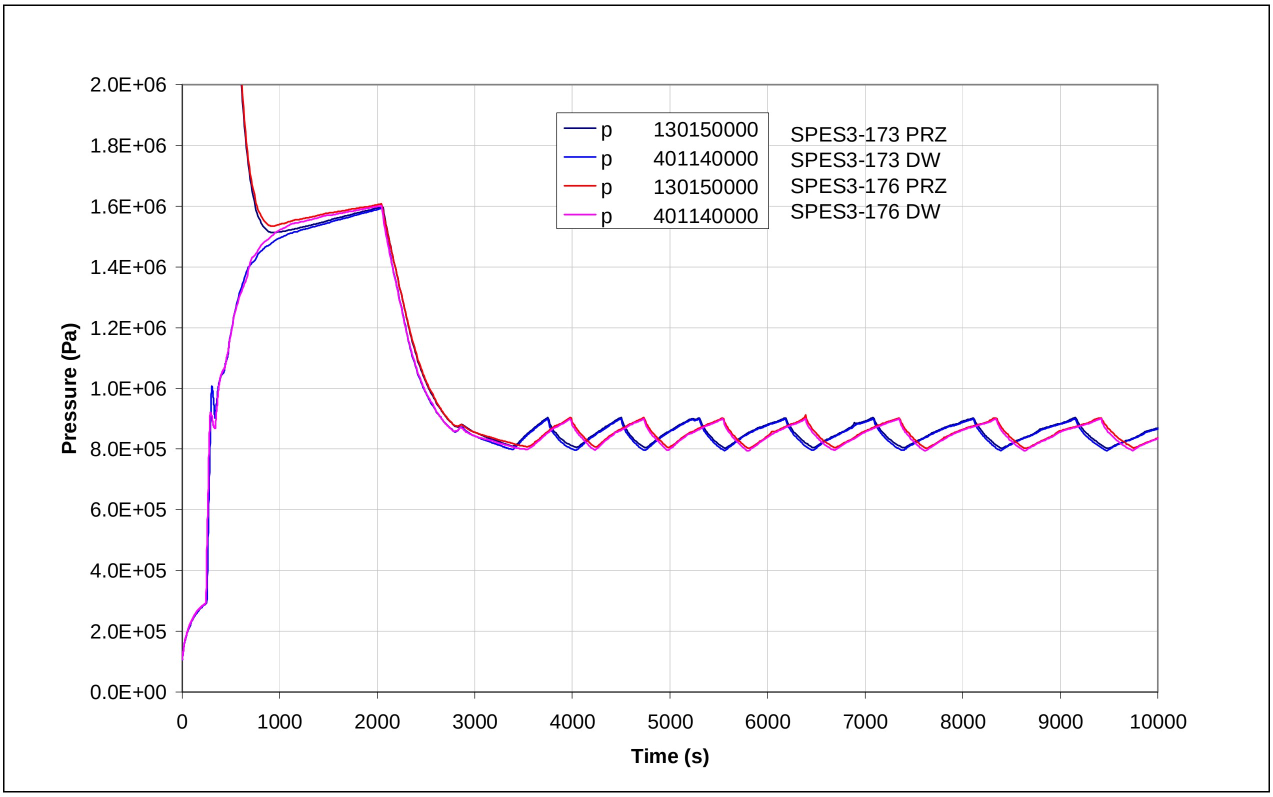


Fig.8. 13 – SPES3-173 and SPES3-176 PRZ and DW pressures (window)

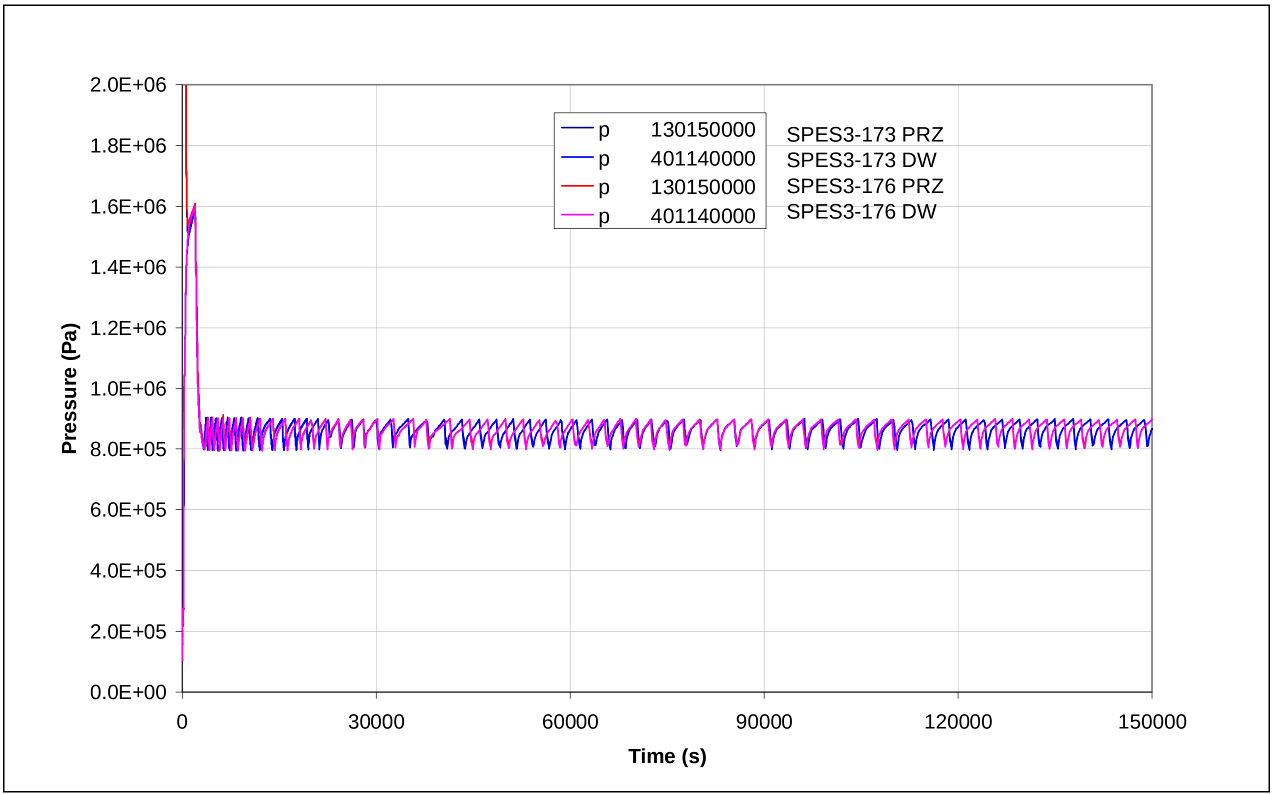


Fig.8. 14 – SPES3-173 and SPES3-176 PRZ and DW pressures

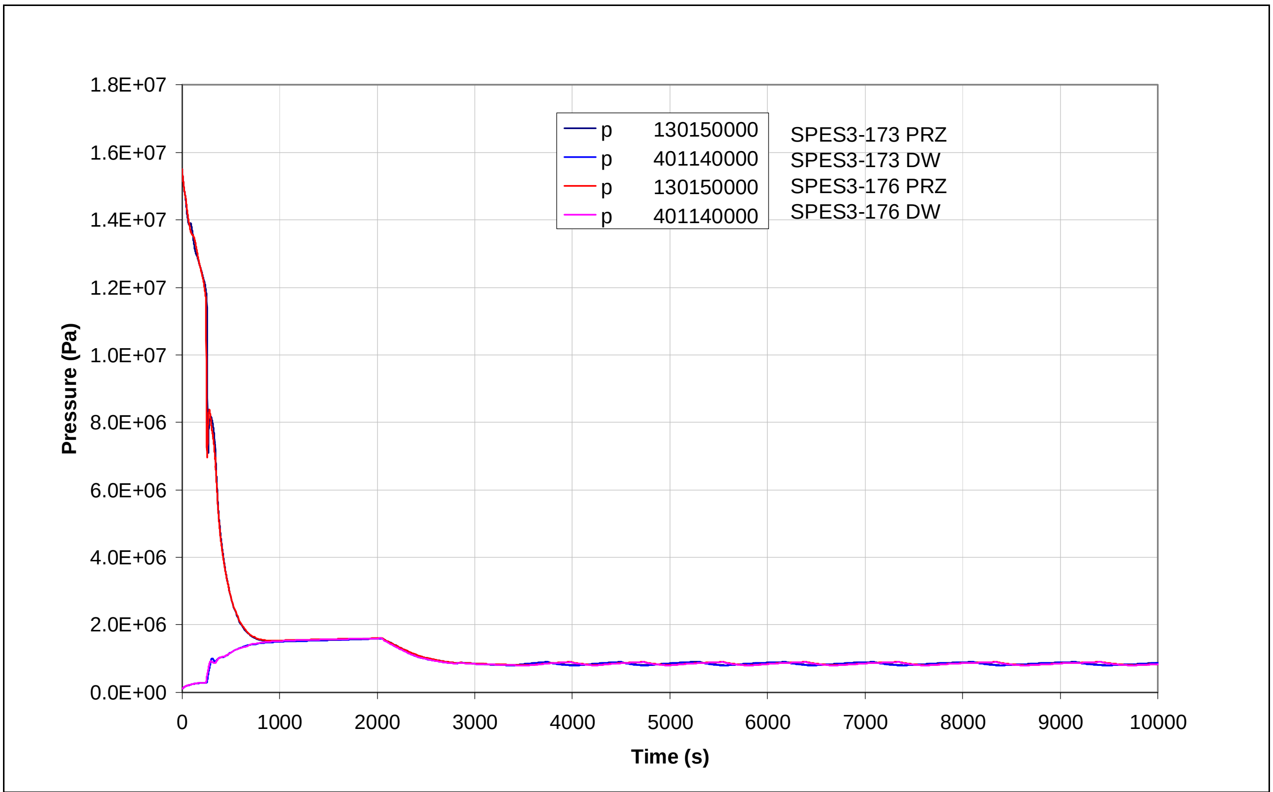


Fig.8. 15 – SPES3-173 and SPES3-176 PRZ pressure (window)

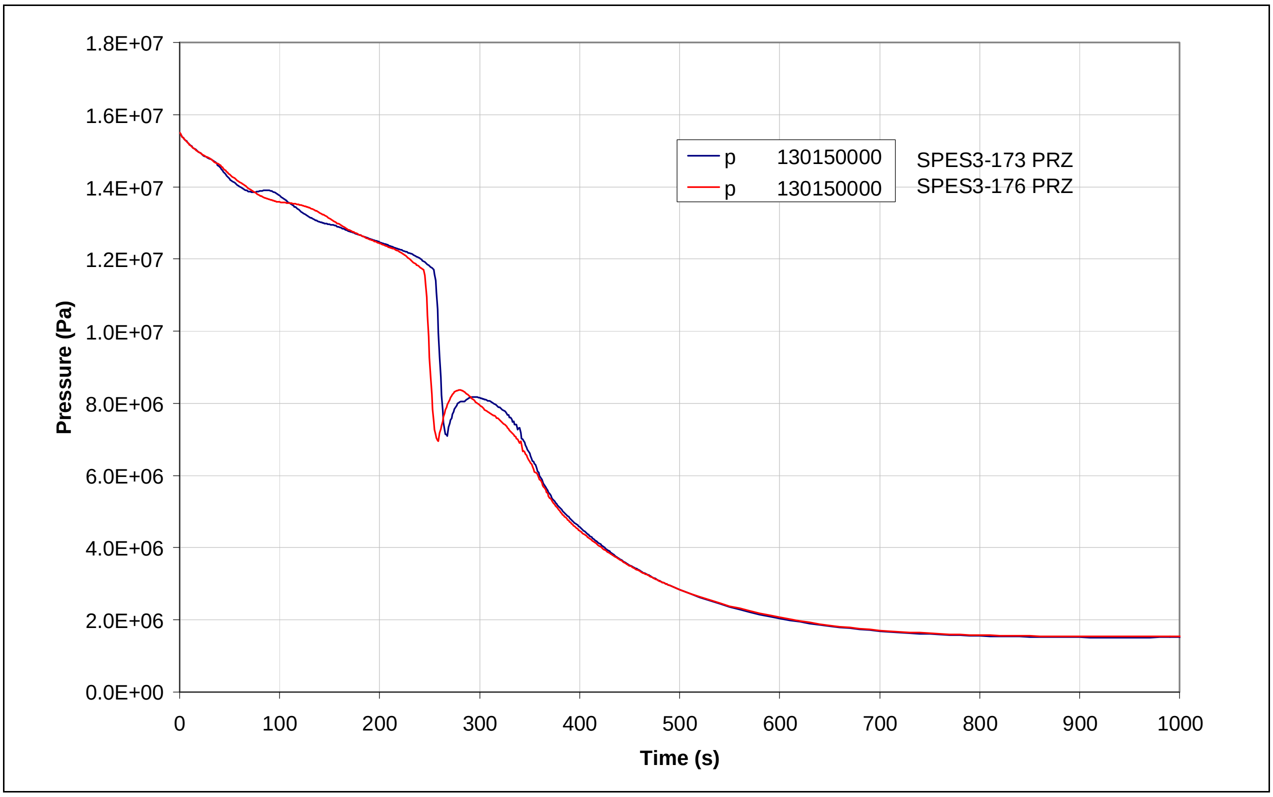


Fig.8. 16 – SPES3-173 and SPES3-176 PRZ pressure (window)

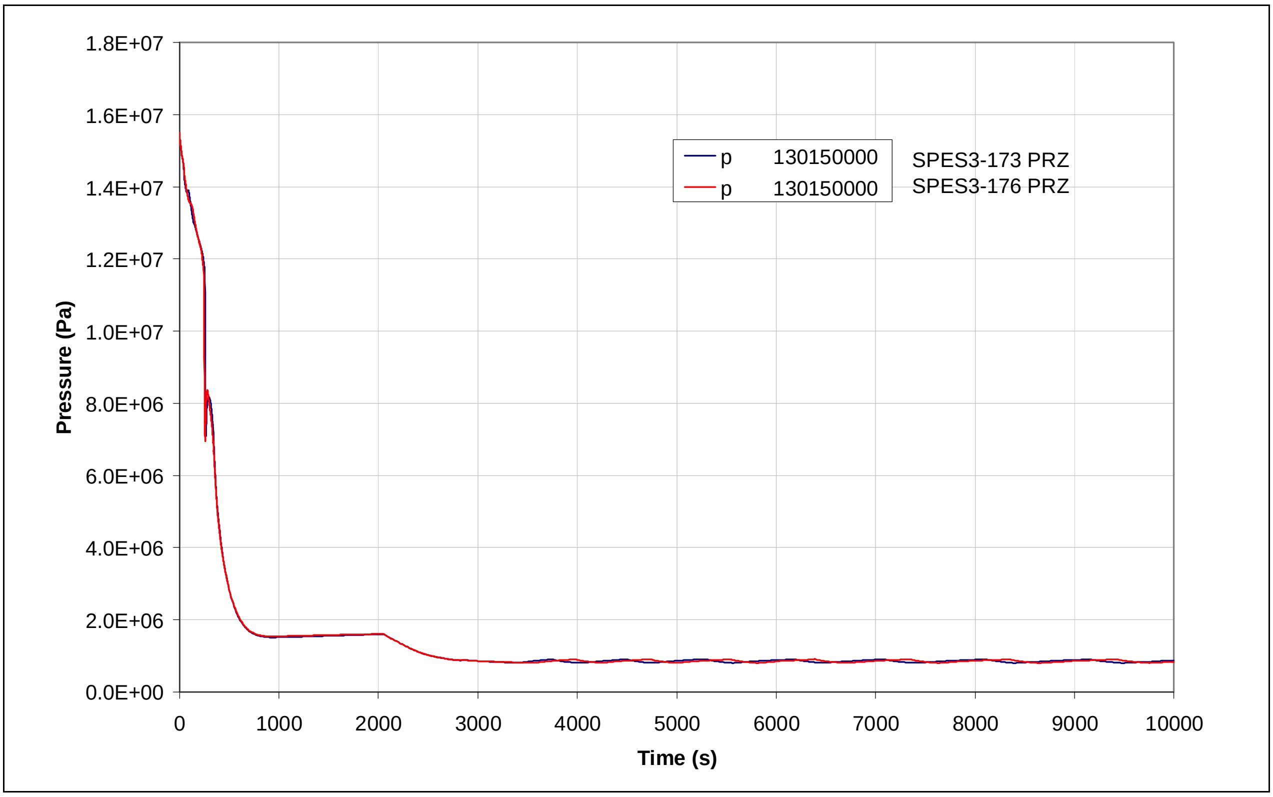


Fig.8. 17 – SPES3-173 and SPES3-176 PRZ pressure

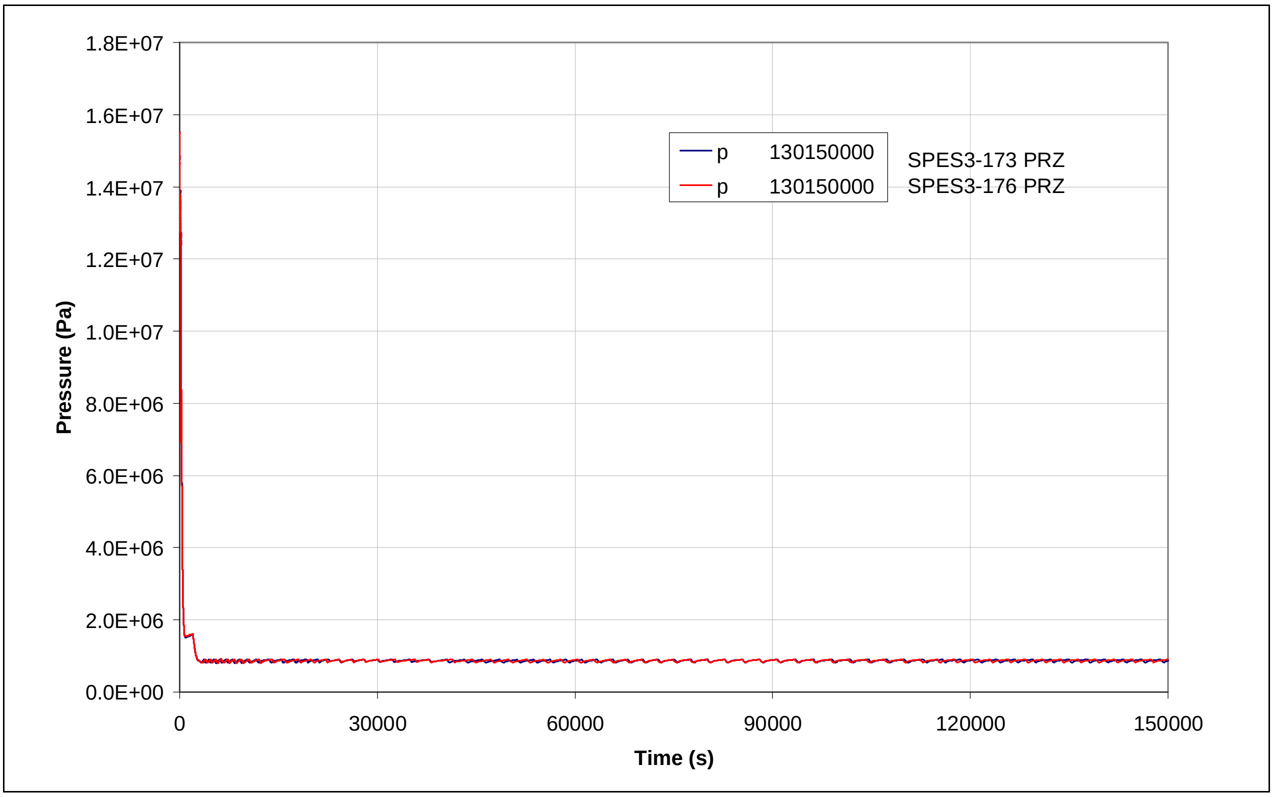


Fig.8. 18 – SPES3-173 and SPES3-176 DW pressure (window)

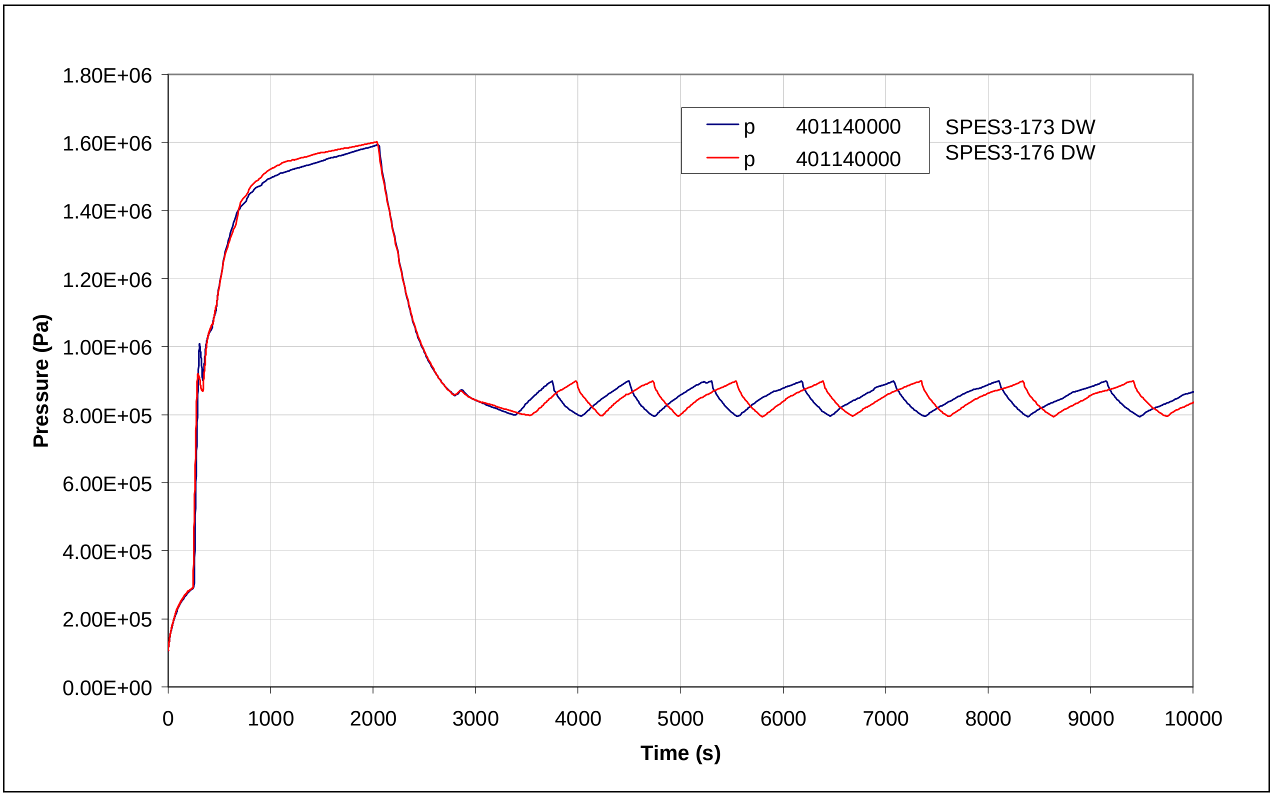


Fig.8. 19 – SPES3-173 and SPES3-176 DW pressure

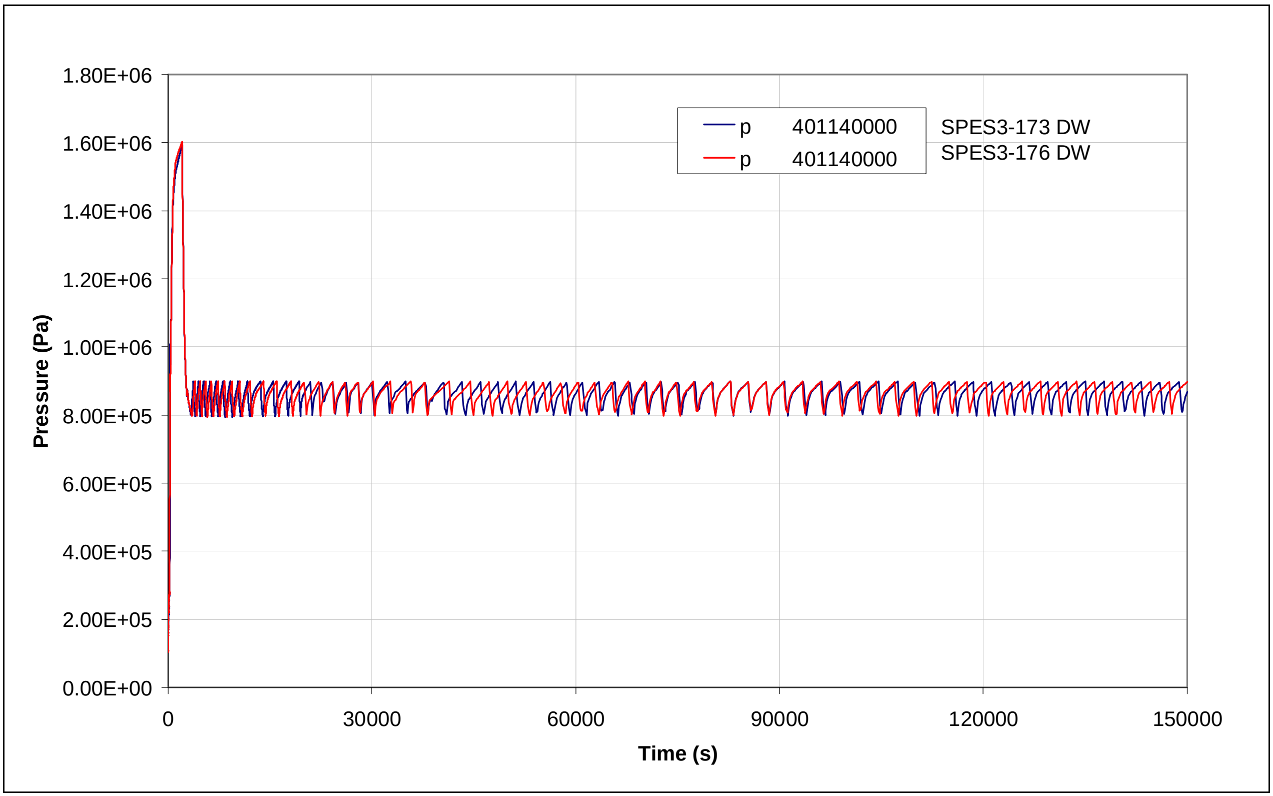


Fig.8. 20 – SPES3-173 and SPES3-176 PCC power (window)

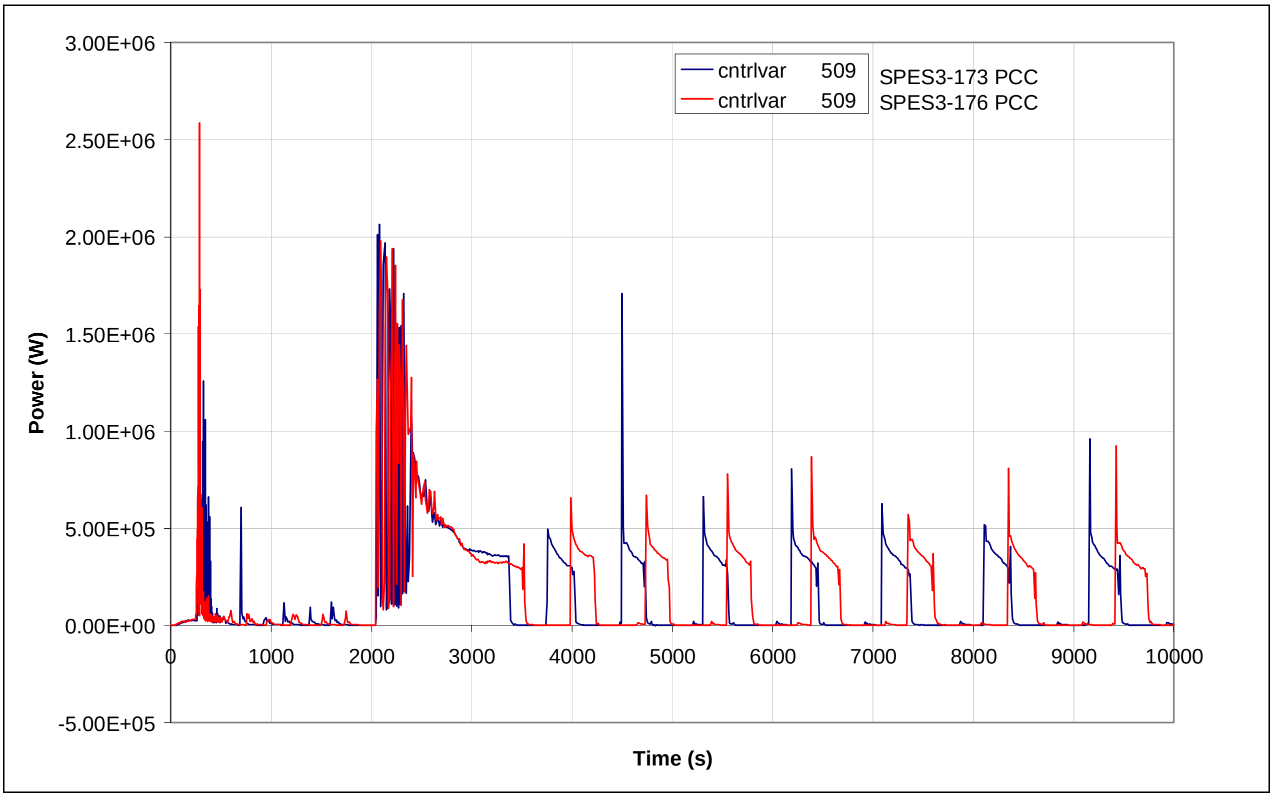


Fig.8. 21 – SPES3-173 and SPES3-176 PCC power

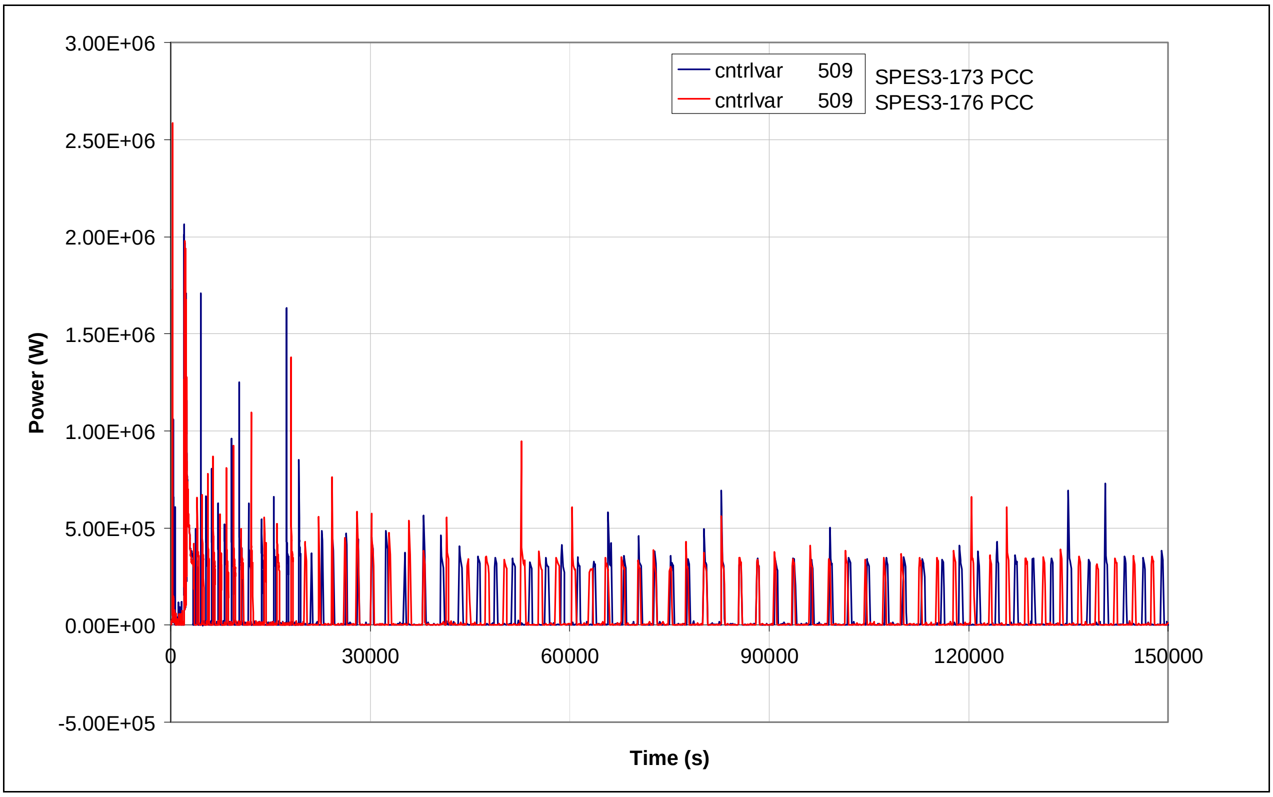


Fig.8. 22 – SPES3-173 and SPES3-176 PSS to DW mass flow (window)

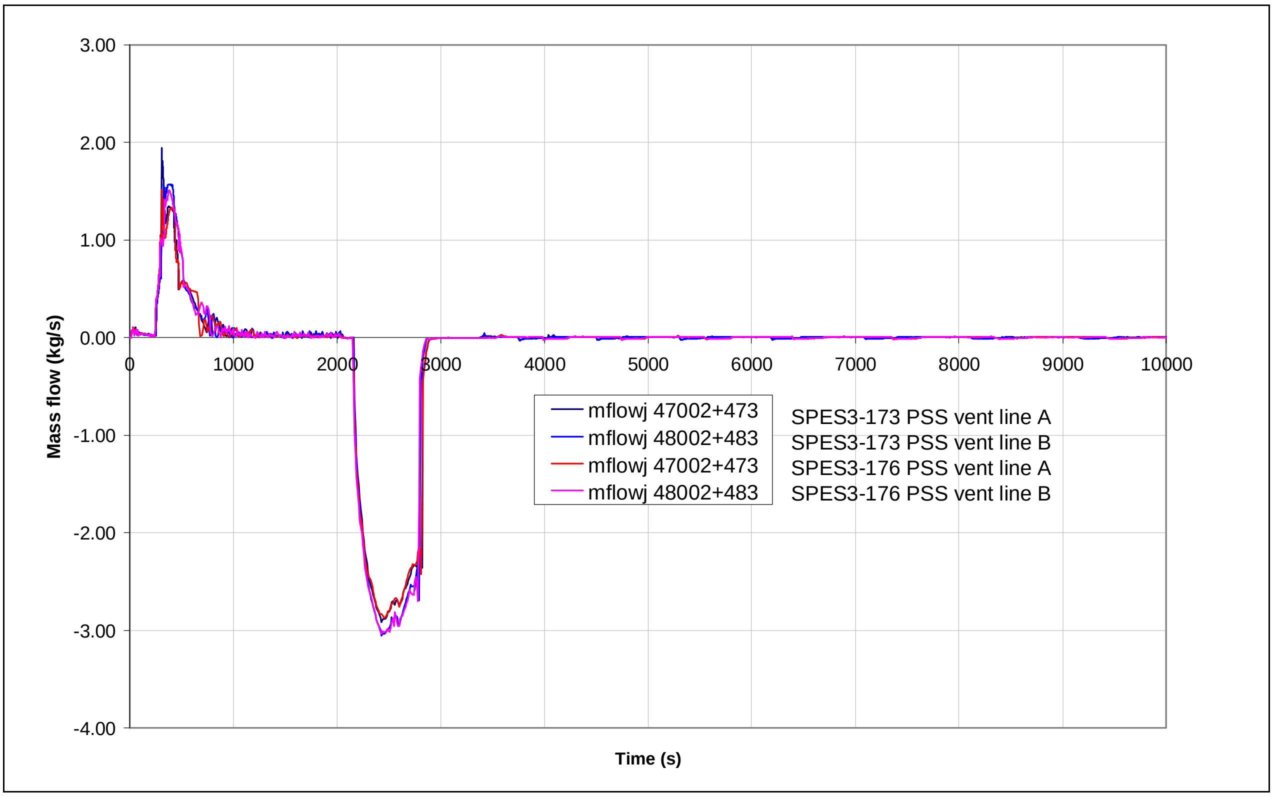


Fig.8. 23 – SPES3-173 and SPES3-176 PSS to DW mass flow

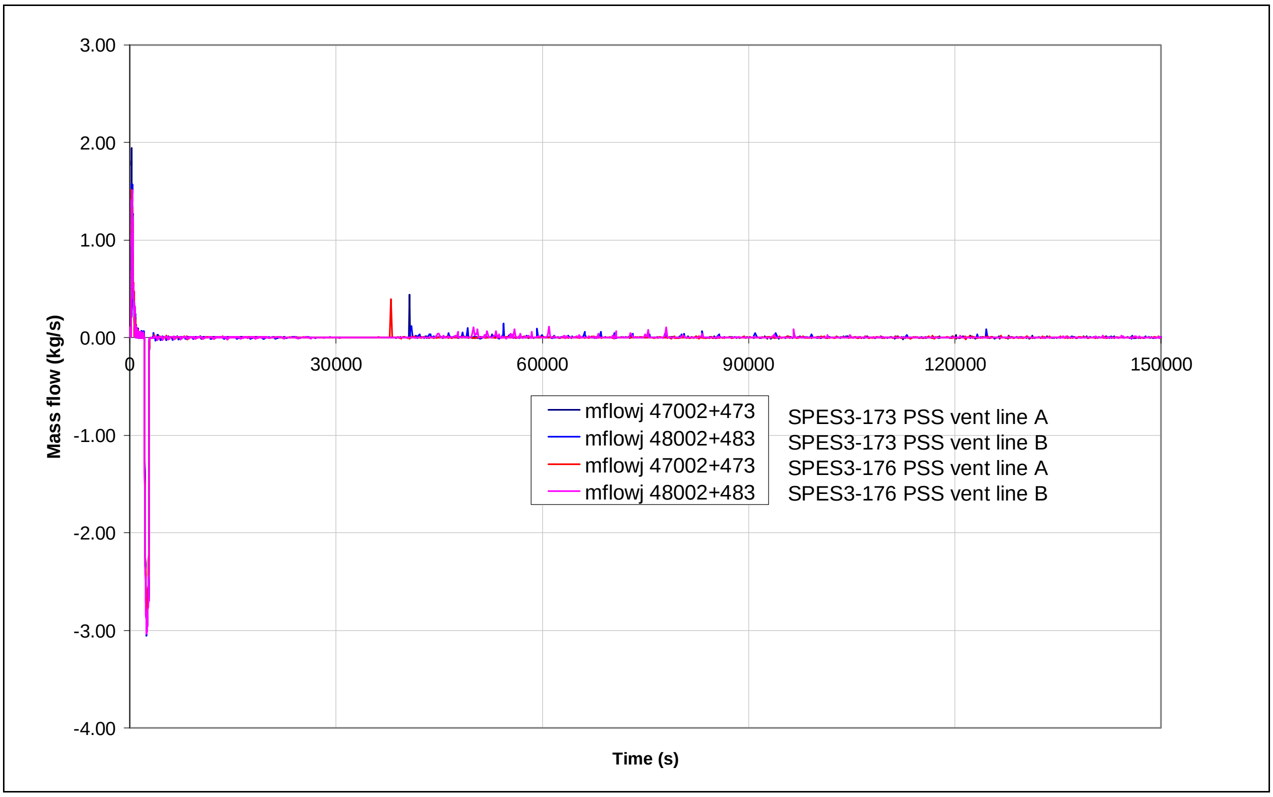


Fig.8. 24 – SPES3-173 and SPES3-176 DW non-condensable quality (window)

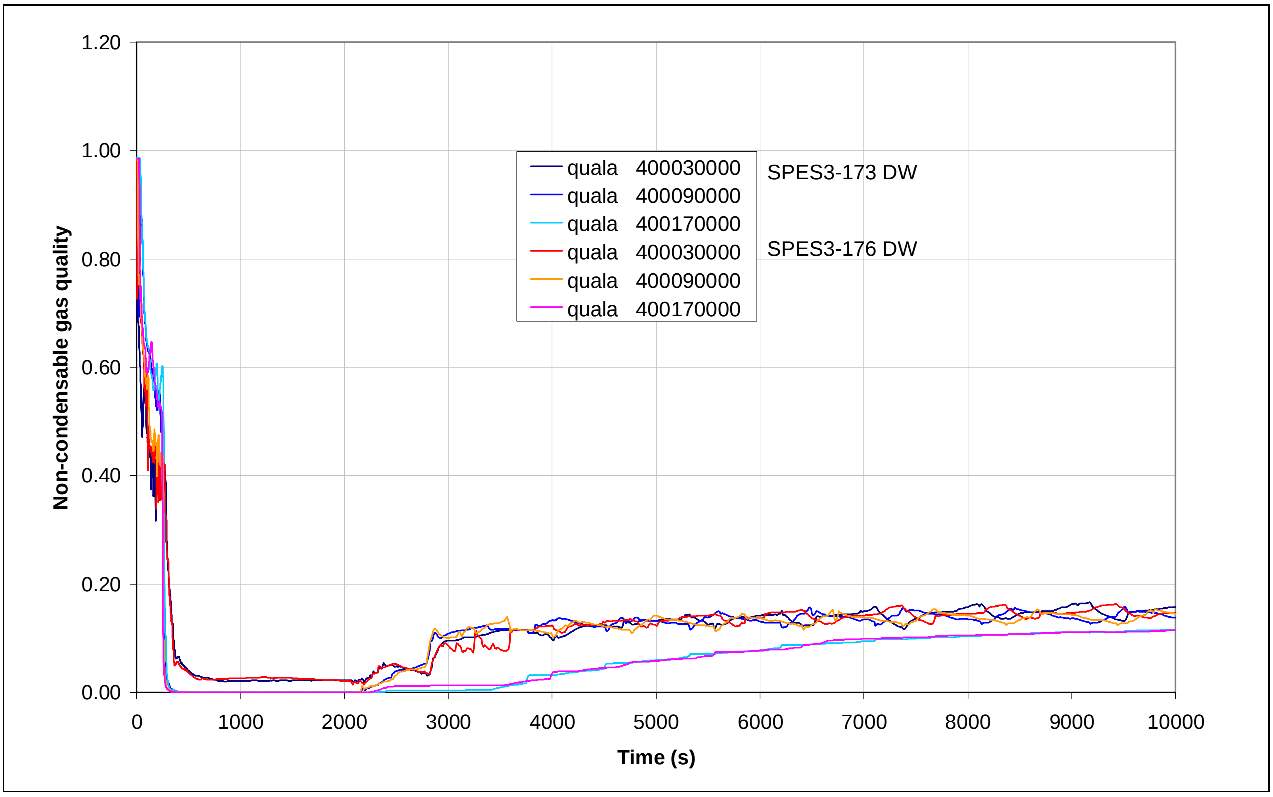


Fig.8. 25 – SPES3-173 and SPES3-176 DW non-condensable quality

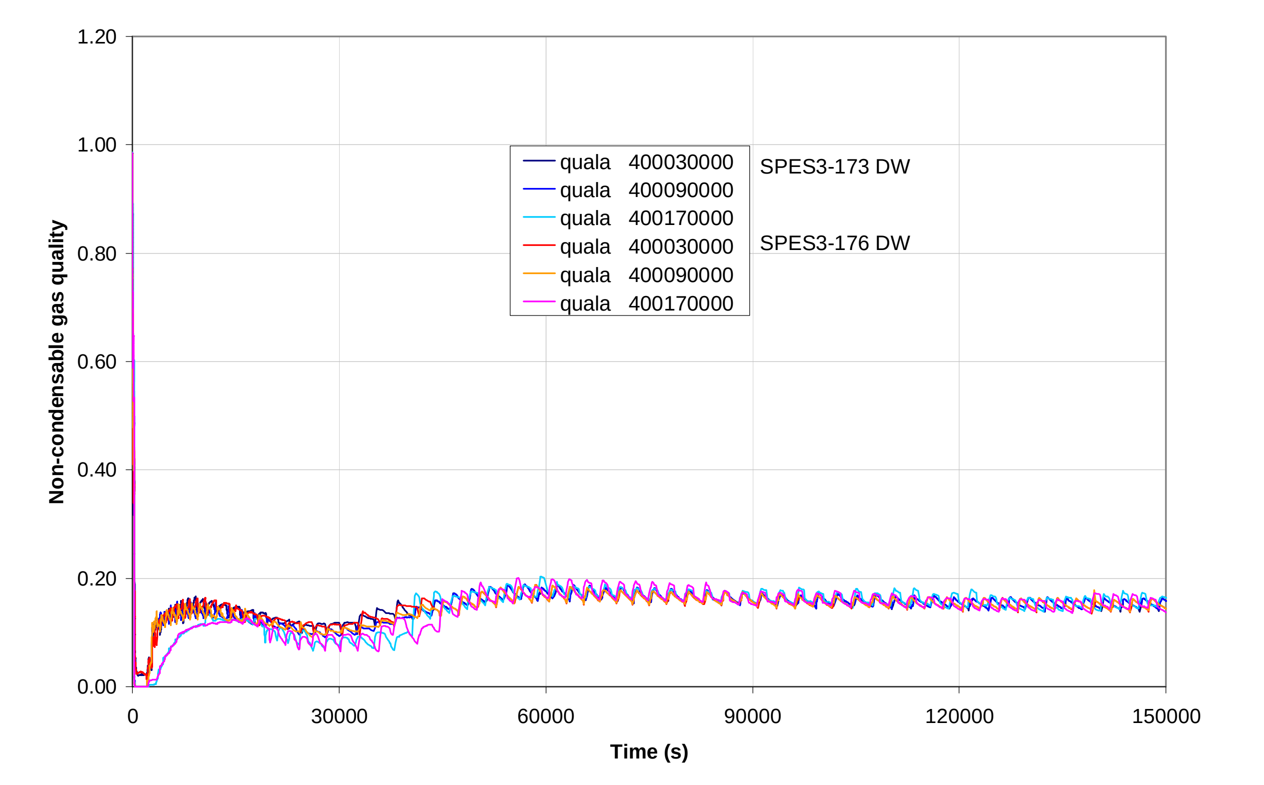


Fig.8. 26 – SPES3-173 and SPES3-176 PSS pressure (window)

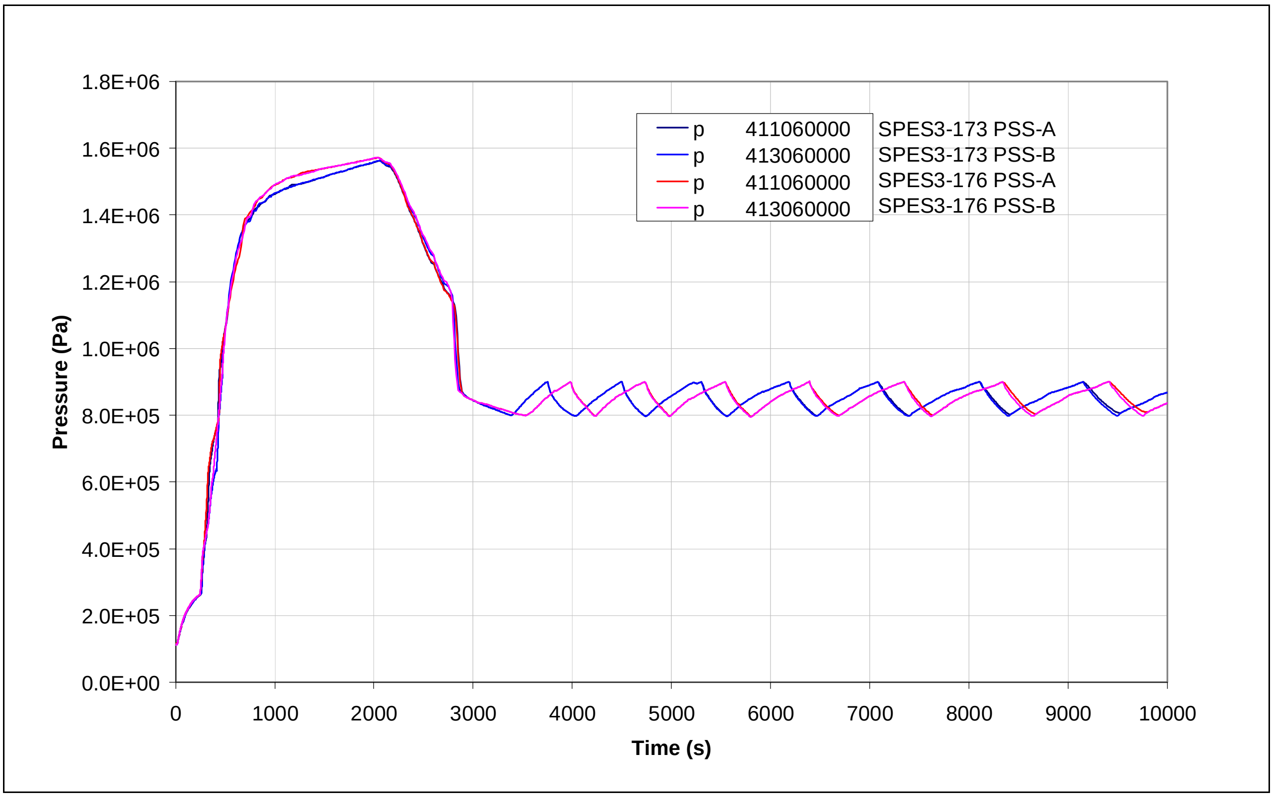


Fig.8. 27 – SPES3-173 and SPES3-176 PSS pressure

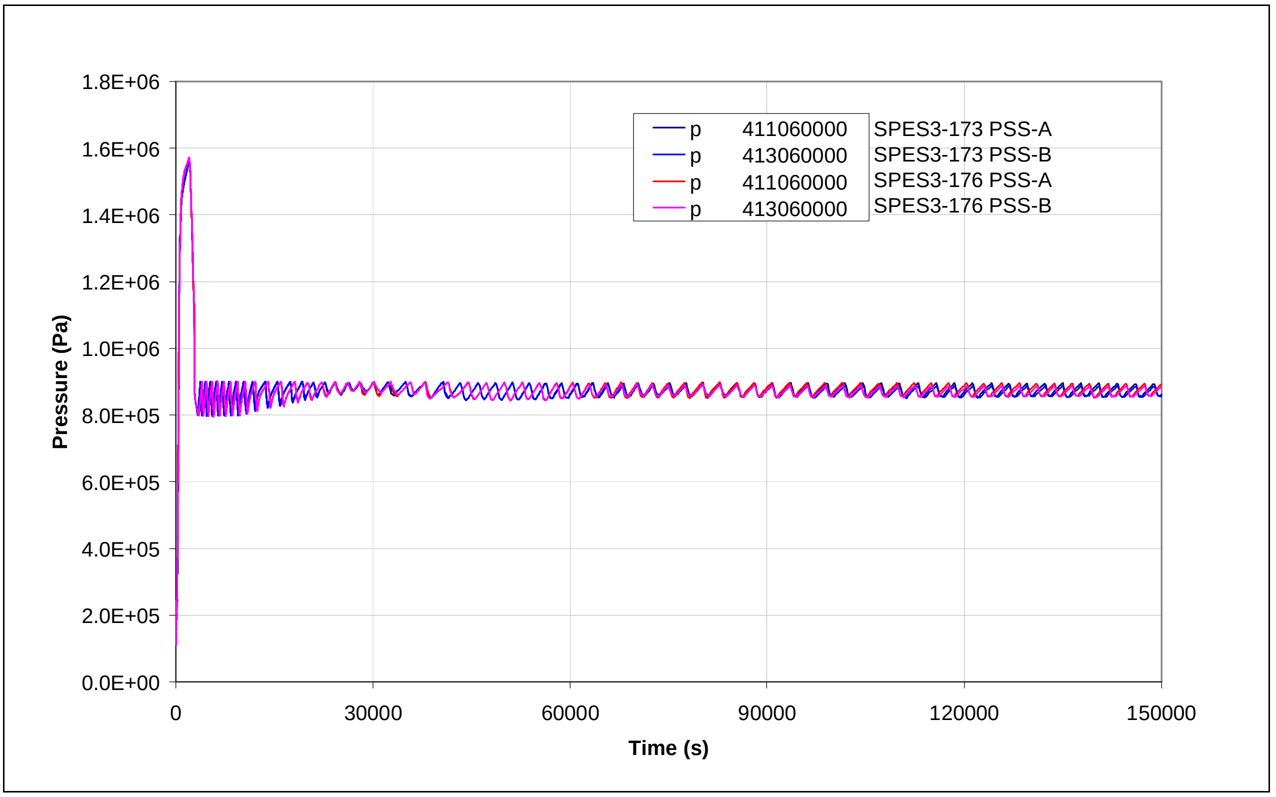


Fig.8. 28 – SPES3-173 and SPES3-176 LGMS pressure (window)

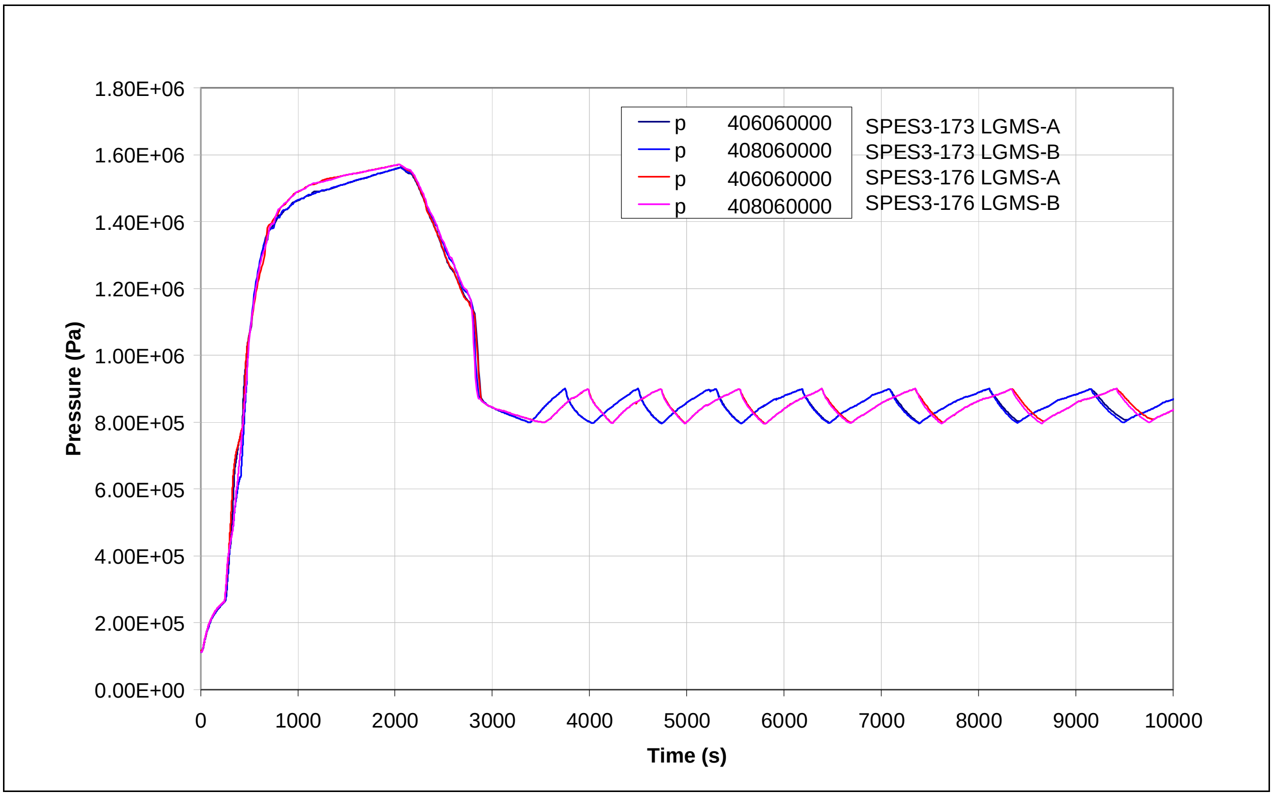


Fig.8. 29 – SPES3-173 and SPES3-176 LGMS pressure

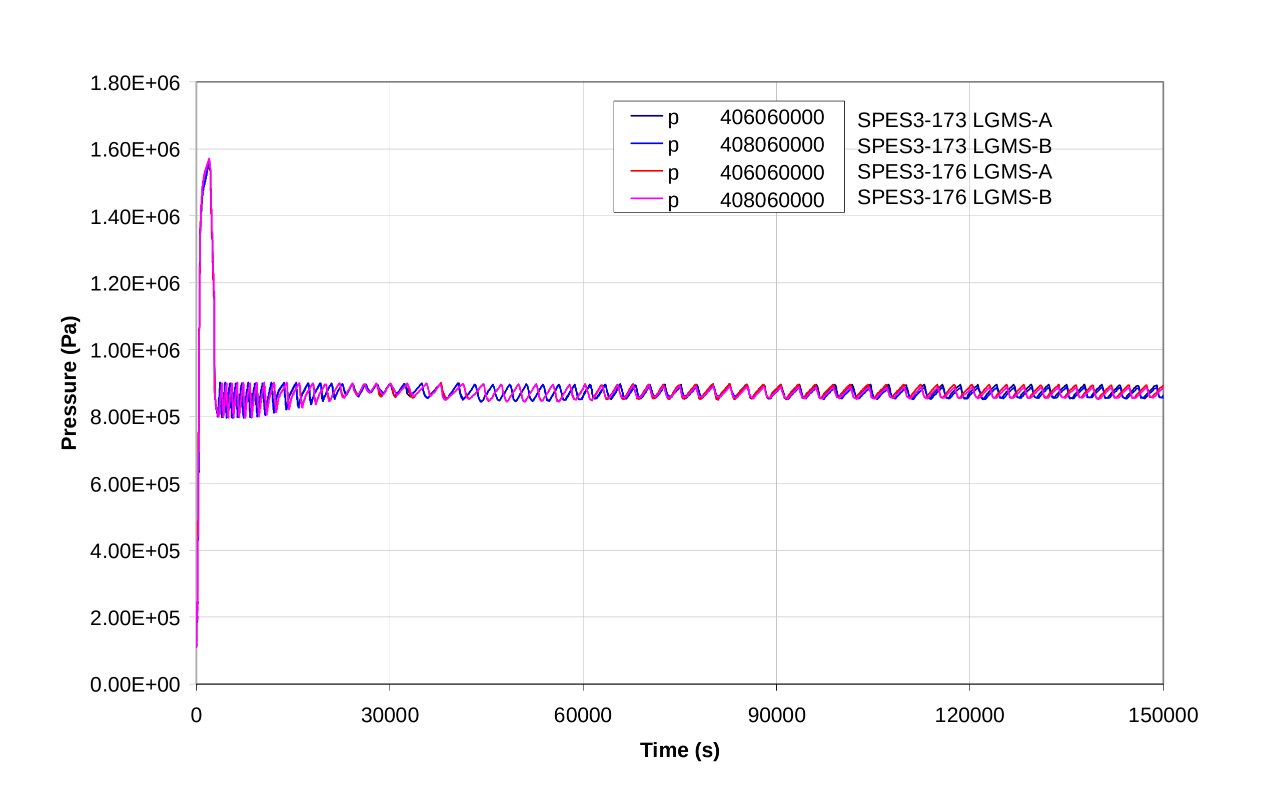


Fig.8. 30 – SPES3-173 and SPES3-176 PSS and DW pressure (window)

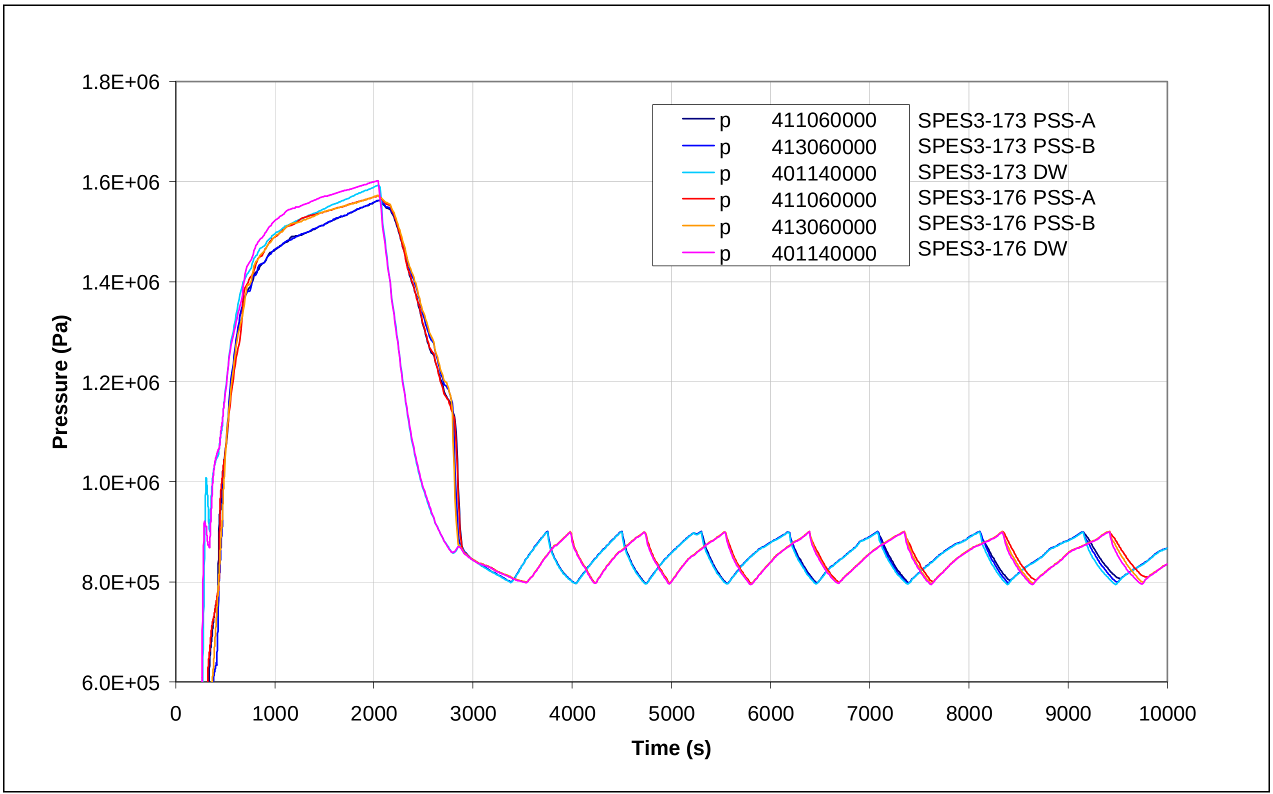


Fig.8. 31 – SPES3-173 and SPES3-176 PSS and DW pressure

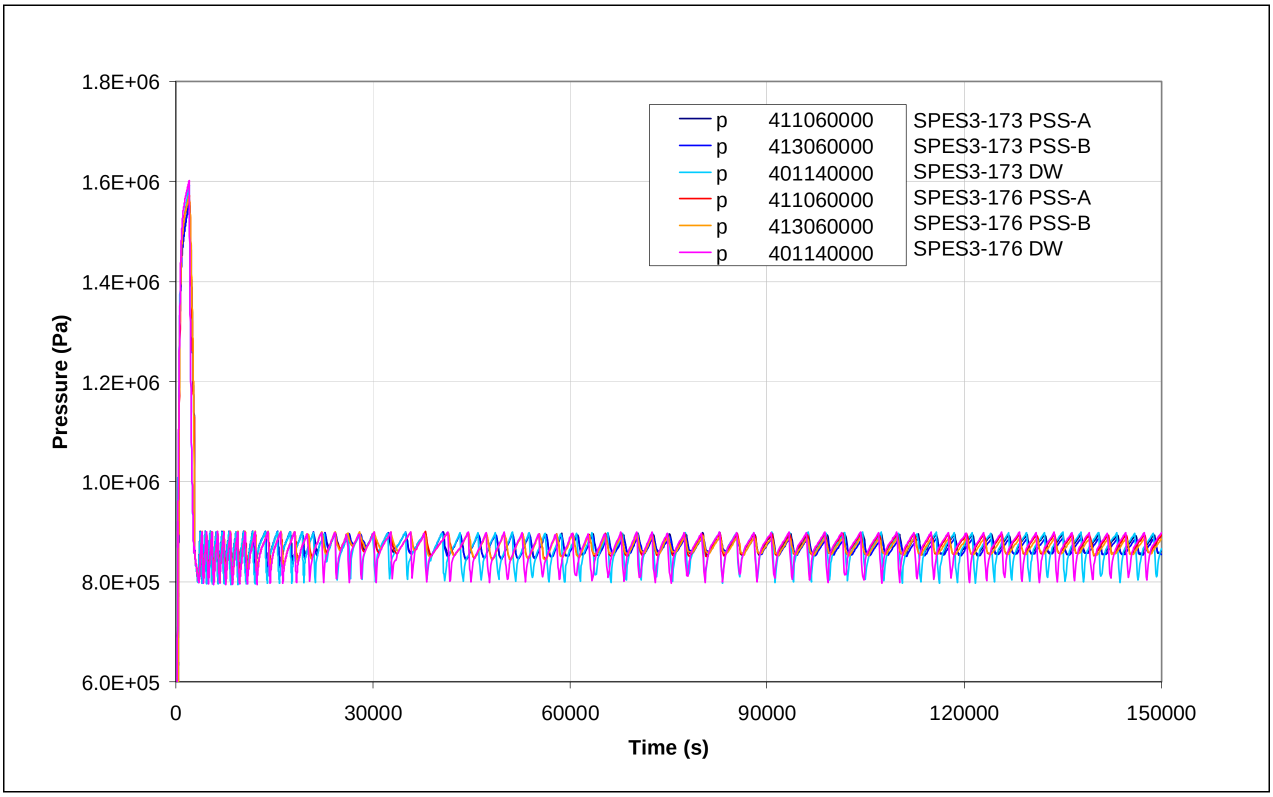


Fig.8. 32 – SPES3-173 and SPES3-176 PSS vent pipe level (window)

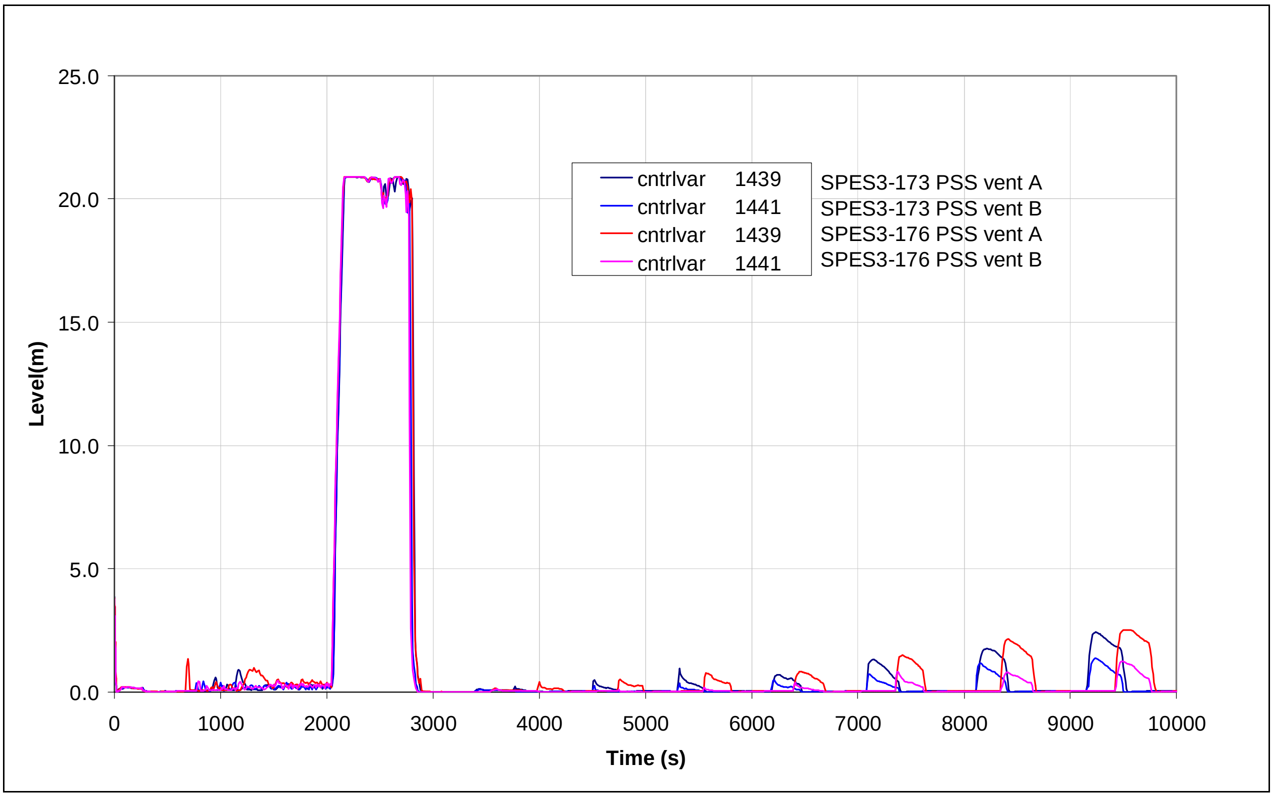


Fig.8. 33 – SPES3-173 and SPES3-176 PSS vent pipe level

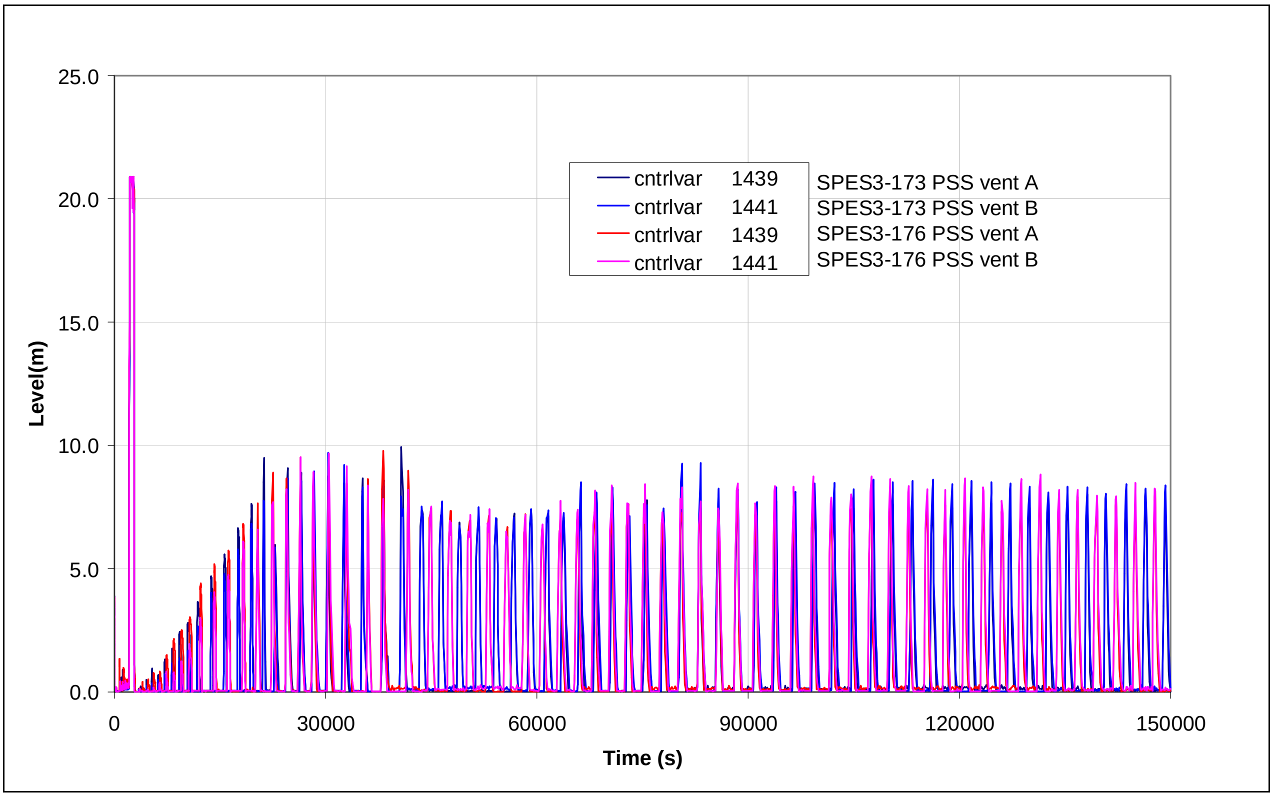


Fig.8. 34 – SPES3-173 and SPES3-176 PSS level (window)

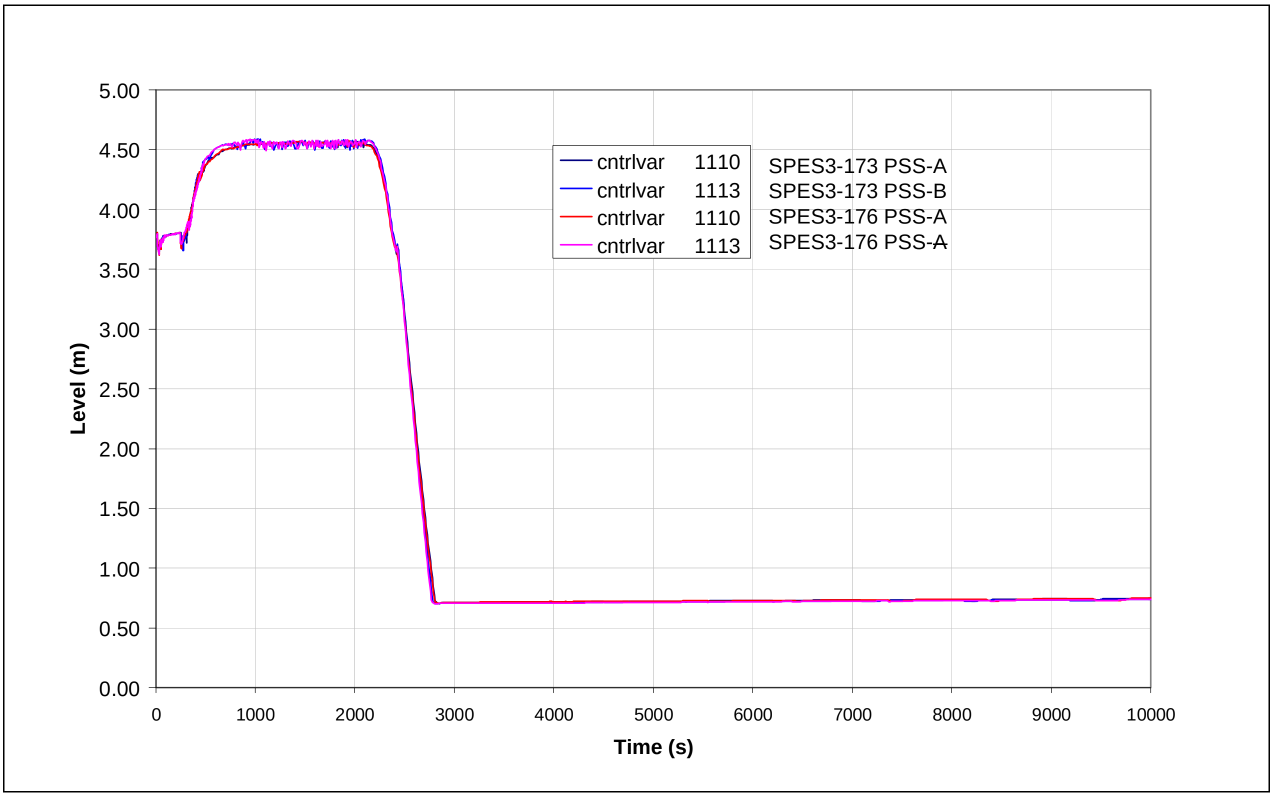


Fig.8. 35 – SPES3-173 and SPES3-176 PSS level

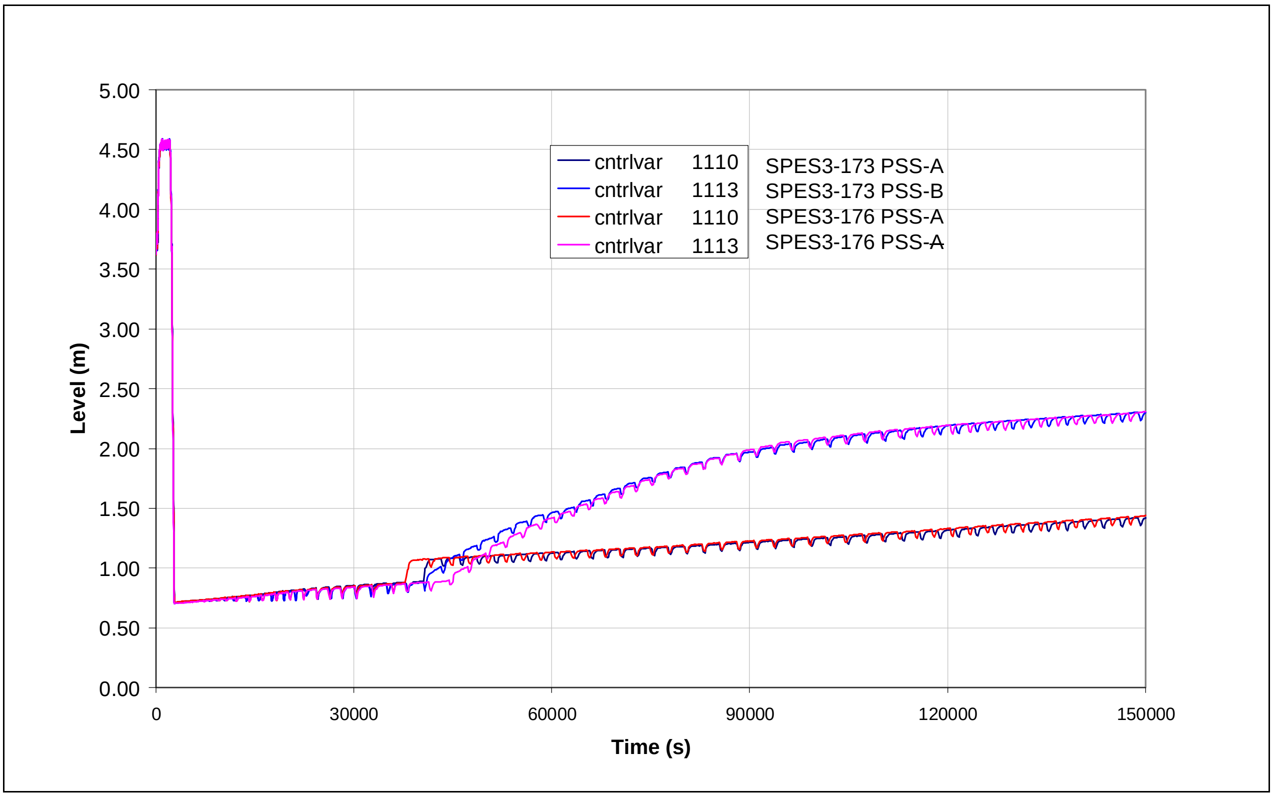


Fig.8. 36 – SPES3-173 and SPES3-176 PSS mass

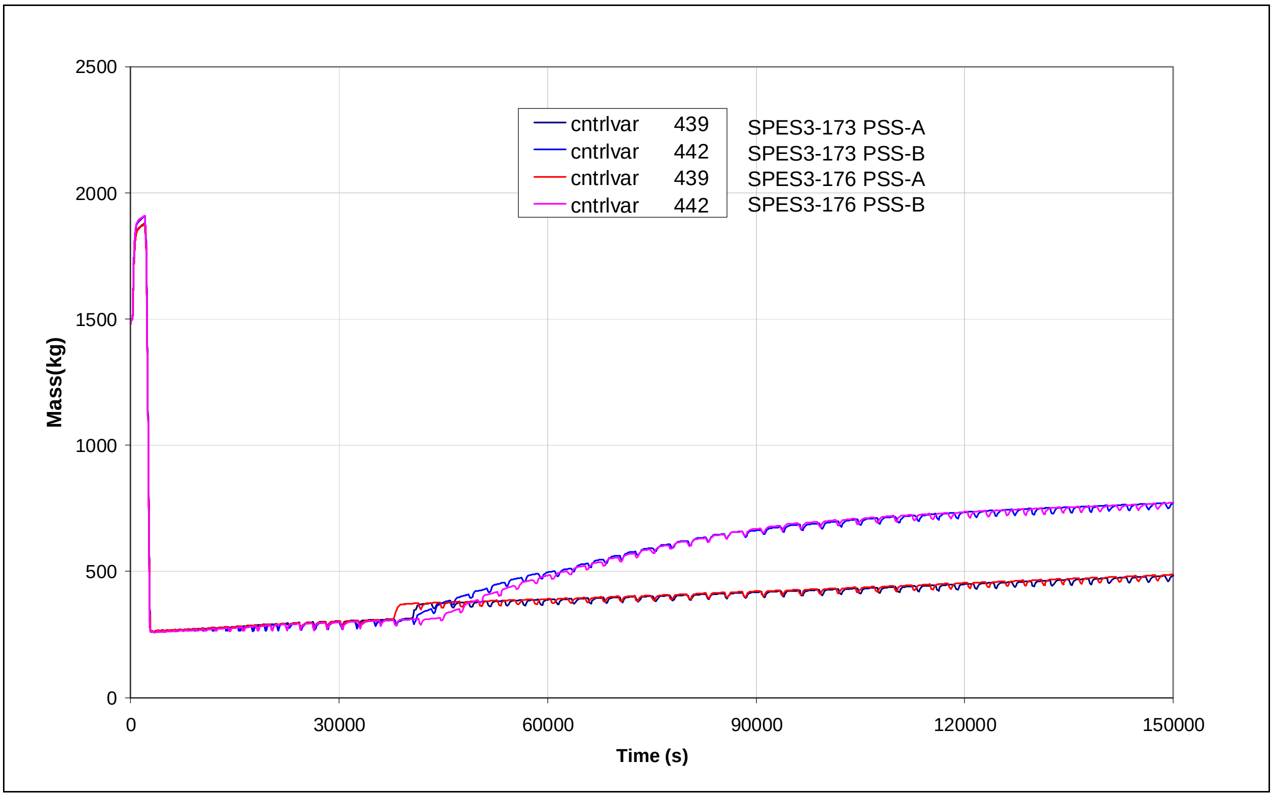


Fig.8. 37 – SPES3-173 and SPES3-176 RC level (window)

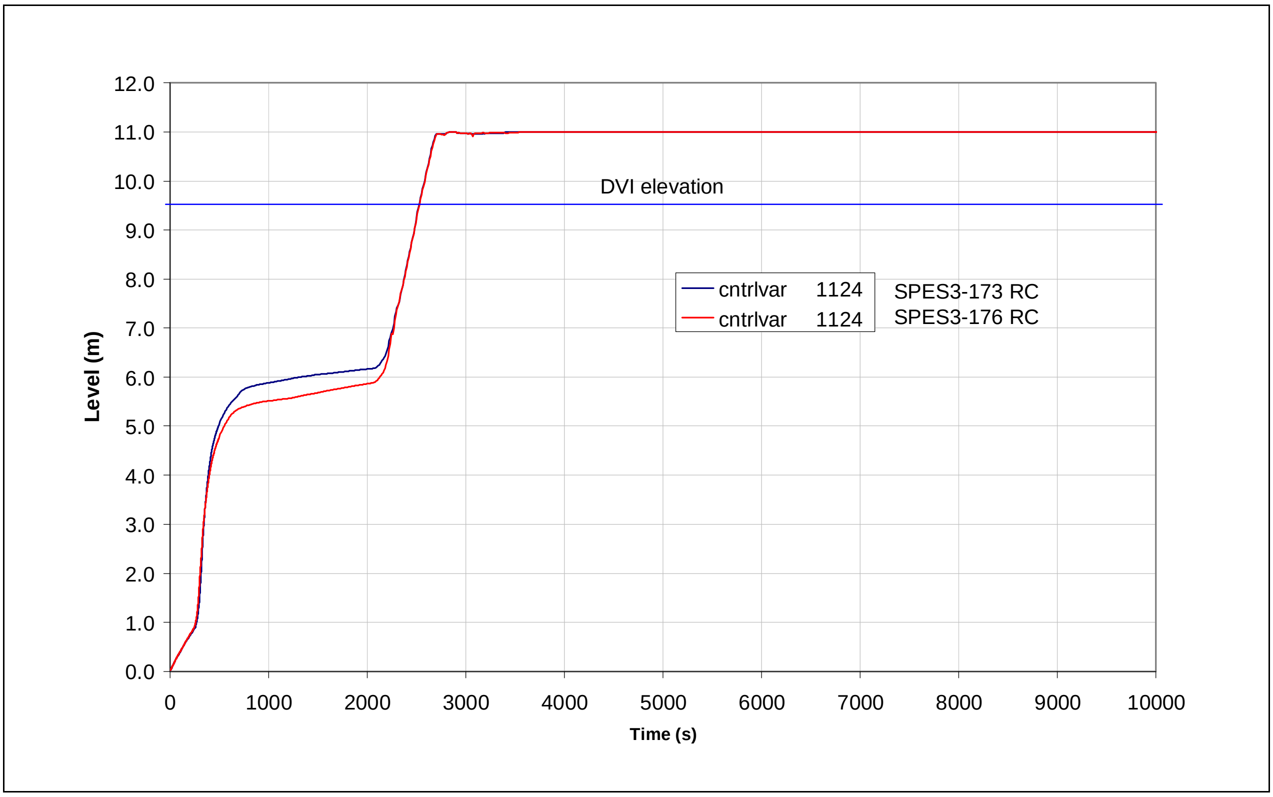


Fig.8. 38 – SPES3-173 and SPES3-176 RC level

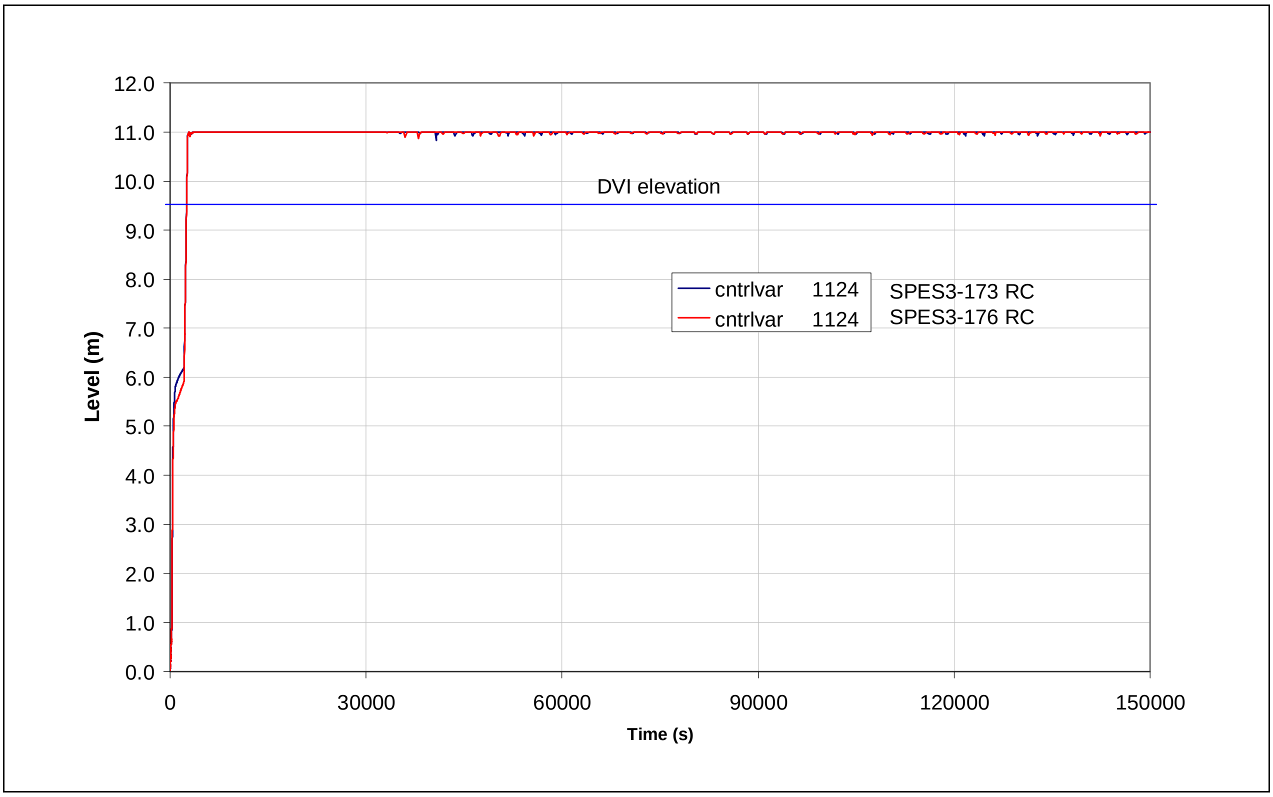


Fig.8. 39 – SPES3-173 and SPES3-176 DW level

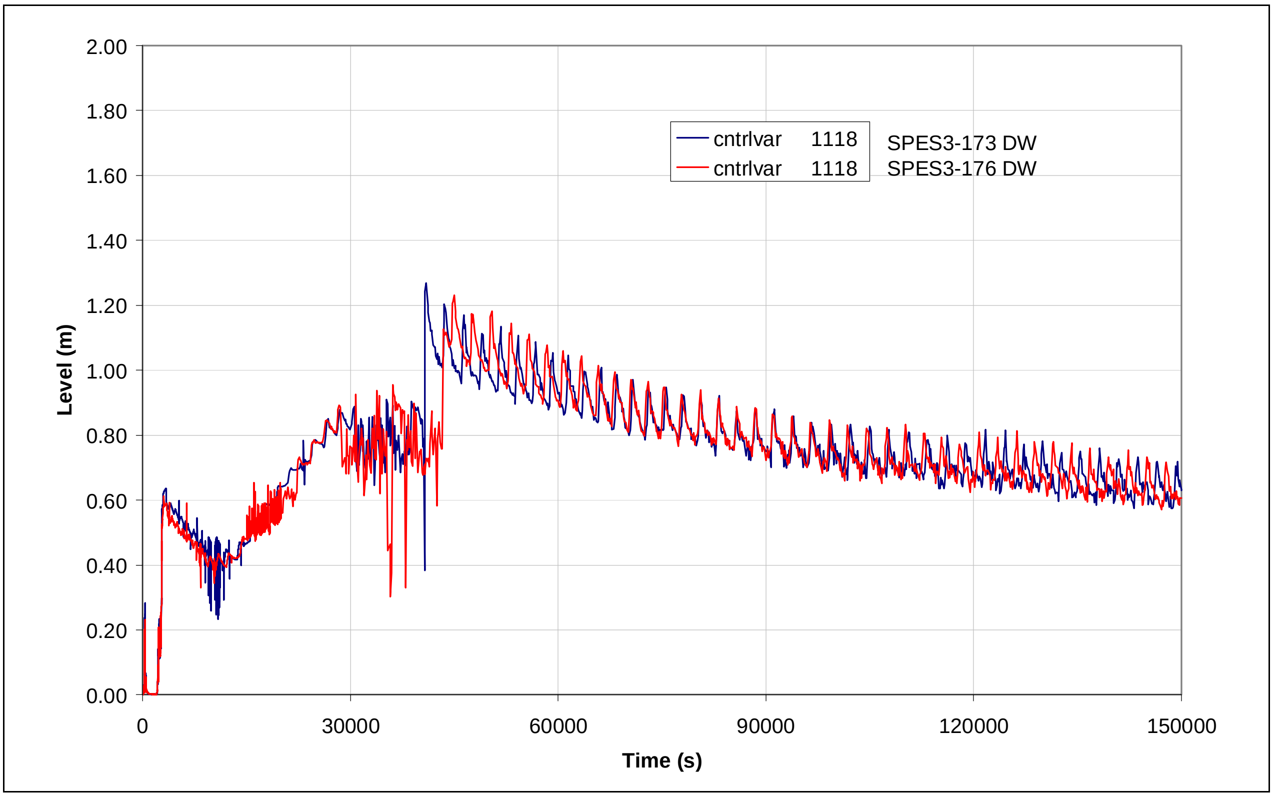


Fig.8. 40 – SPES3-173 and SPES3-176 QT level

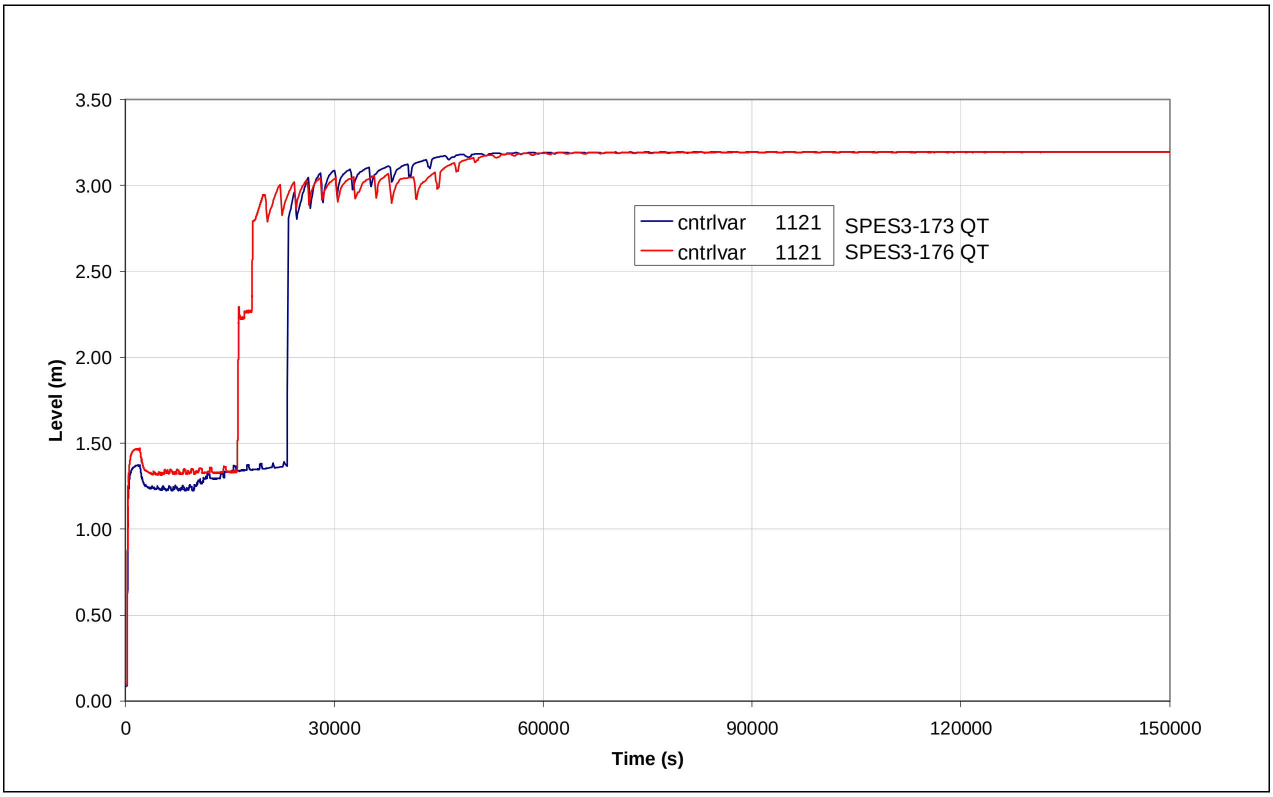


Fig.8. 41 – SPES3-173 and SPES3-176 PSS temperature (window)

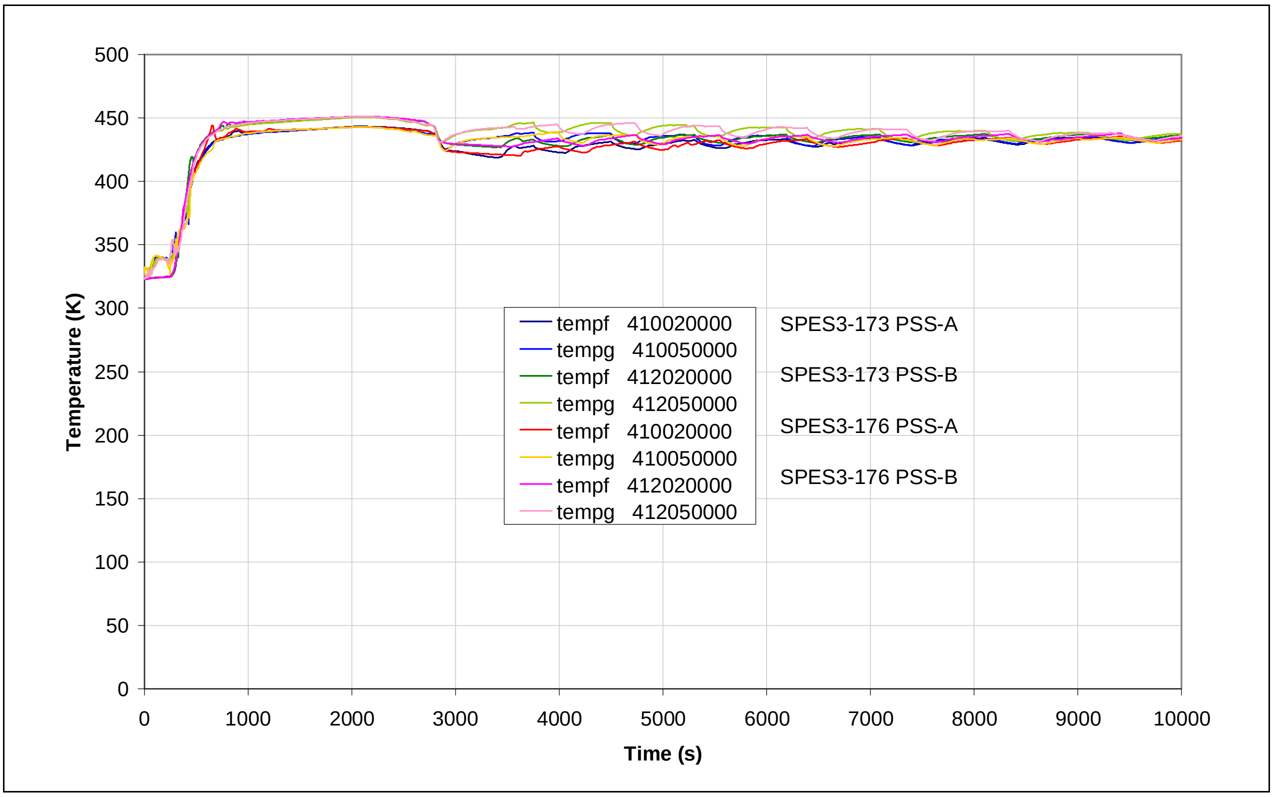


Fig.8. 42 – SPES3-173 and SPES3-176 PSS temperature

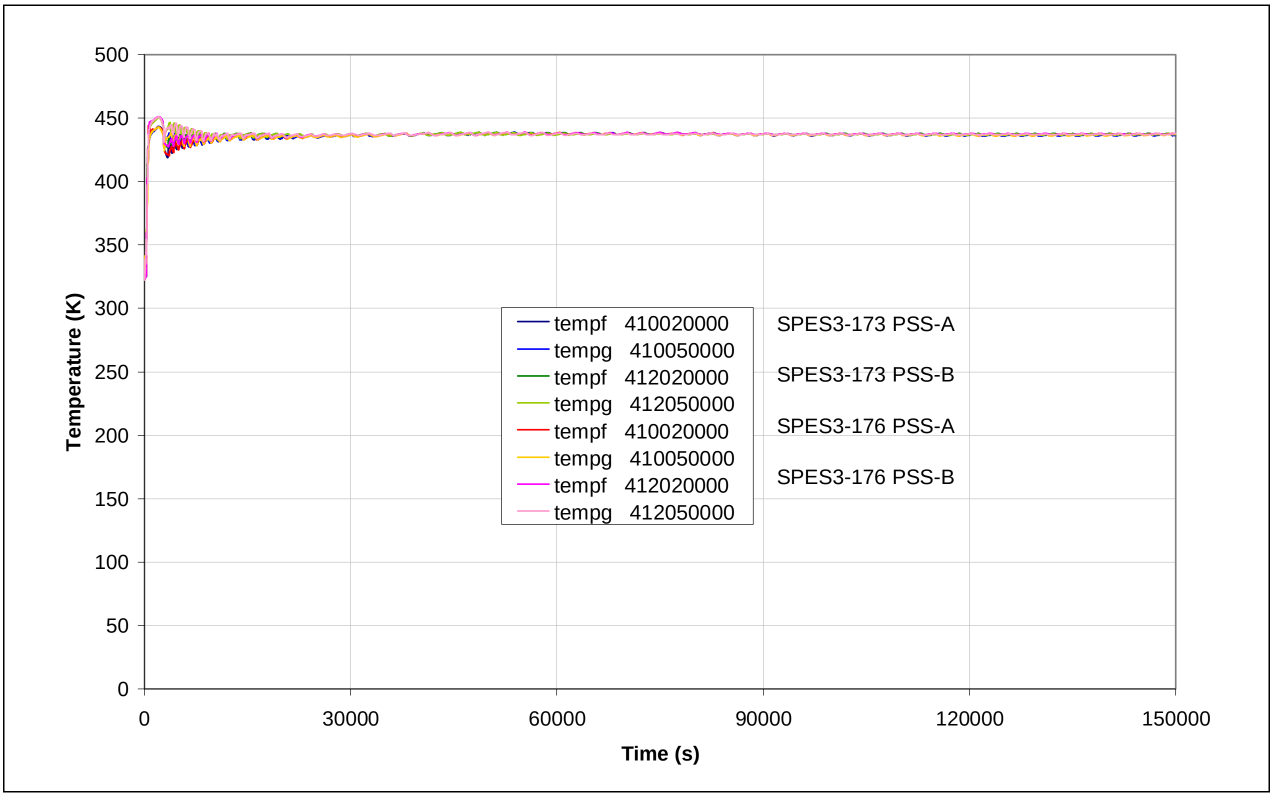


Fig.8. 43 – SPES3-173 and SPES3-176 core power (window)

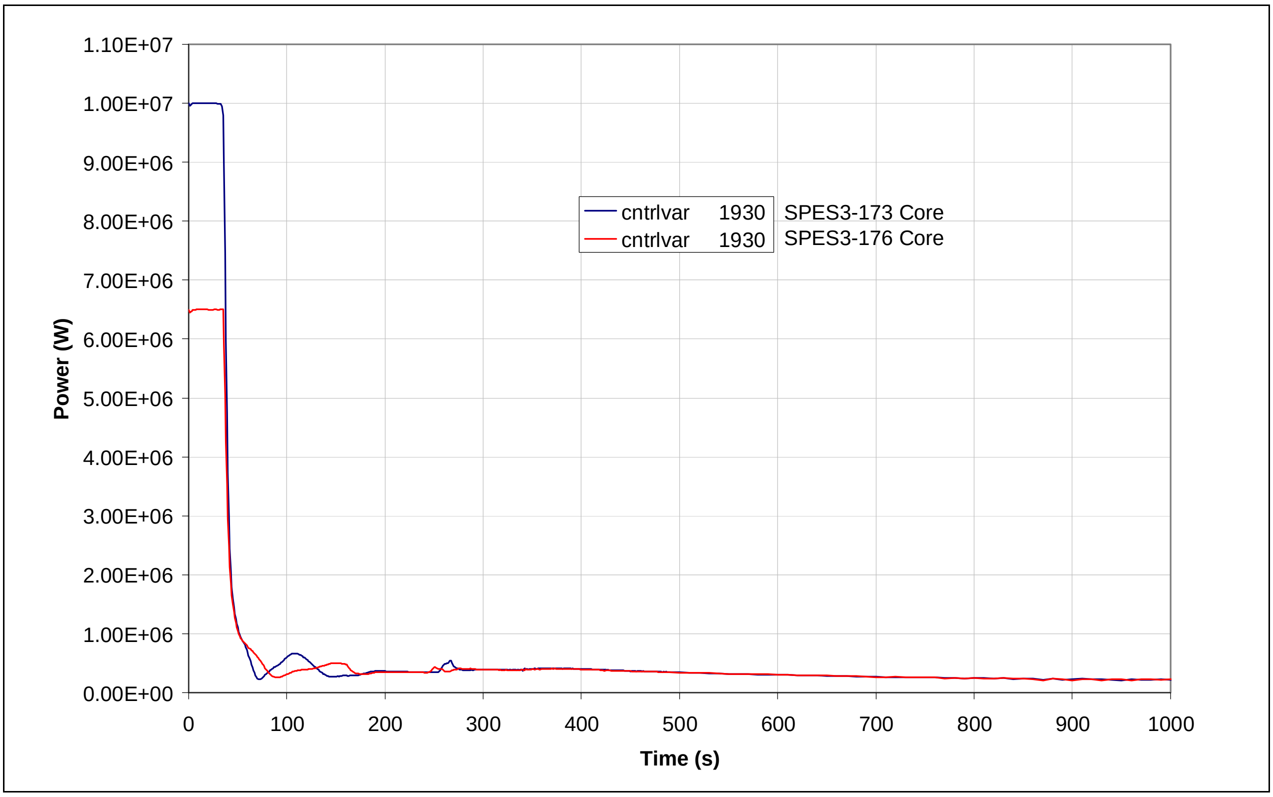


Fig.8. 44 – SPES3-173 and SPES3-176 core power (window)

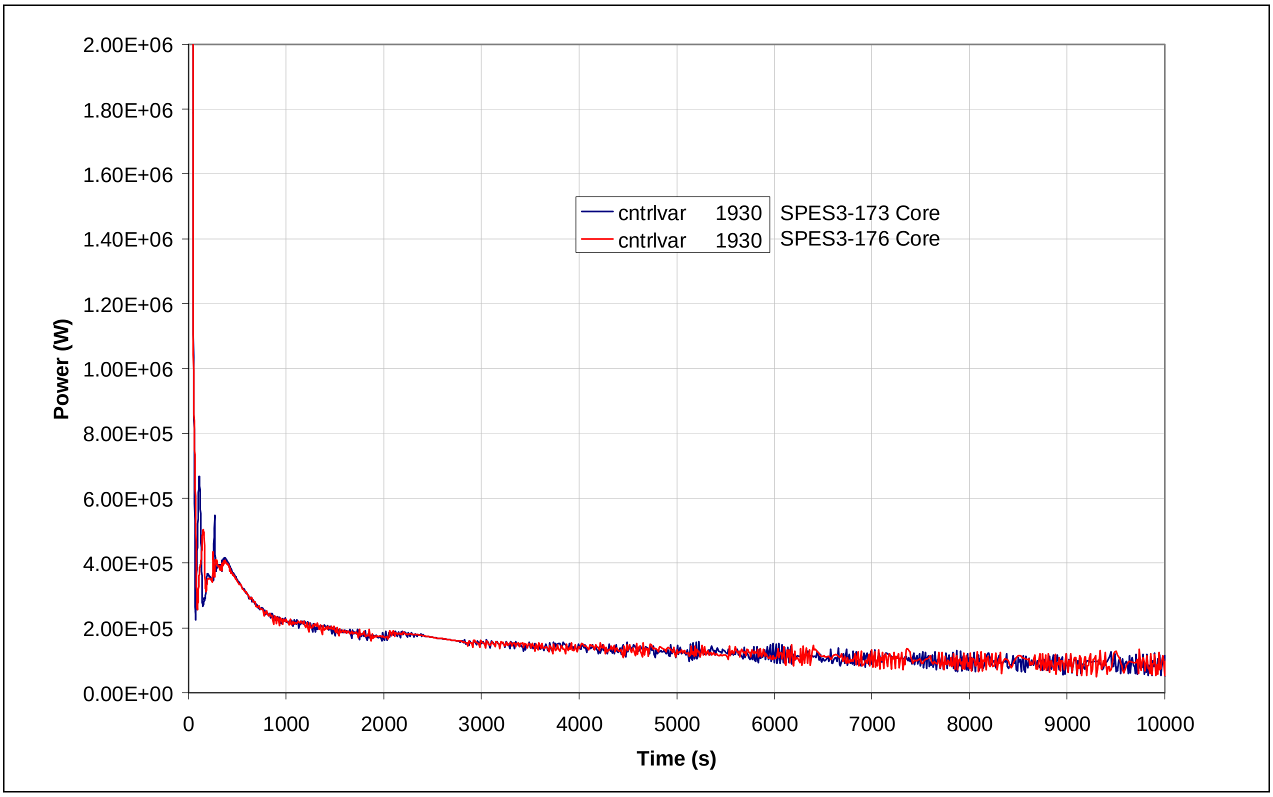


Fig.8. 45 – SPES3-173 and SPES3-176 core power

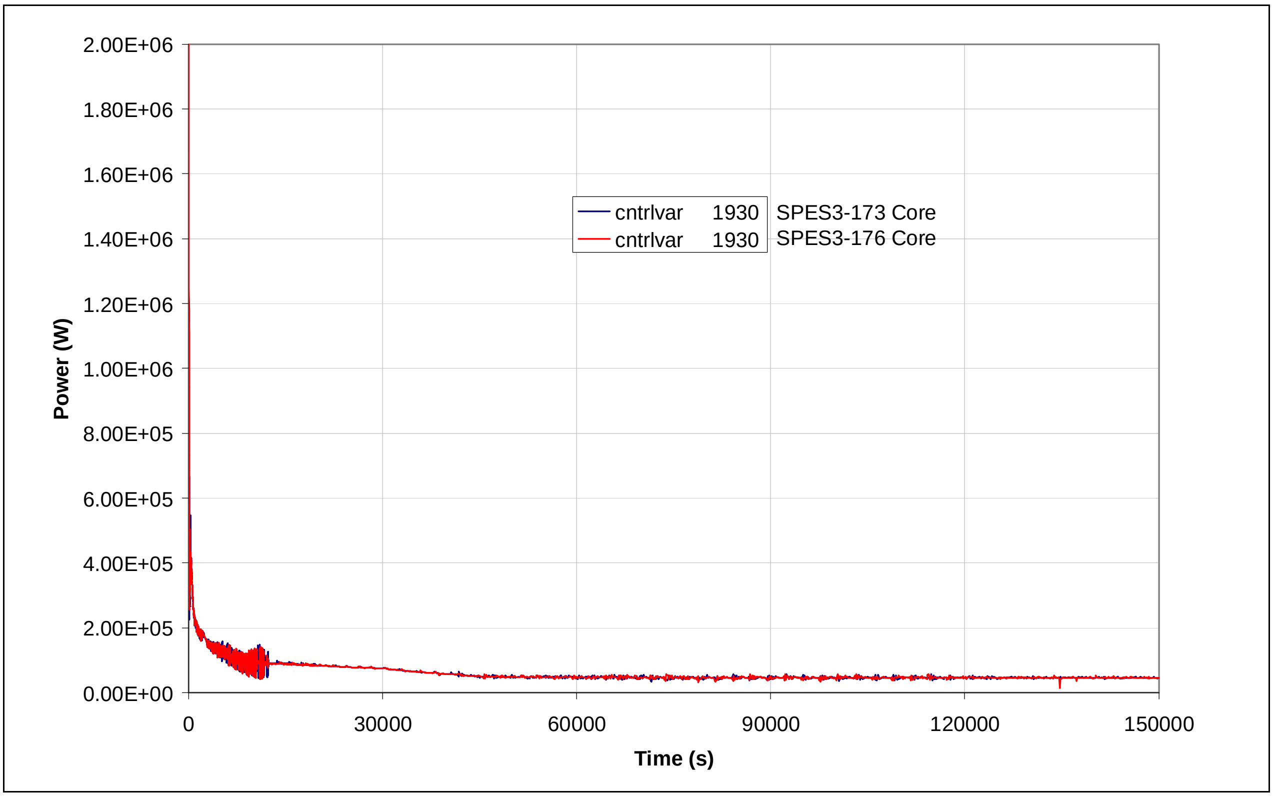


Fig.8. 46 – SPES3-173 and SPES3-176 SG power (window)

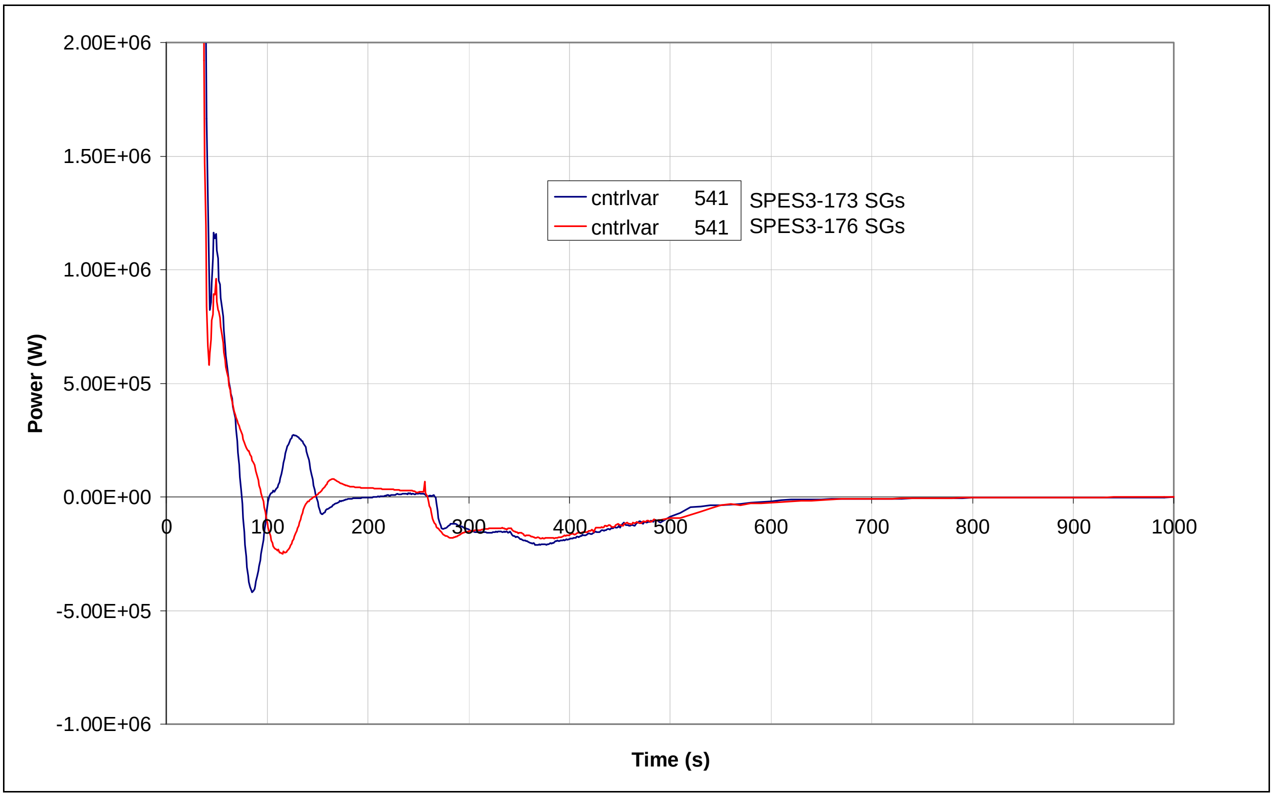


Fig.8. 47 – SPES3-173 and SPES3-176 SG power (window)

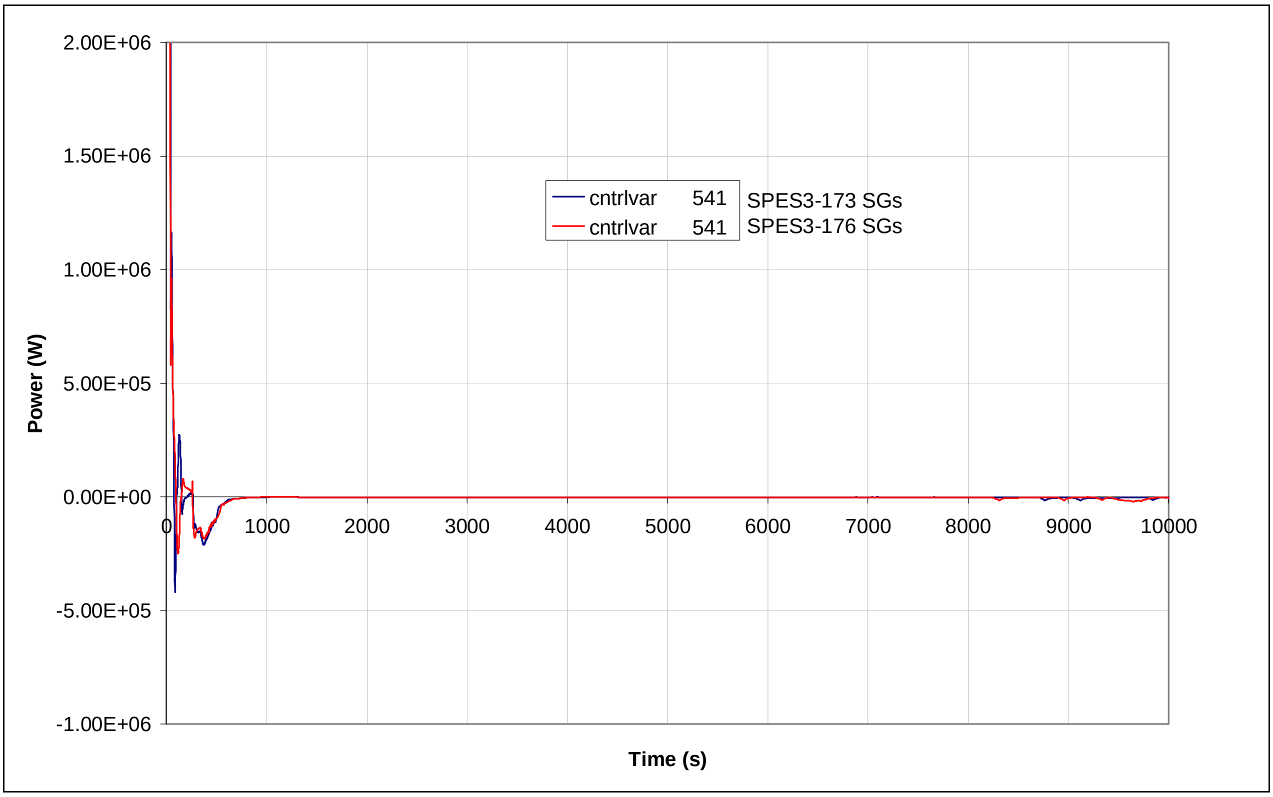


Fig.8. 48 – SPES3-173 and SPES3-176 SG ss mass flow (window)

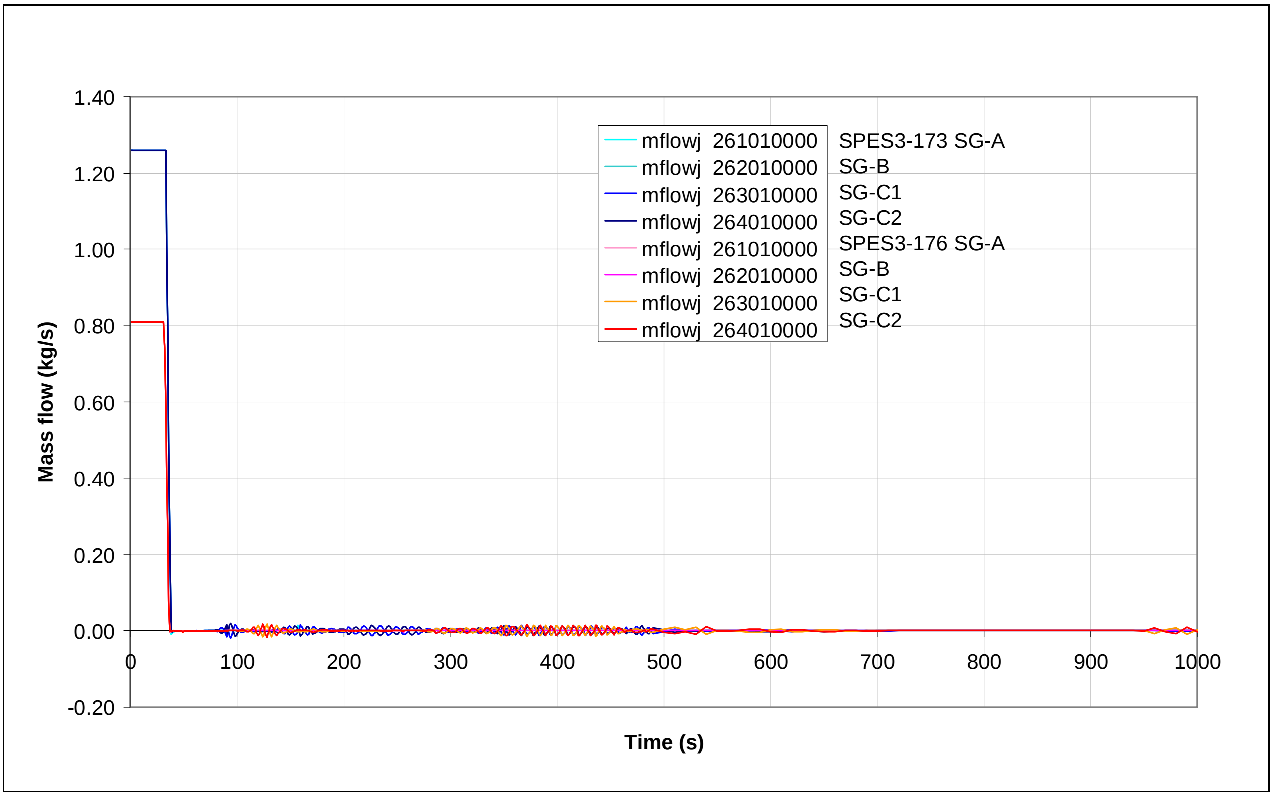


Fig.8. 49 – SPES3-173 and SPES3-176 SG ss outlet pressure (window)

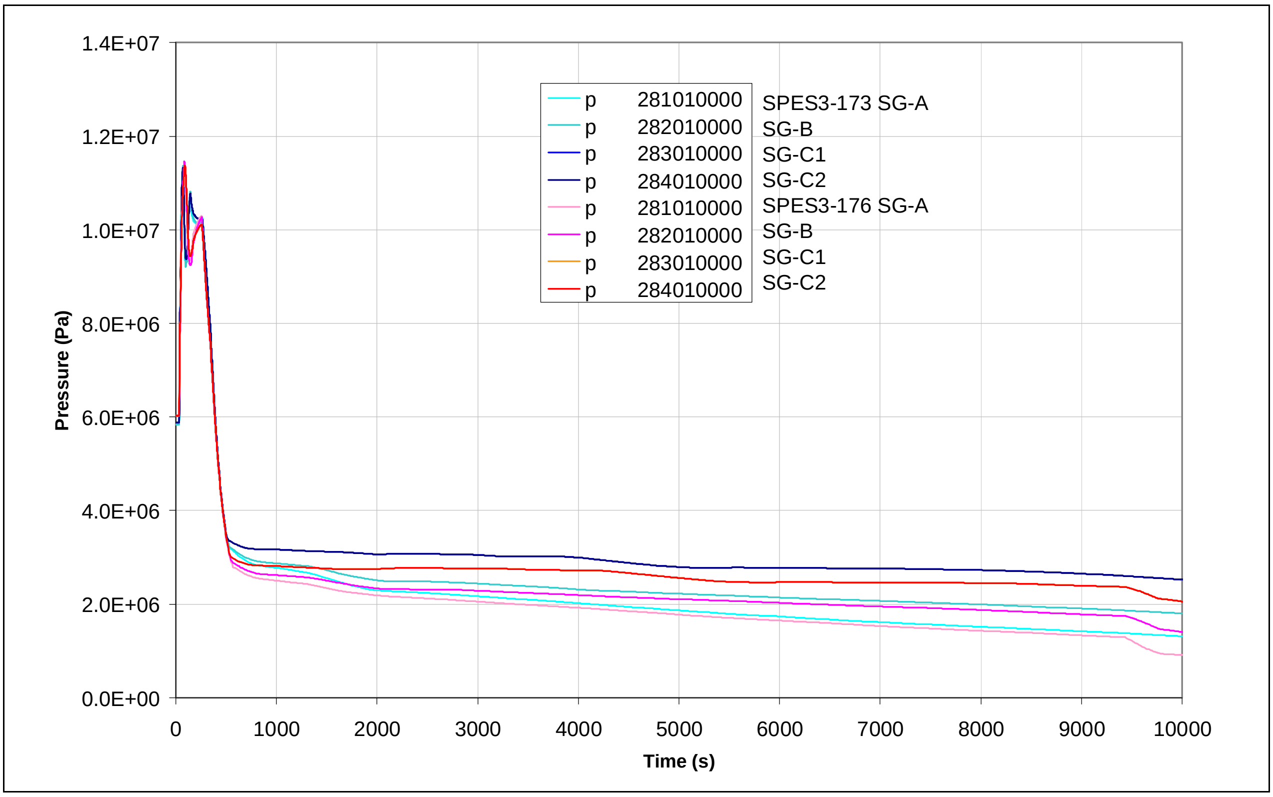


Fig.8. 50 – SPES3-173 and SPES3-176 SG ss outlet pressure

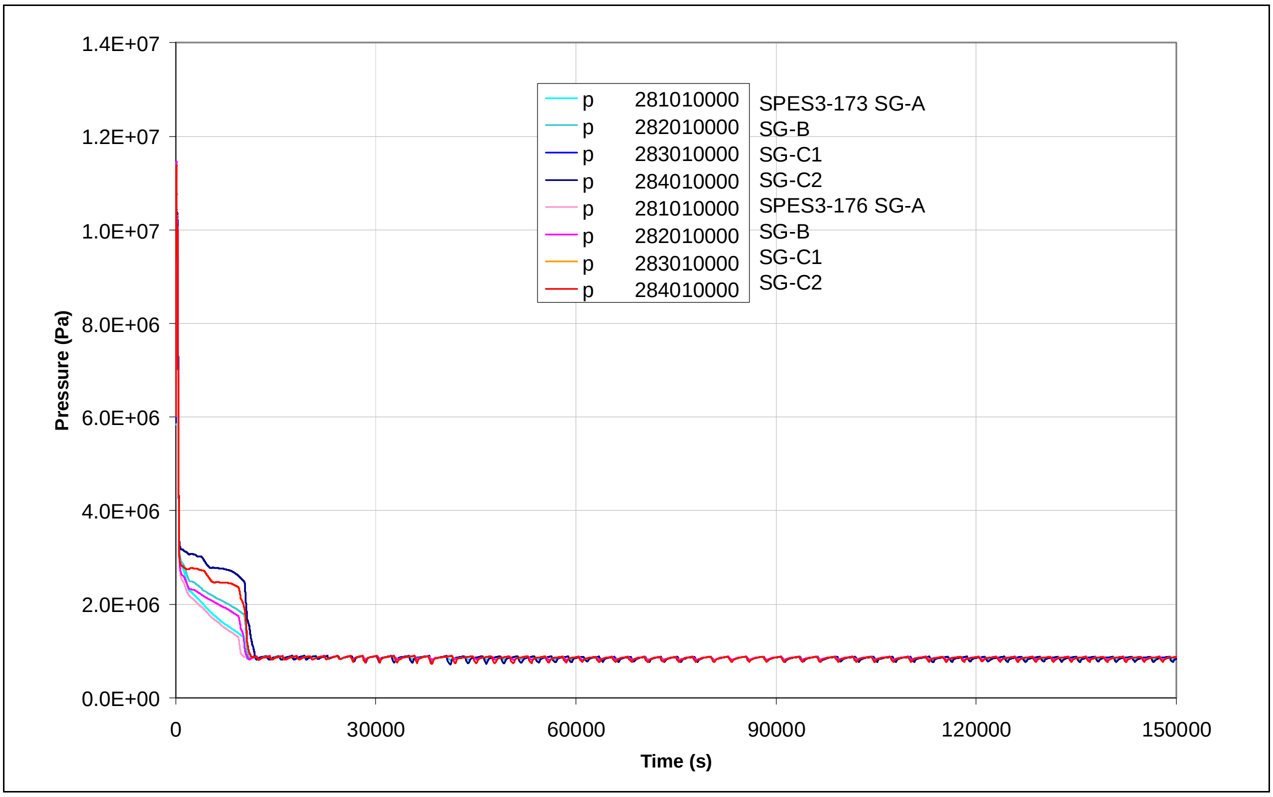


Fig.8. 51 – SPES3-173 and SPES3-176 SGss level (window)

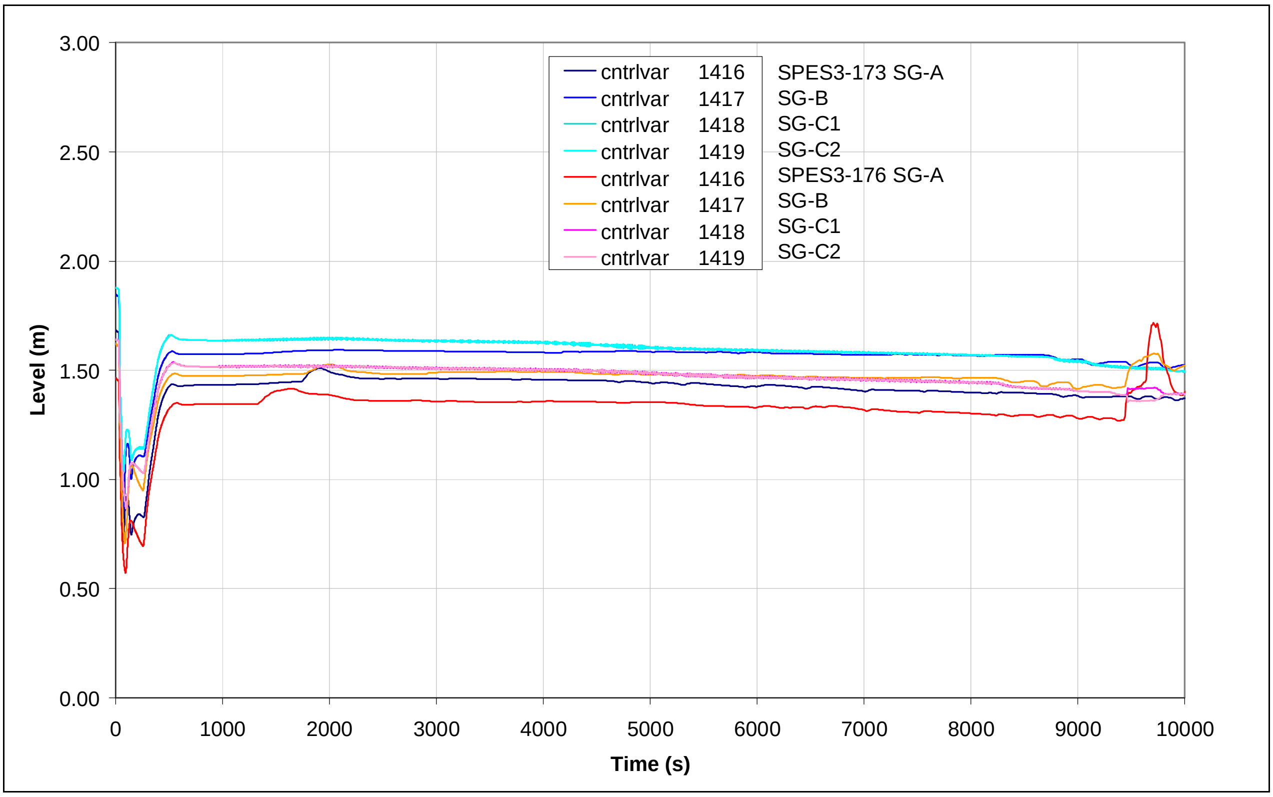


Fig.8. 52 – SPES3-173 and SPES3-176 SGss level

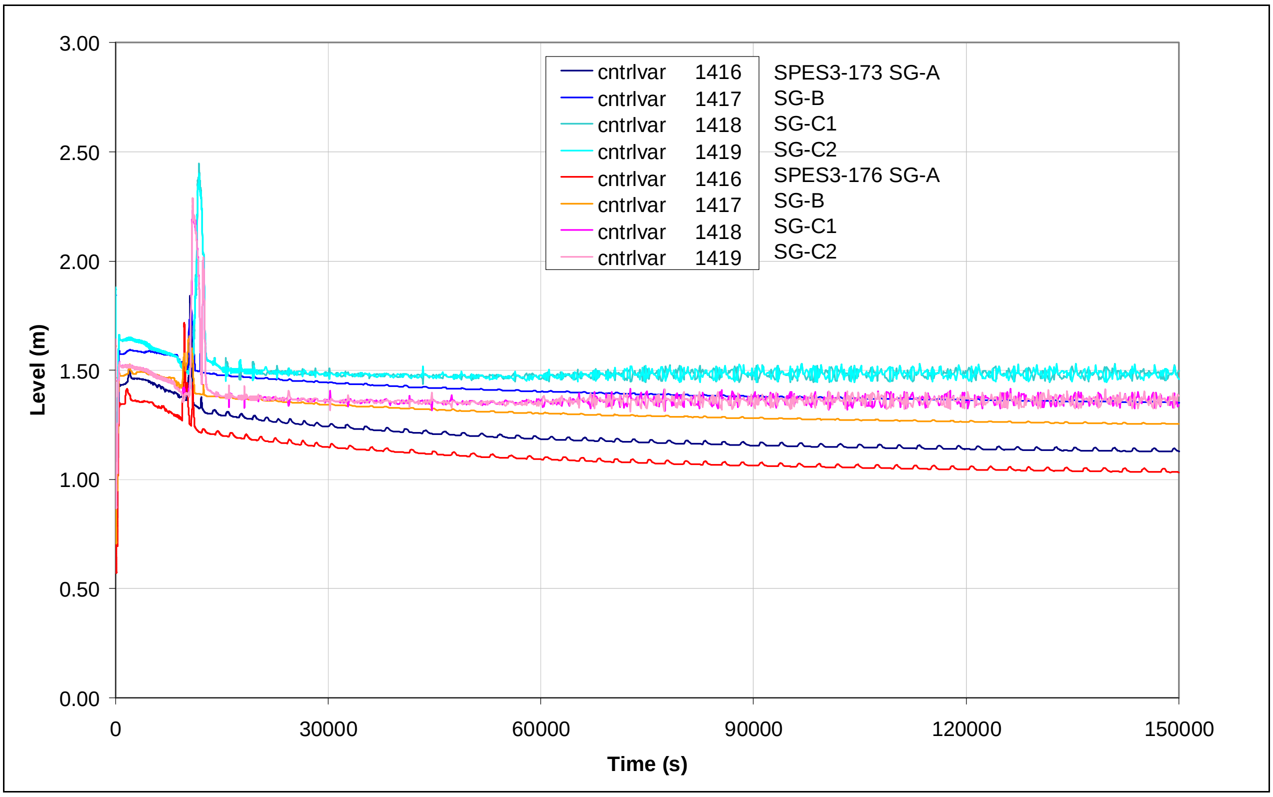


Fig.8. 53 – SPES3-173 and SPES3-176 PRZ level

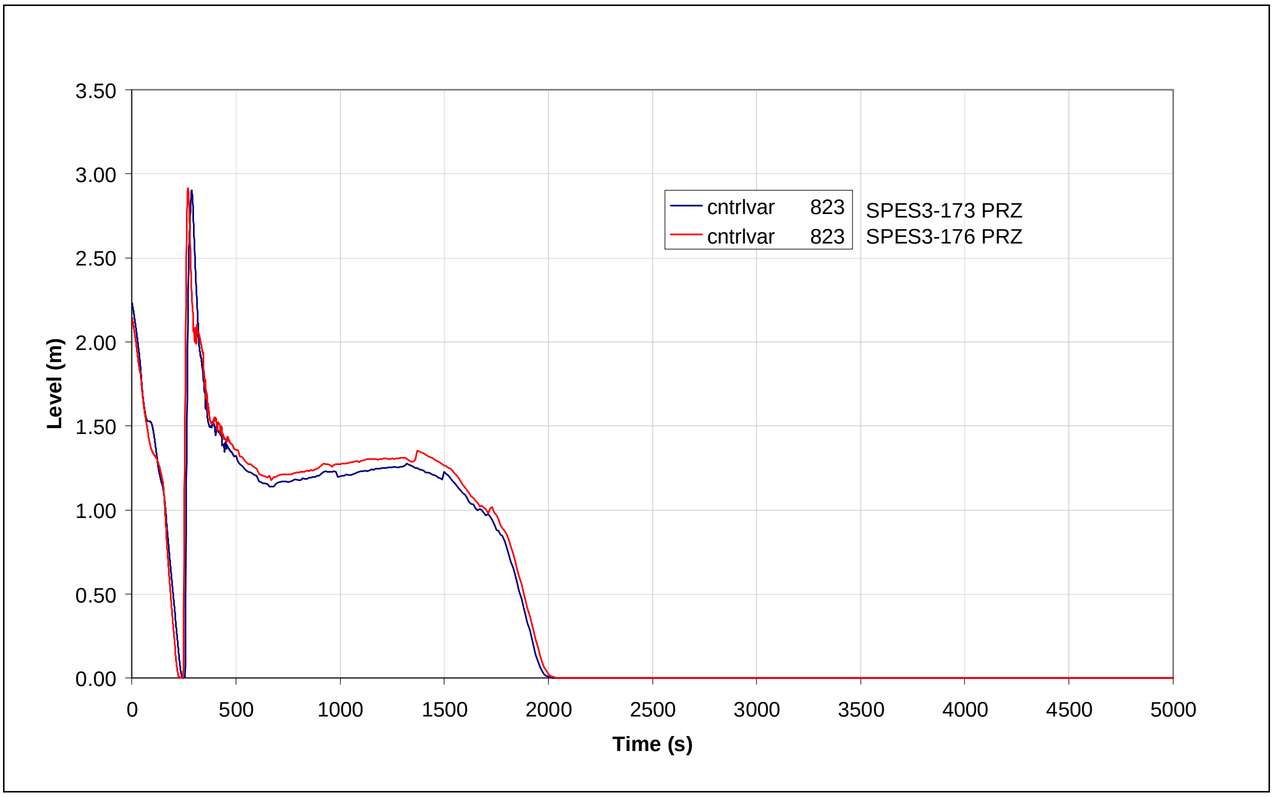


Fig.8. 54 – SPES3-173 and SPES3-176 Pump velocity

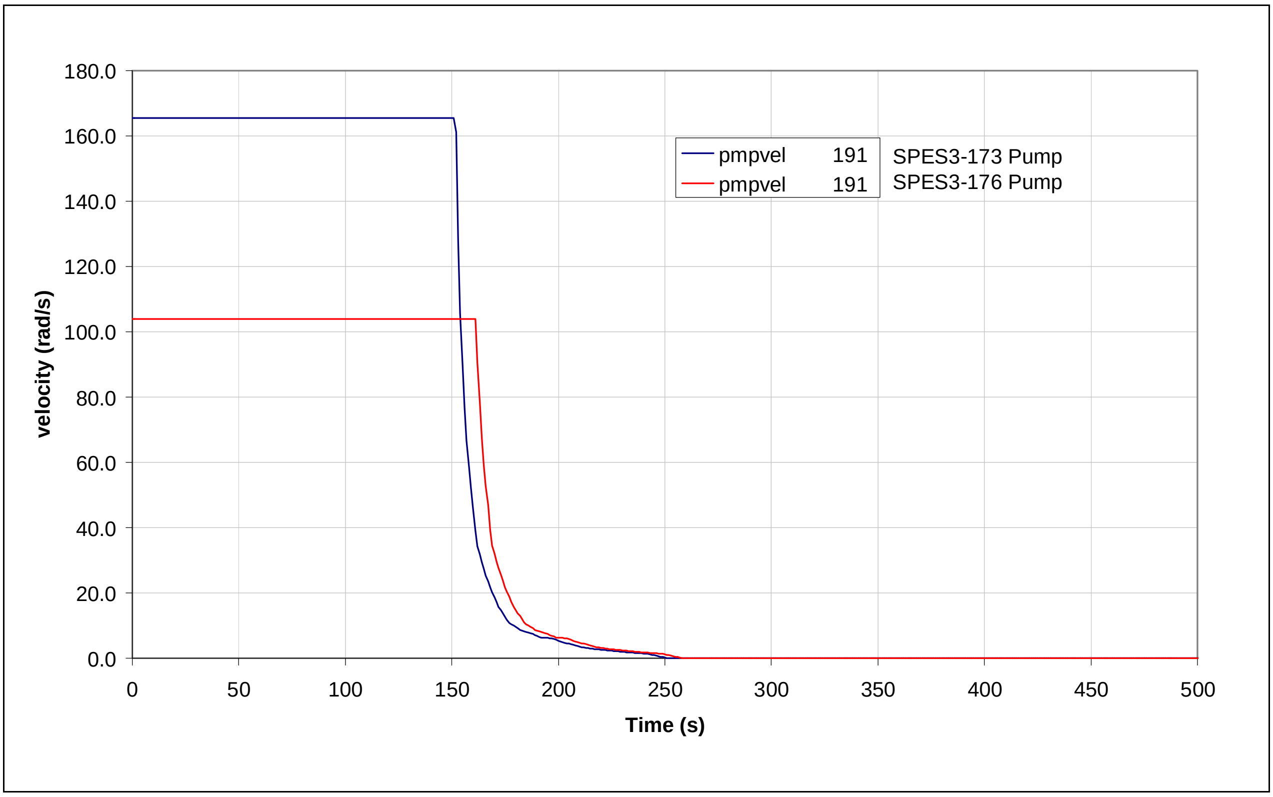


Fig.8. 55 – SPES3-173 and SPES3-176 pump inlet liquid fraction

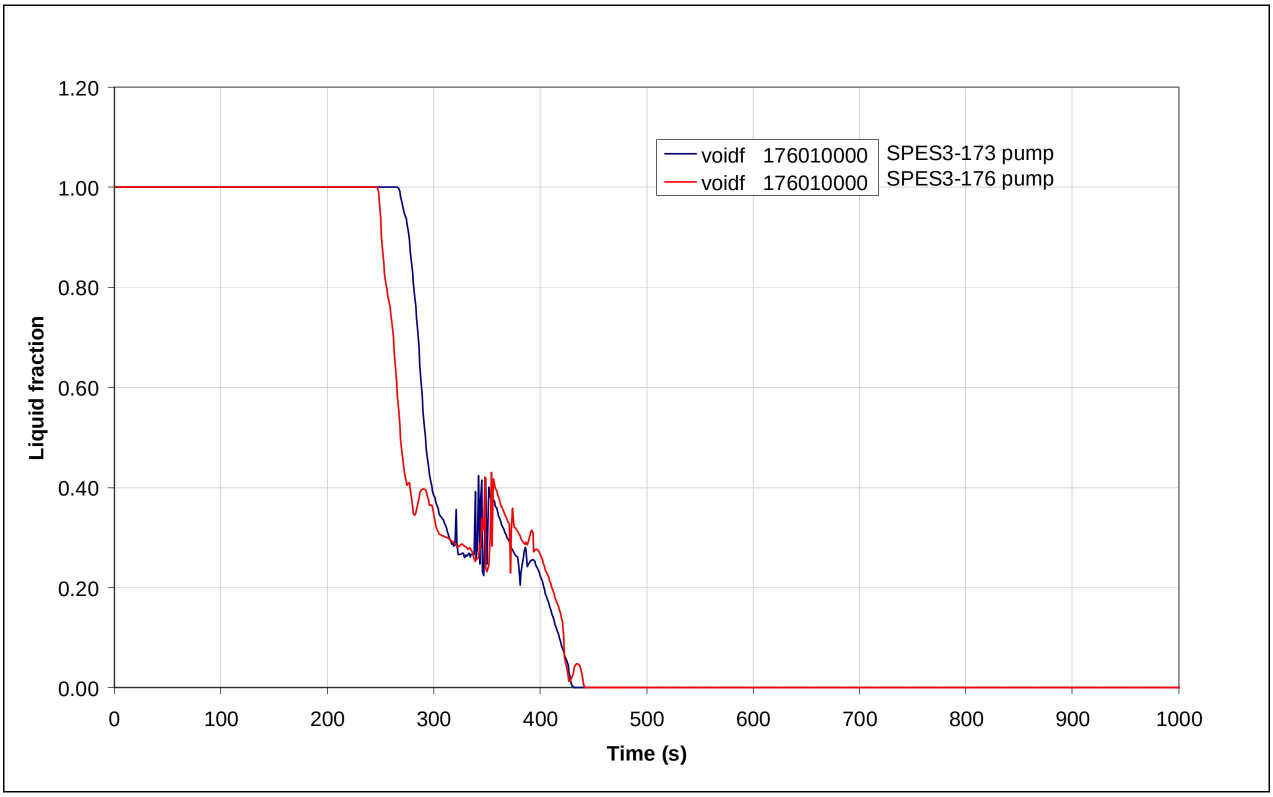


Fig.8. 56 – SPES3-173 and SPES3-176 core inlet flow (window)

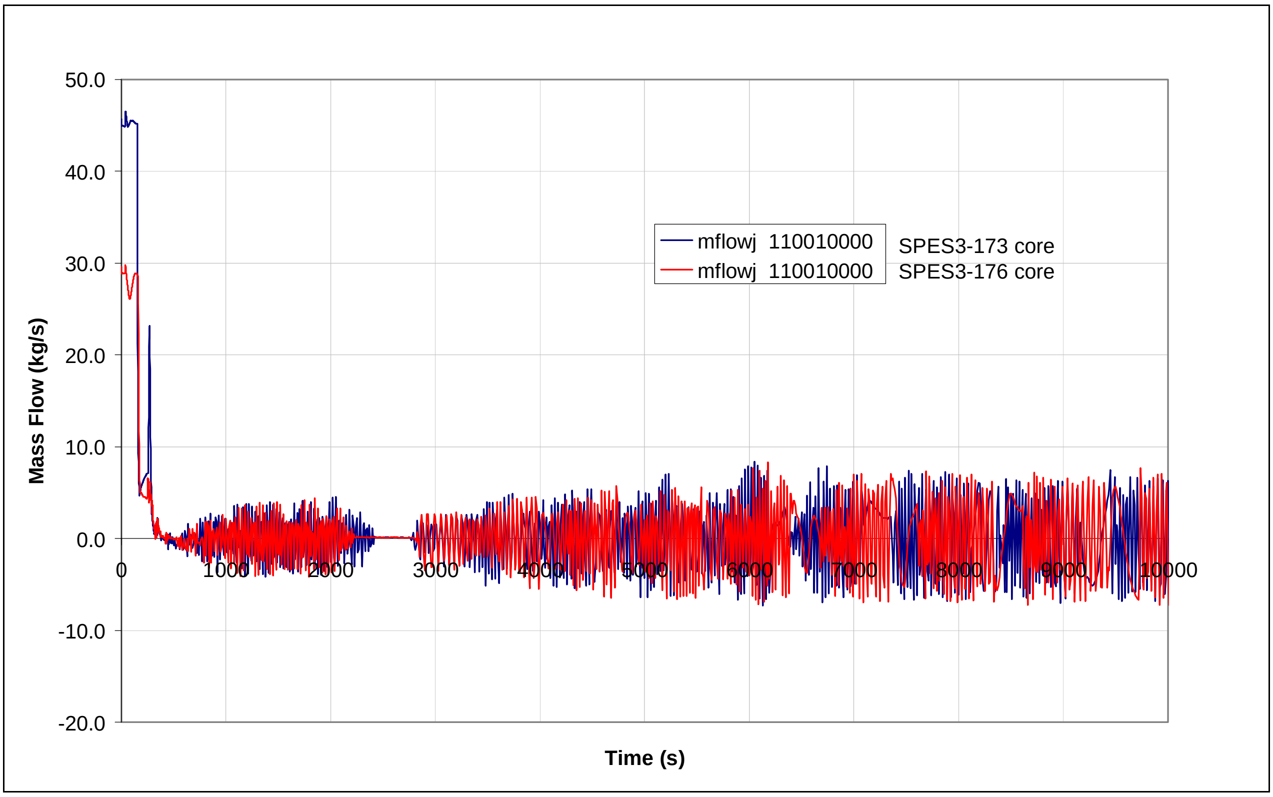


Fig.8. 57 – SPES3-173 and SPES3-176 core inlet flow

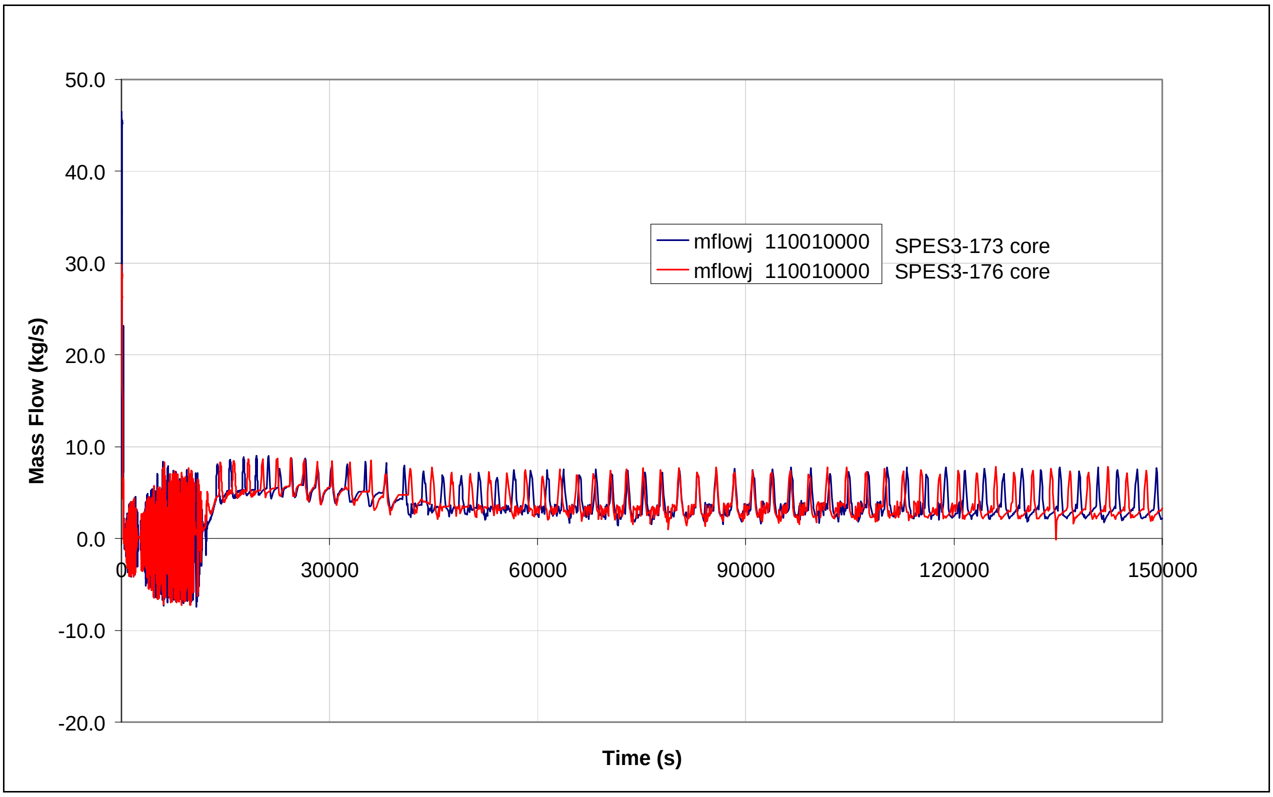


Fig.8. 58 – SPES3-173 and SPES3-176 RI-DC check valve mass flow (window)

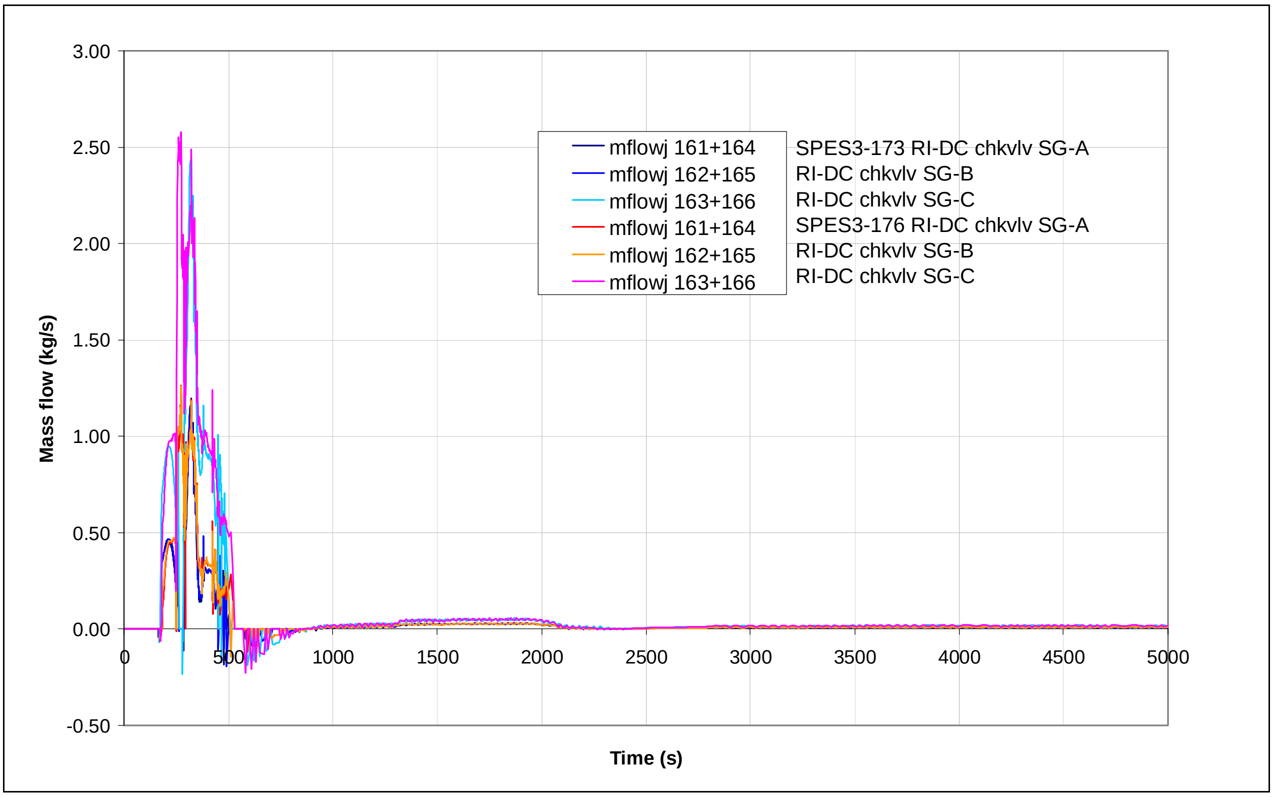


Fig.8. 59 – SPES3-173 and SPES3-176 RI-DC check valve mass flow

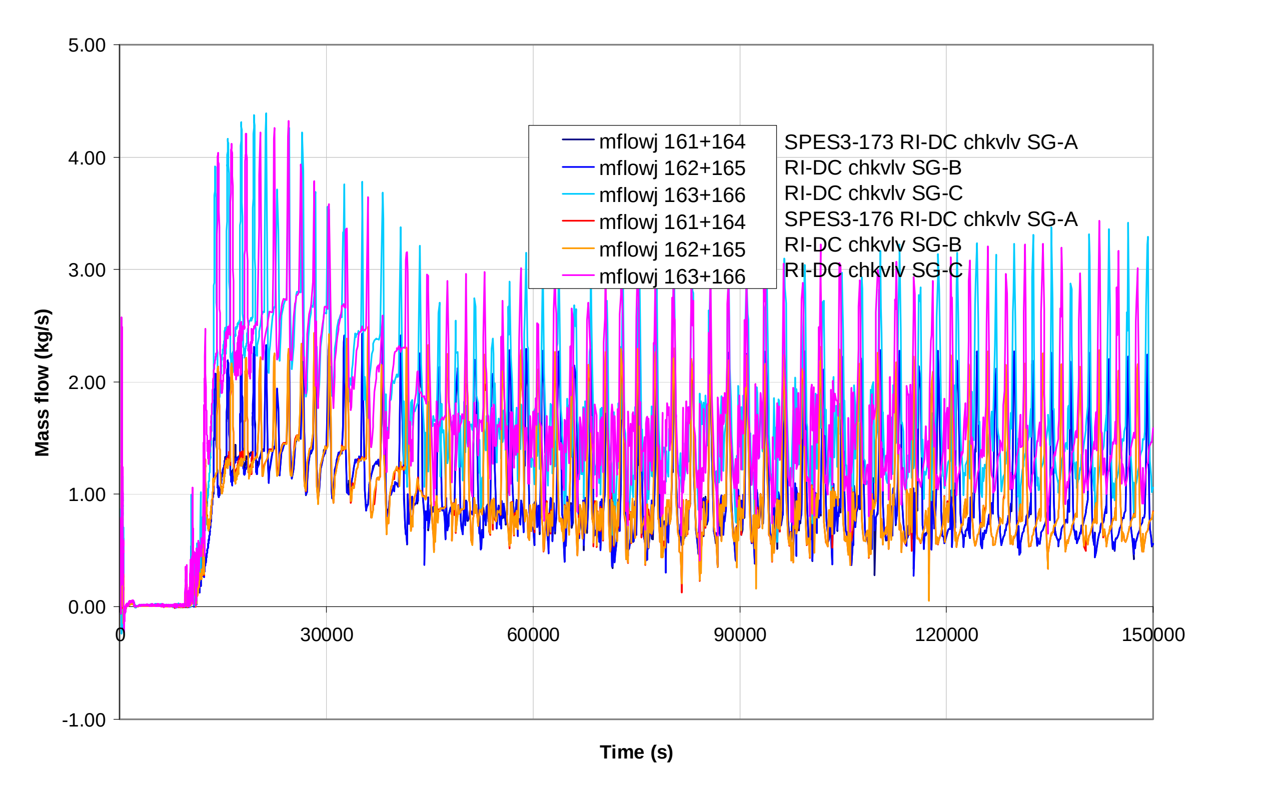


Fig.8. 60 – SPES3-173 and SPES3-176 RPV mass

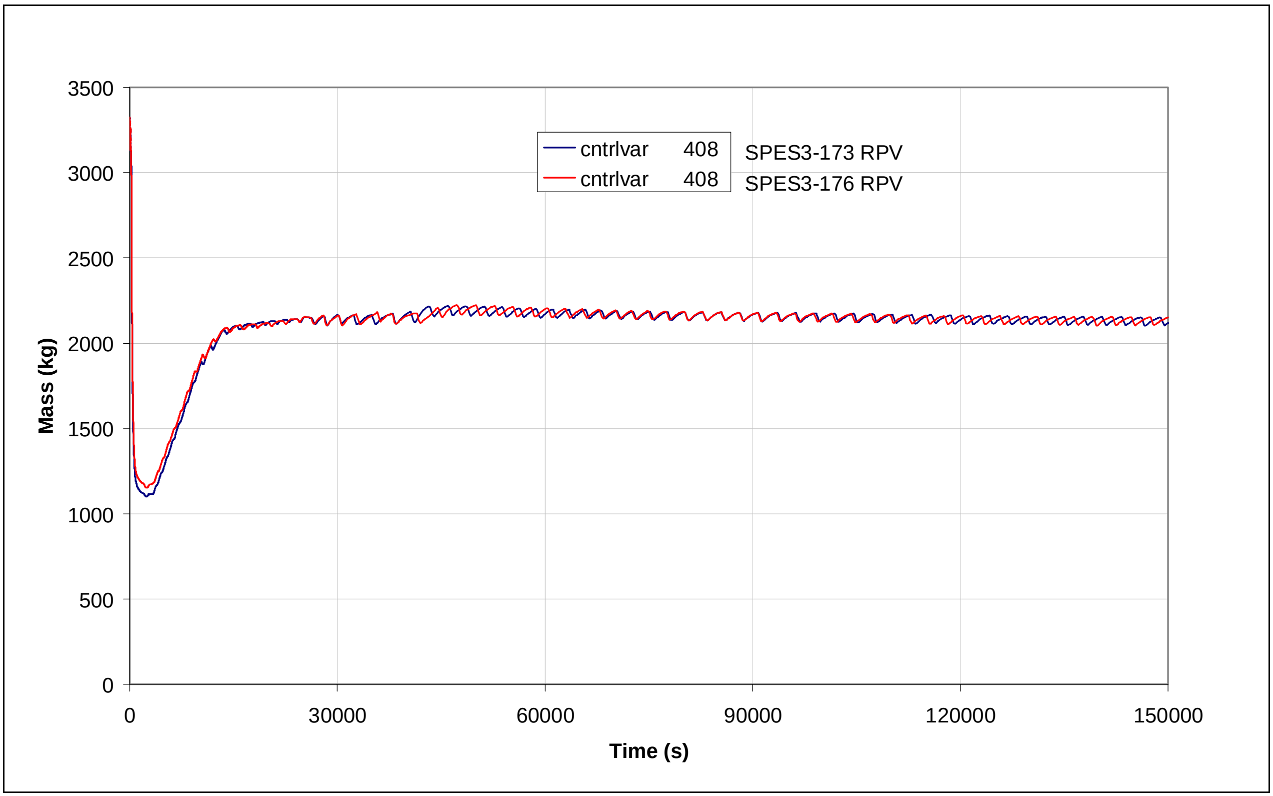


Fig.8. 61 – SPES3-173 and SPES3-176 EBT mass

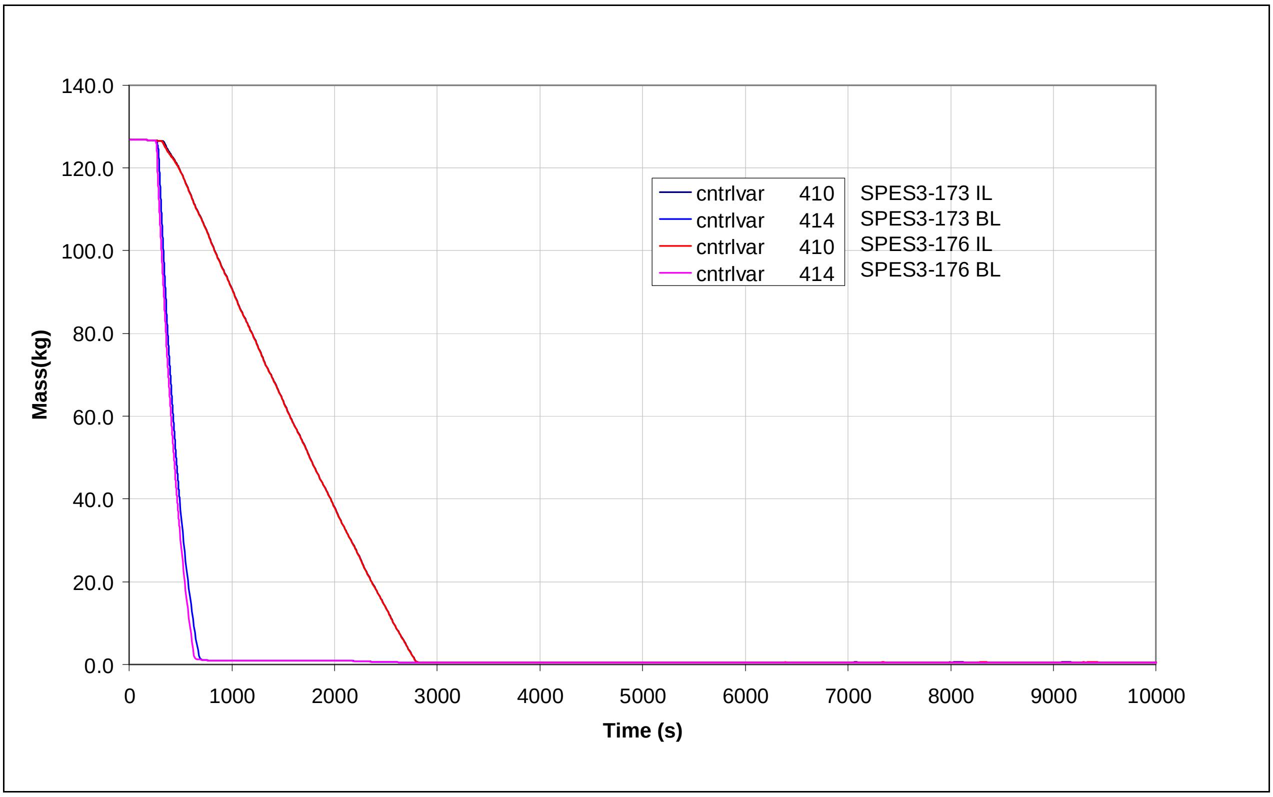


Fig.8. 62 – SPES3-173 and SPES3-176 EBT level

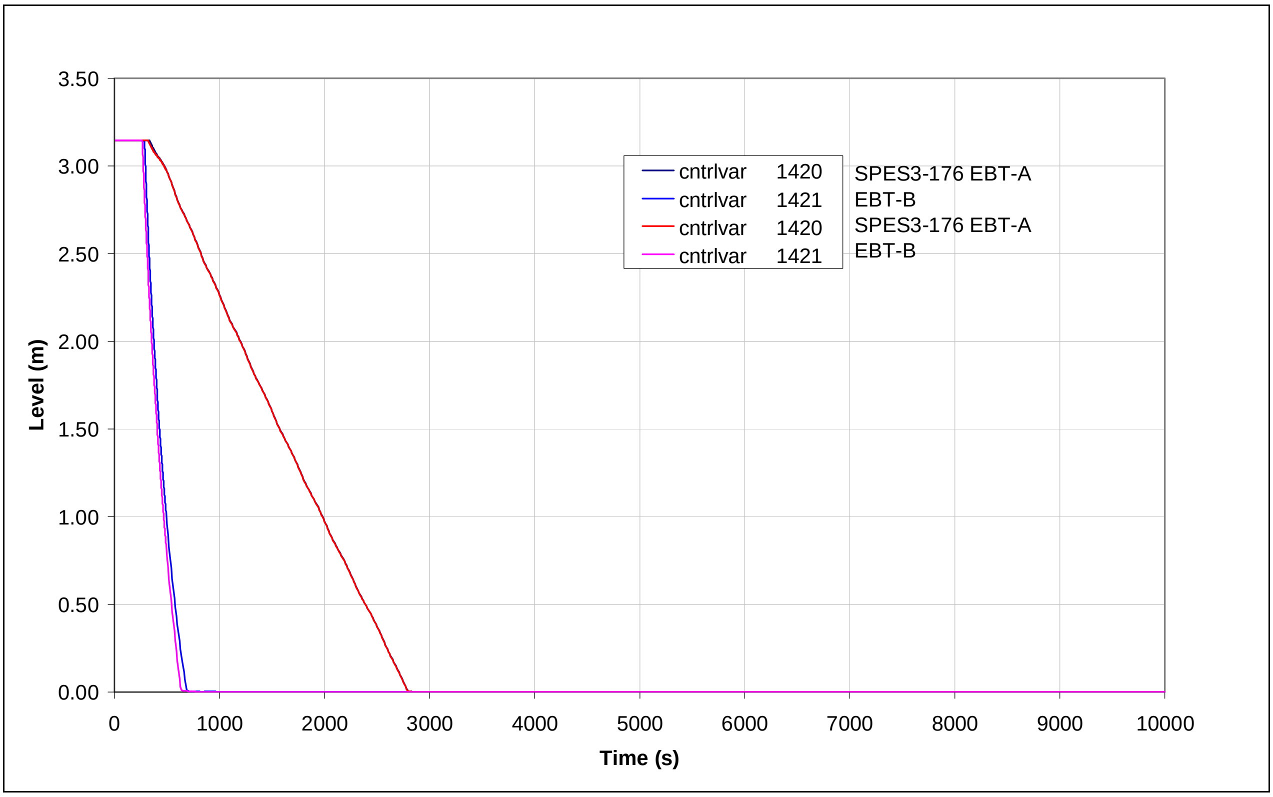


Fig.8. 63 – SPES3-173 and SPES3-176 EBT balance line mass flow (mass flow)

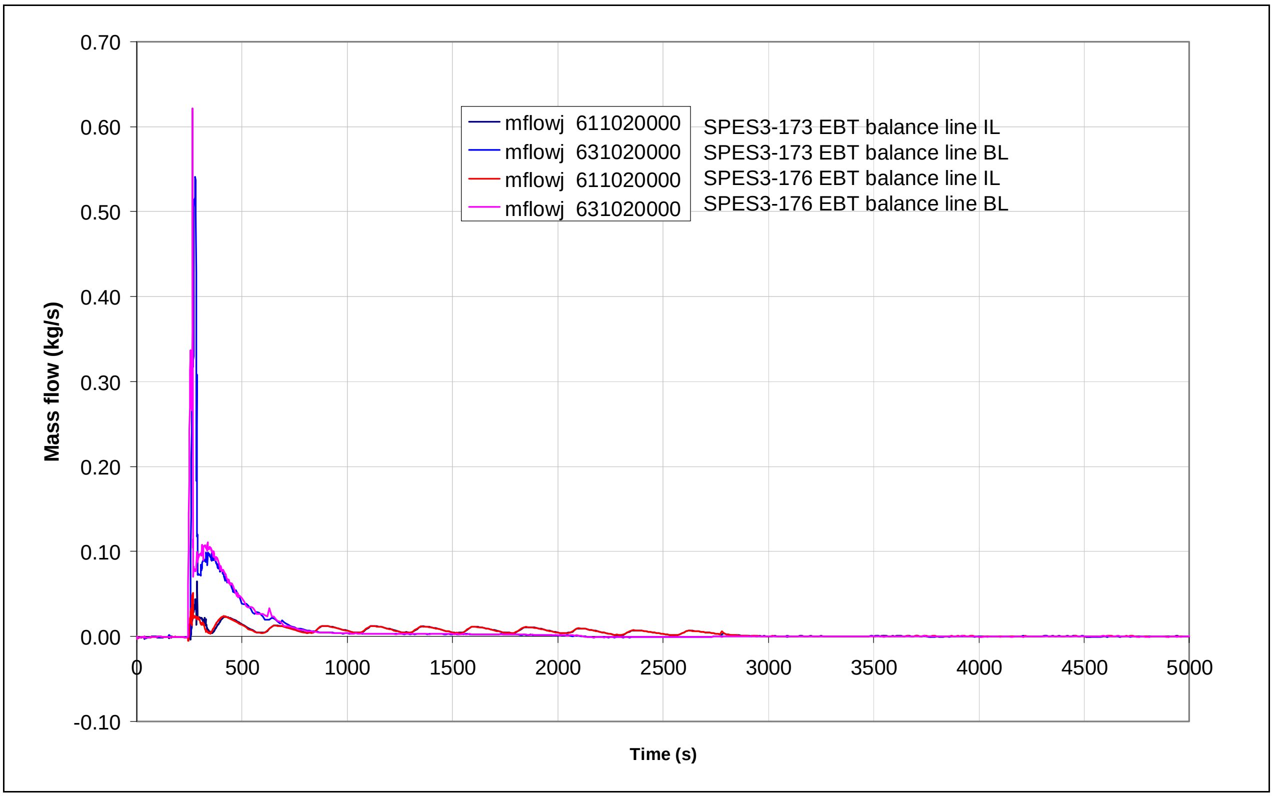


Fig.8. 64 – SPES3-173 and SPES3-176 Core liquid fraction (window)

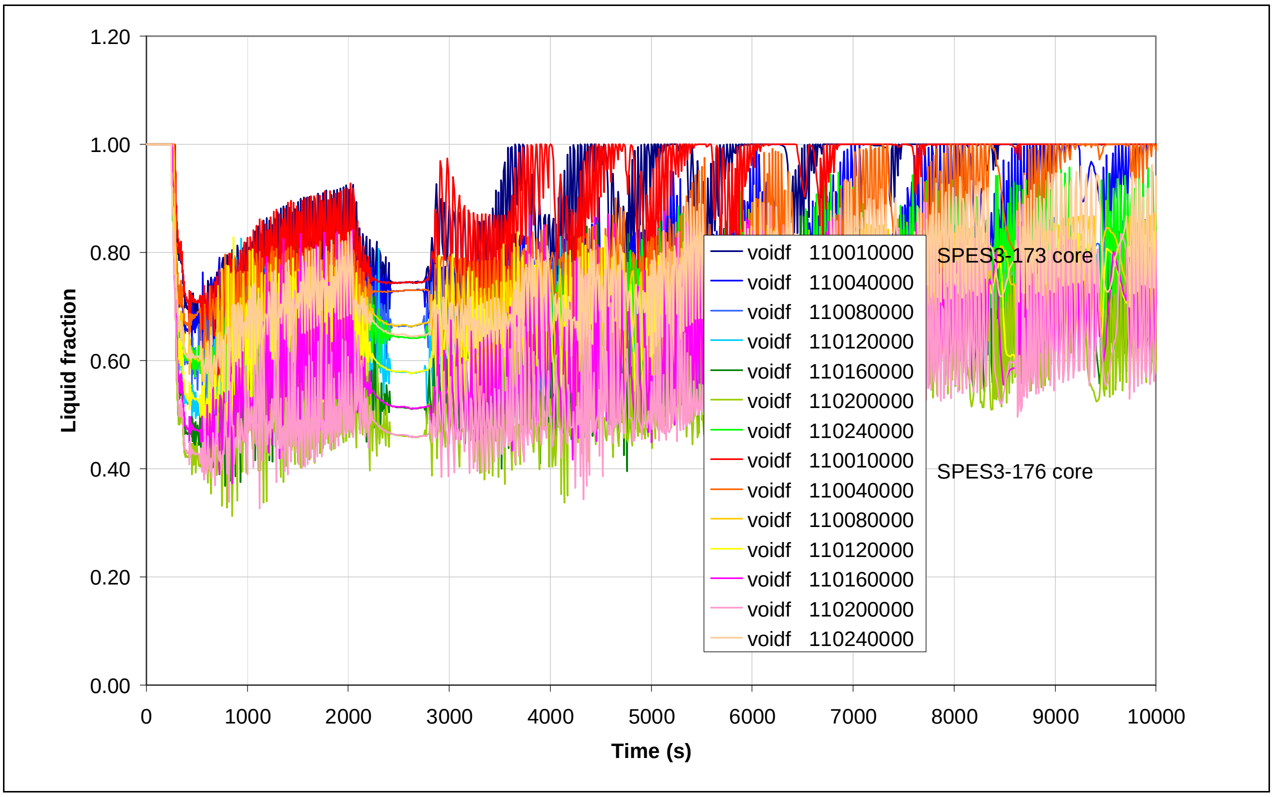


Fig.8. 65 – SPES3-173 and SPES3-176 Core liquid fraction

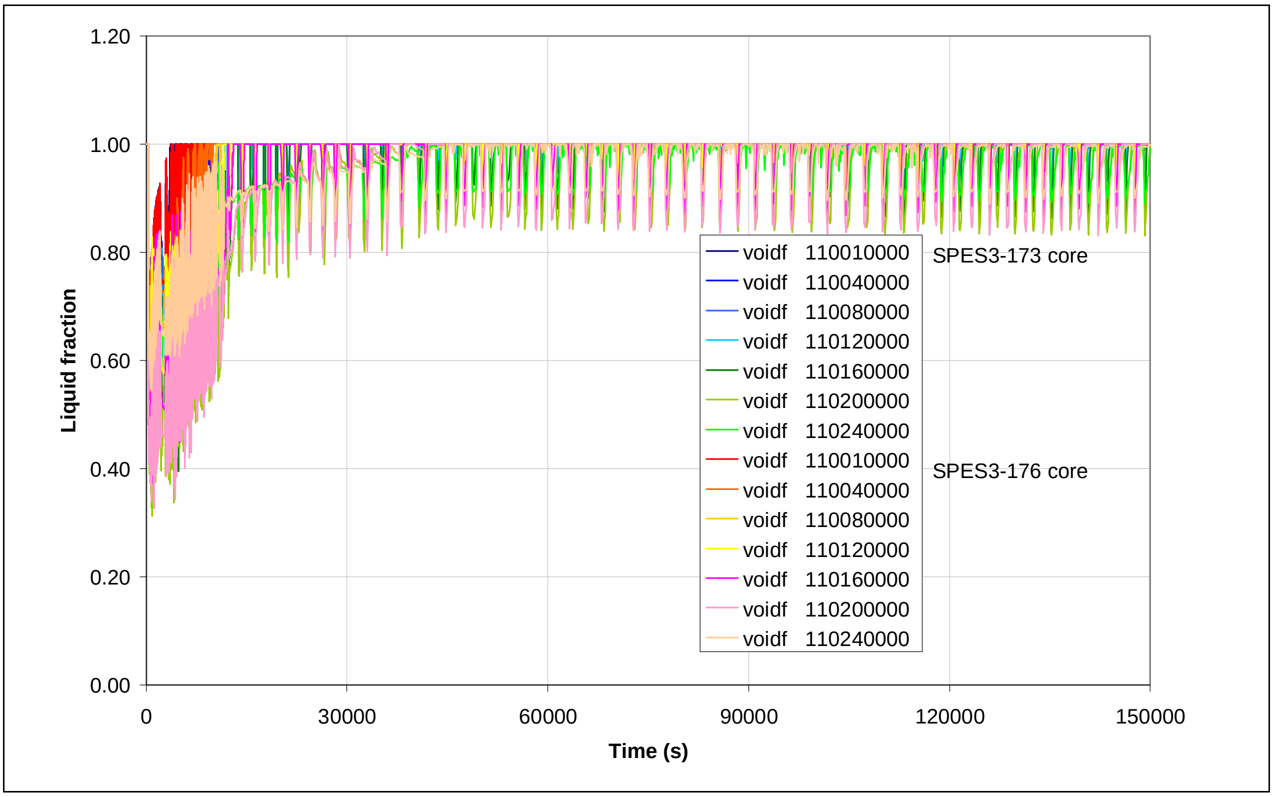


Fig.8. 66 – SPES3-173 and SPES3-176 RC to DVI line mass flow

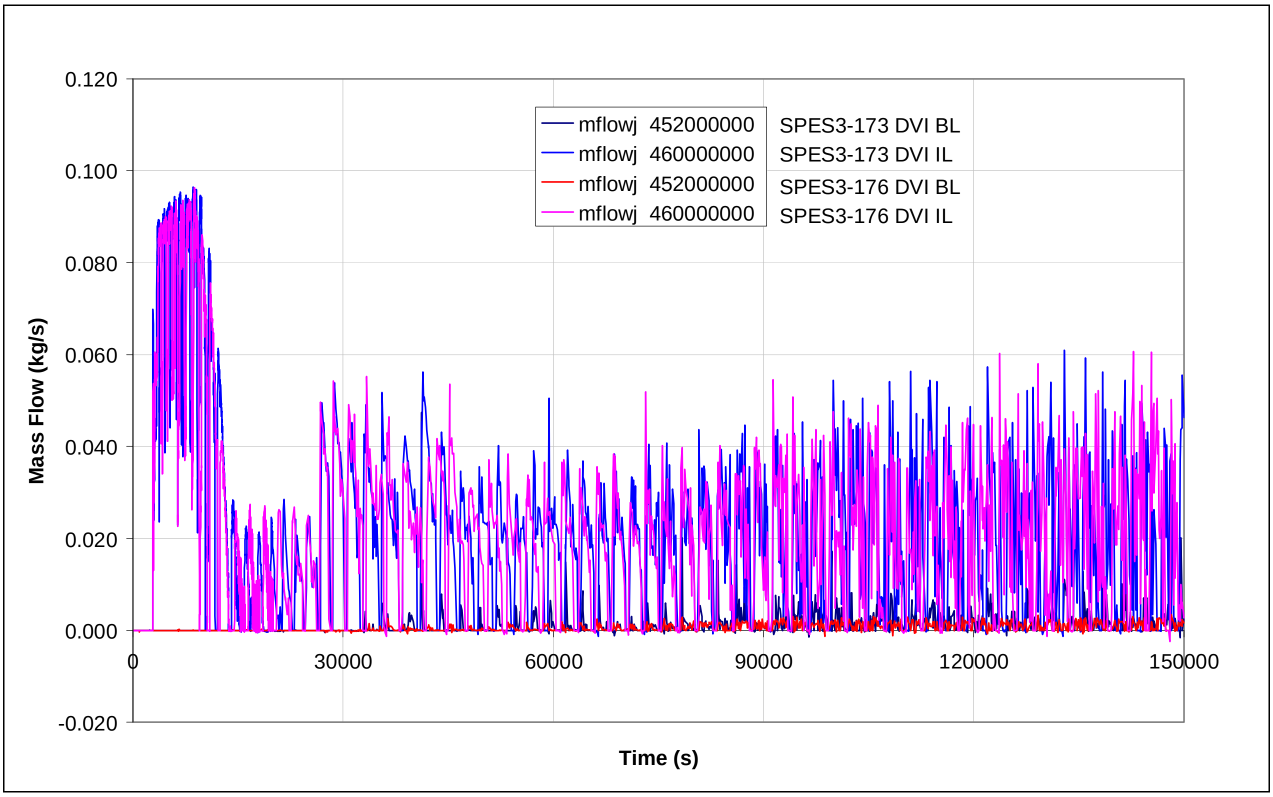


Fig.8. 67 – SPES3-173 and SPES3-176 DVI line mass flow (window)

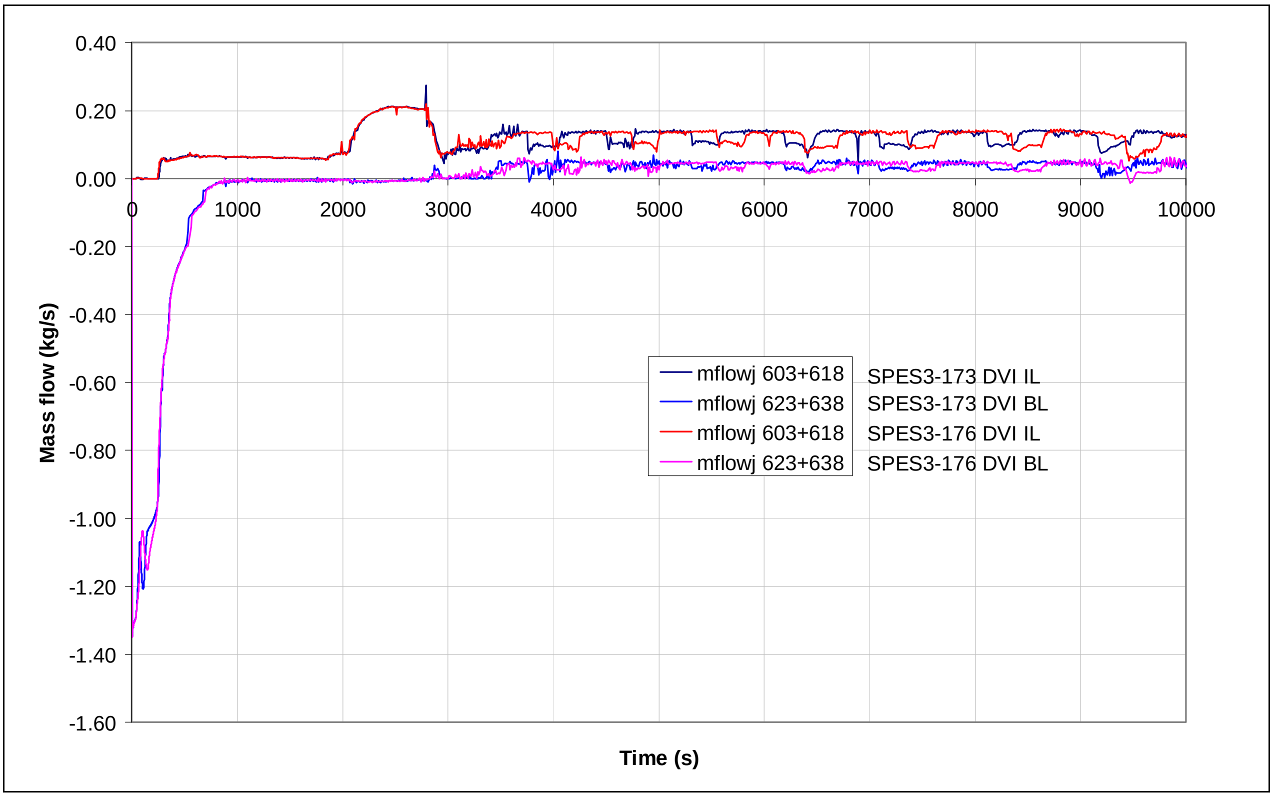


Fig.8. 68 – SPES3-173 and SPES3-176 DVI line mass flow

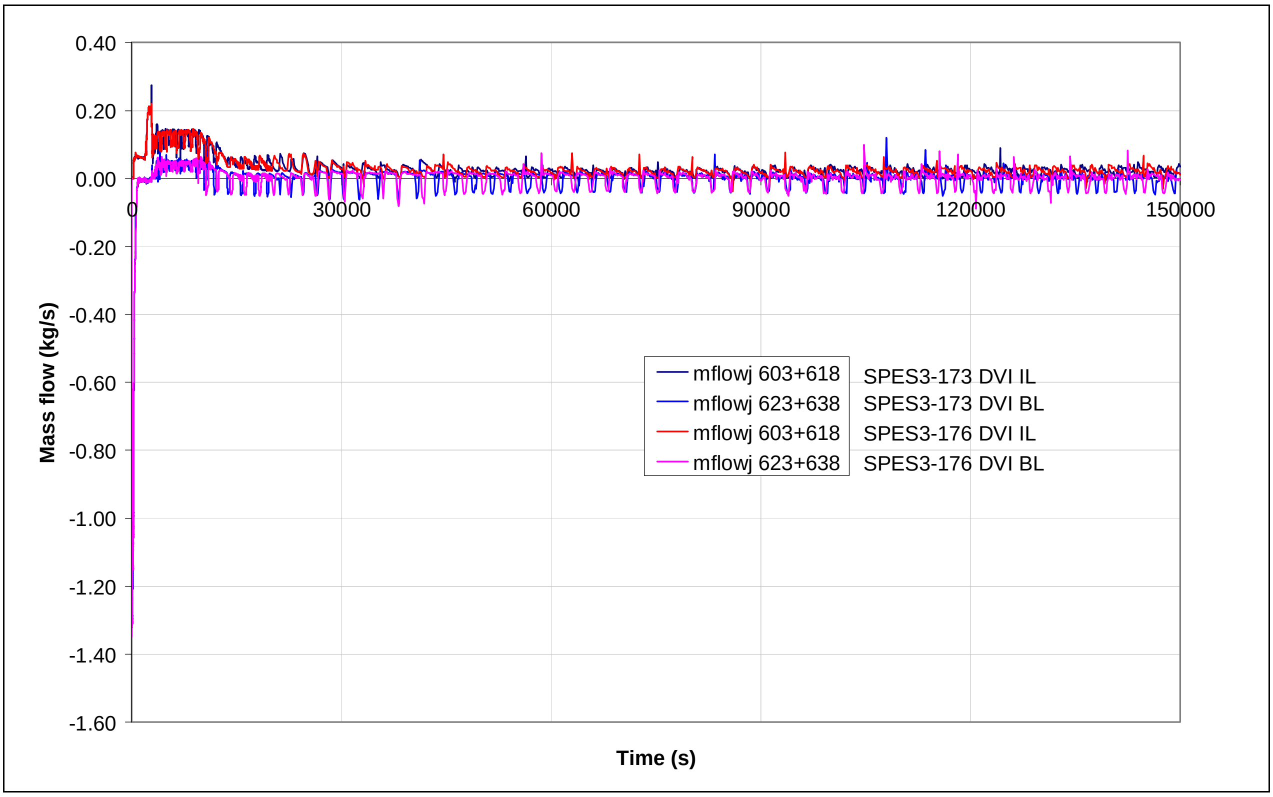


Fig.8. 69 – SPES3-173 and SPES3-176 Core inlet and outlet temperatures (window)

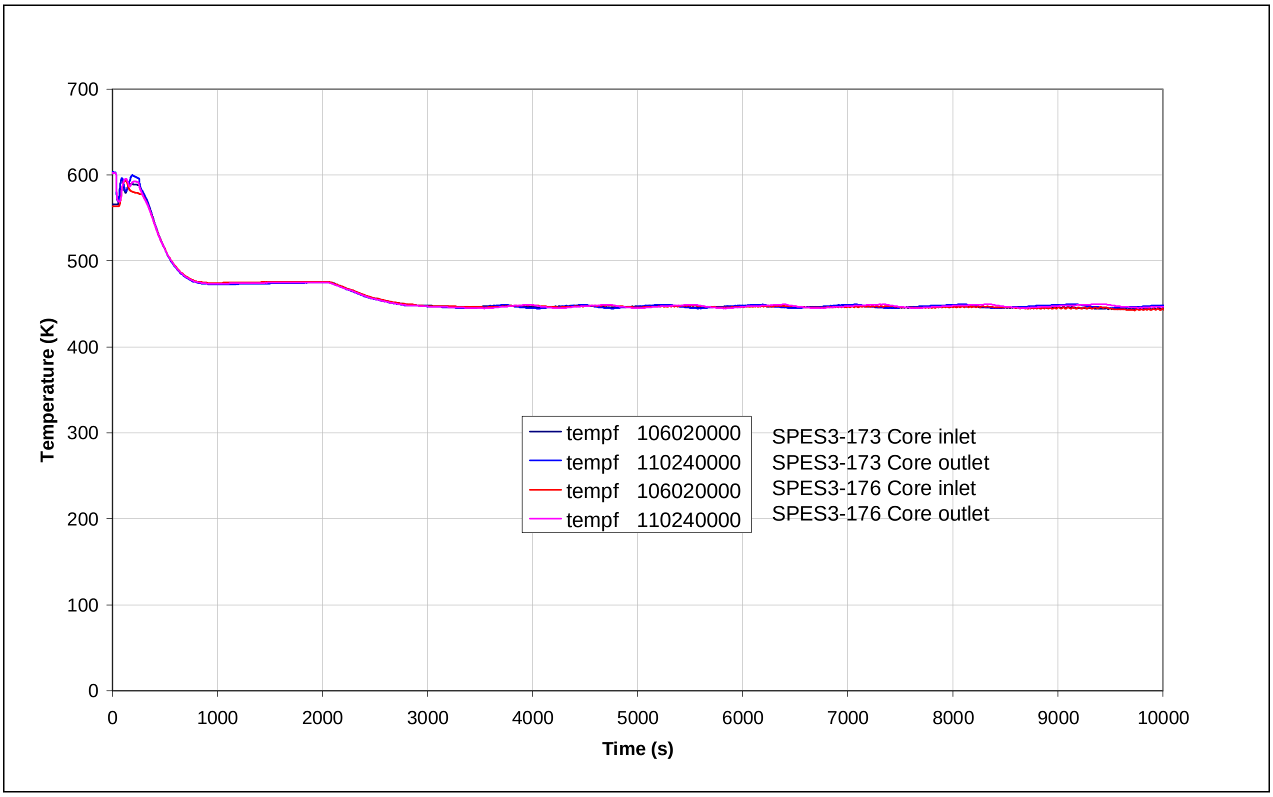


Fig.8. 70 – SPES3-173 and SPES3-176 Core inlet and outlet temperatures

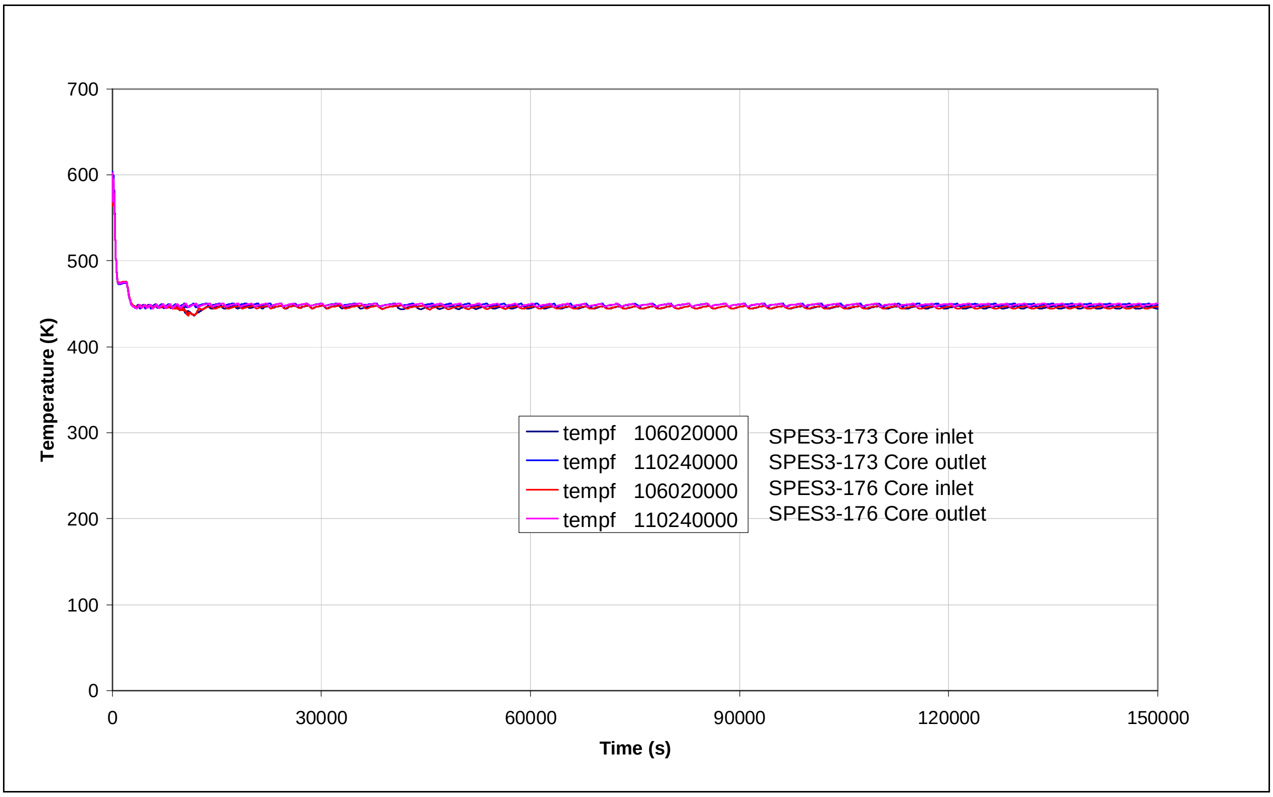


Fig.8. 71 – SPES3-173 and SPES3-176 Core heater rod clad surface temperatures (normal rods) (window)

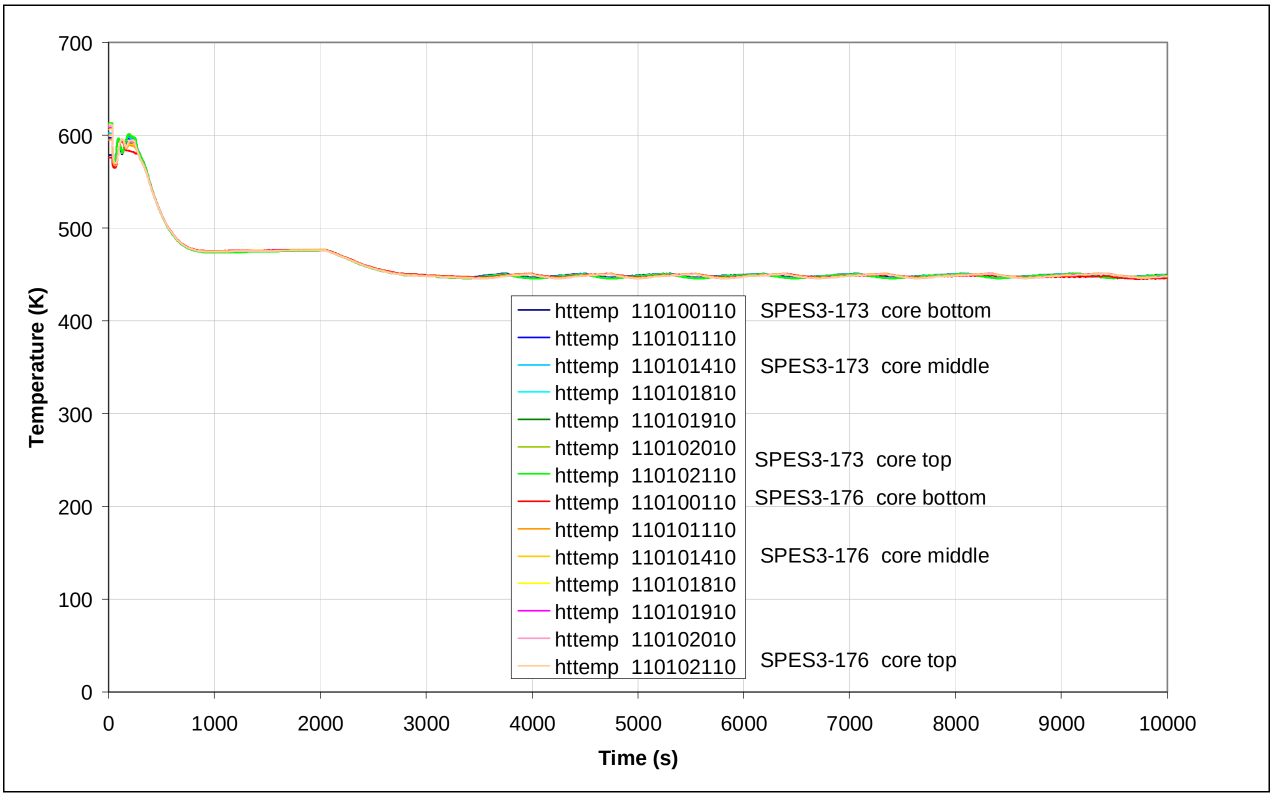


Fig.8. 72 – SPES3-173 and SPES3-176 Core heater rod clad surface temperatures (normal rods)

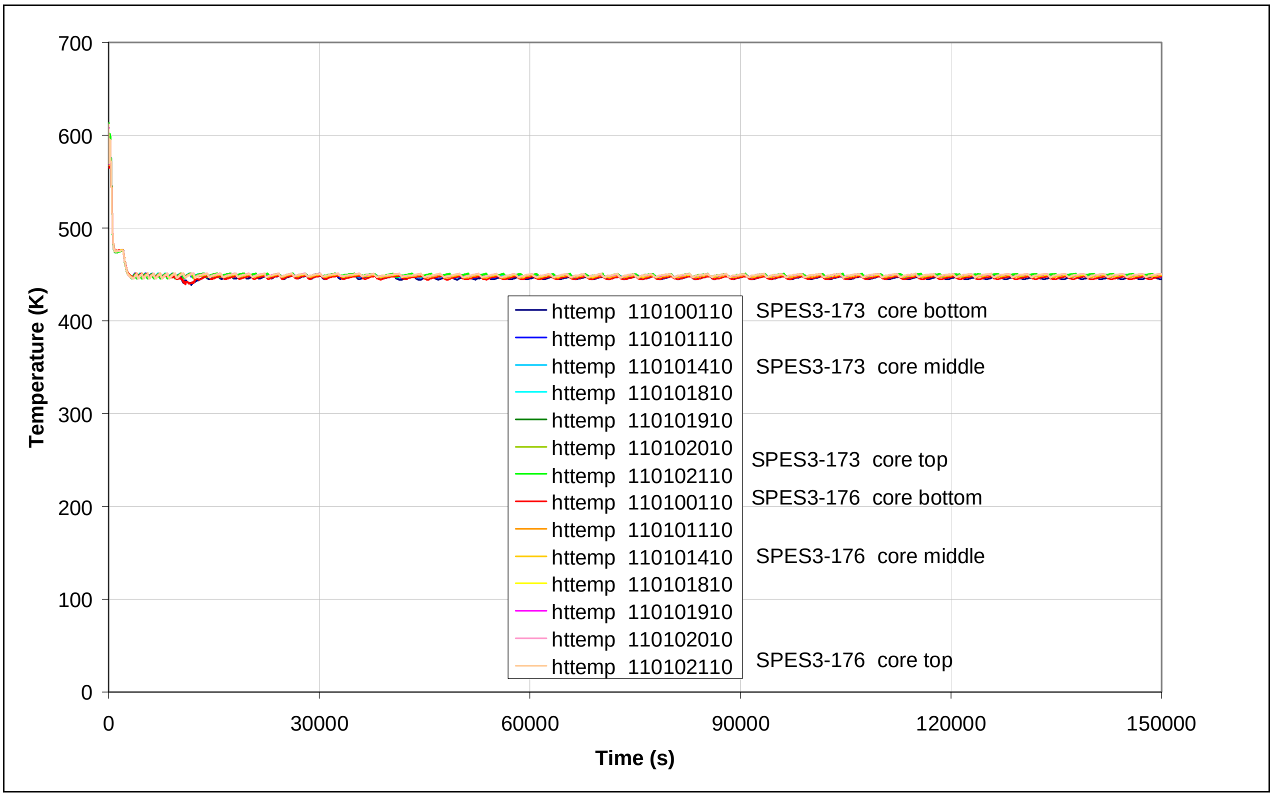


Fig.8. 73 – SPES3-173 and SPES3-176 Core heater rod clad surface temperatures (hot rods) (window)

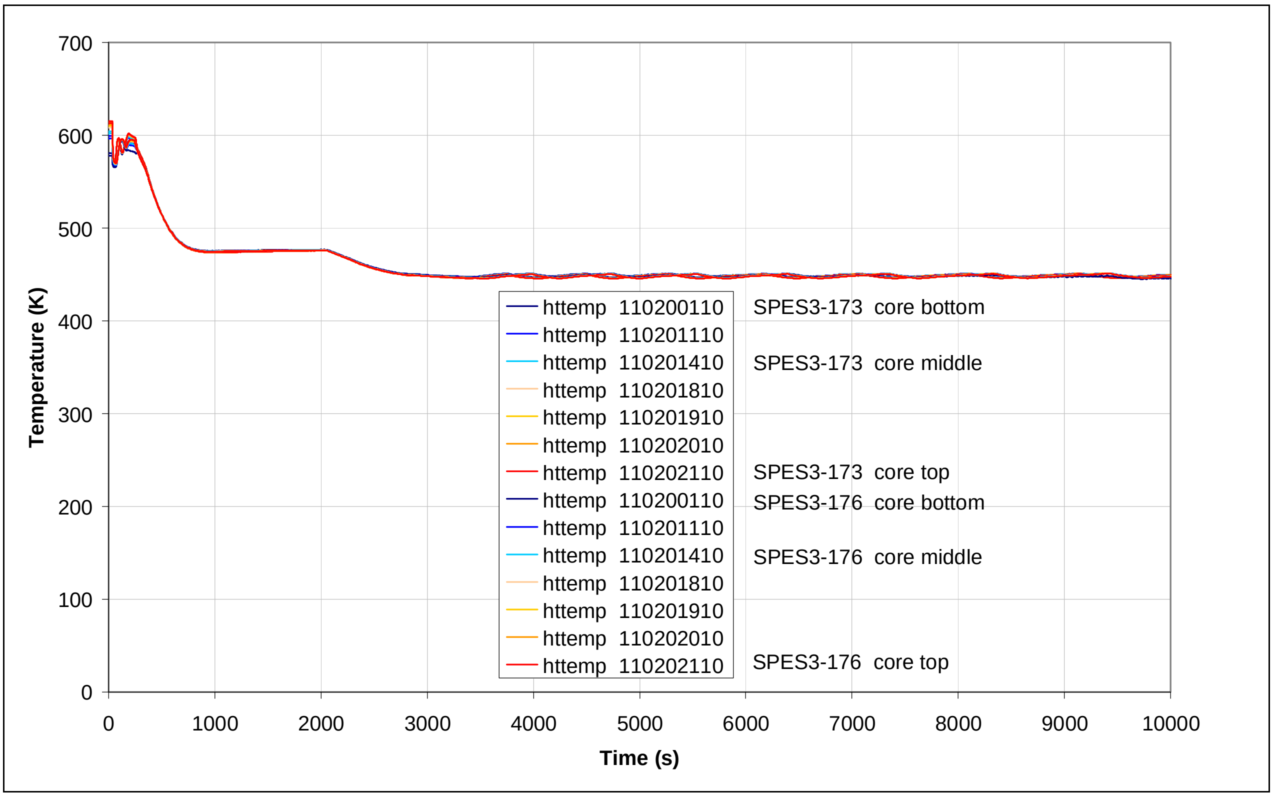


Fig.8. 74 – SPES3-173 and SPES3-176 Core heater rod clad surface temperatures (hot rods)

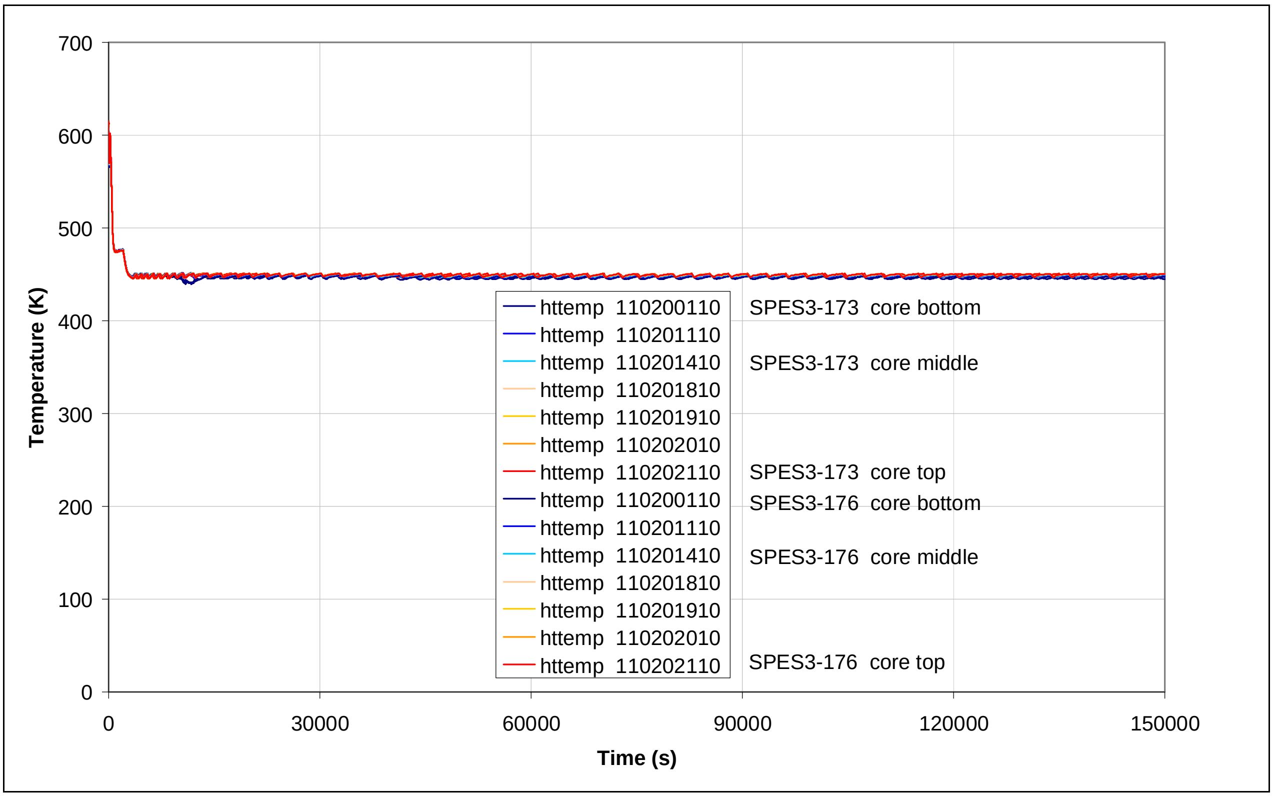


Fig.8. 75 – SPES3-173 and SPES3-176 PCC mass flow

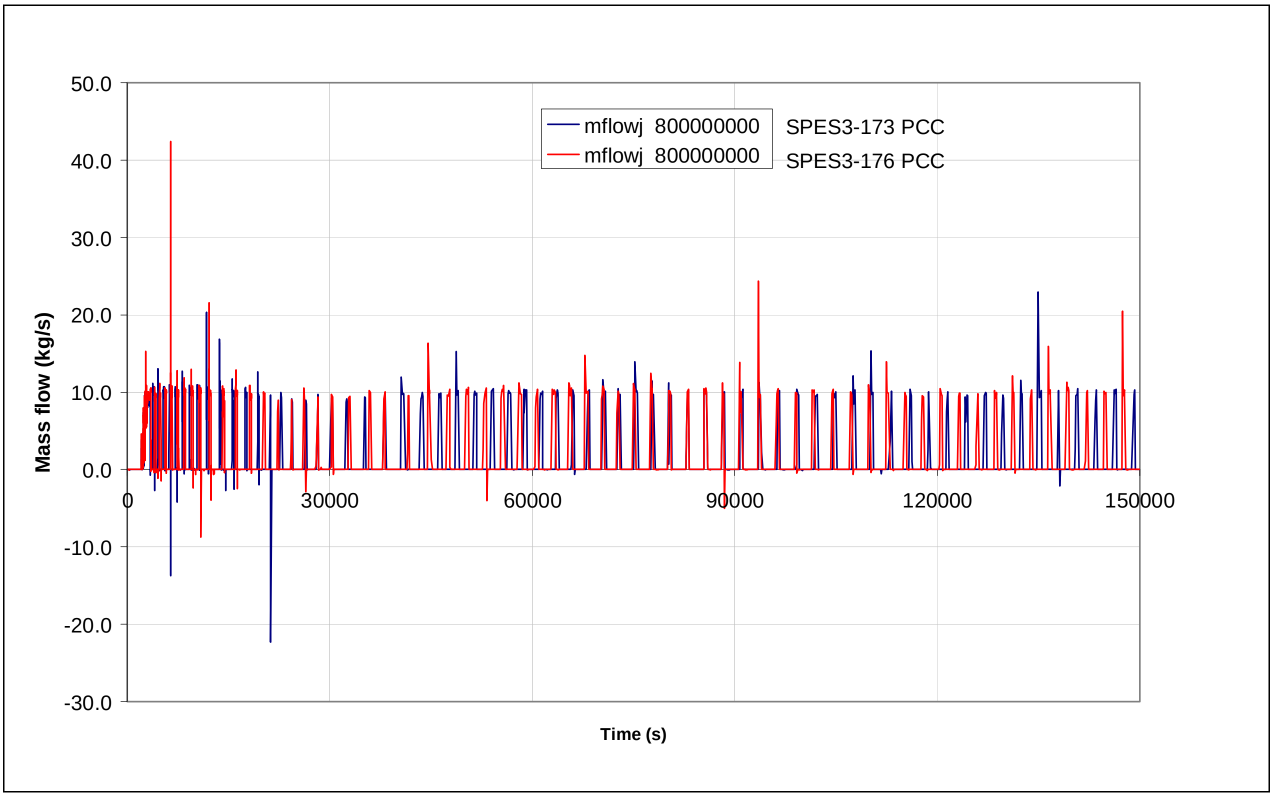


Fig.8. 76 – SPES3-173 and SPES3-176 PCC tank level

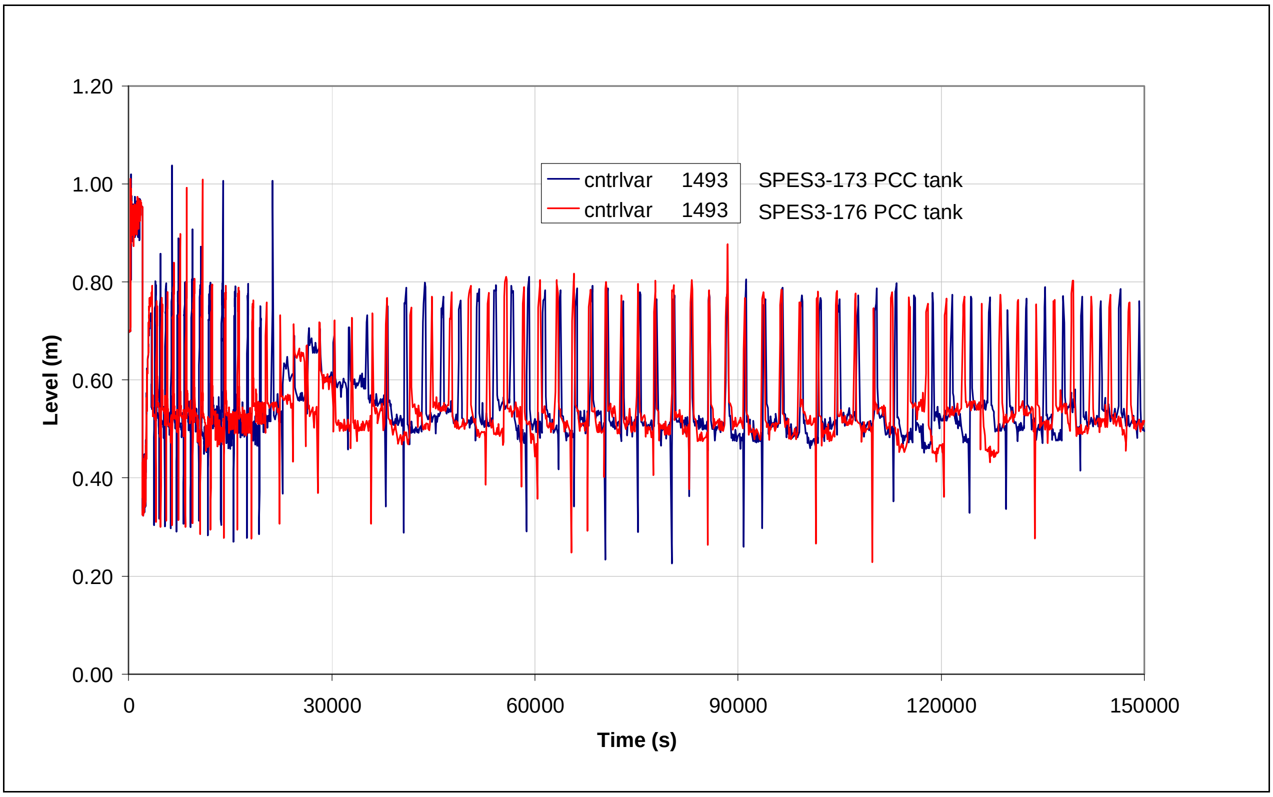


Fig.8. 77 – SPES3-173 and SPES3-176 PCC inlet and outlet temperature

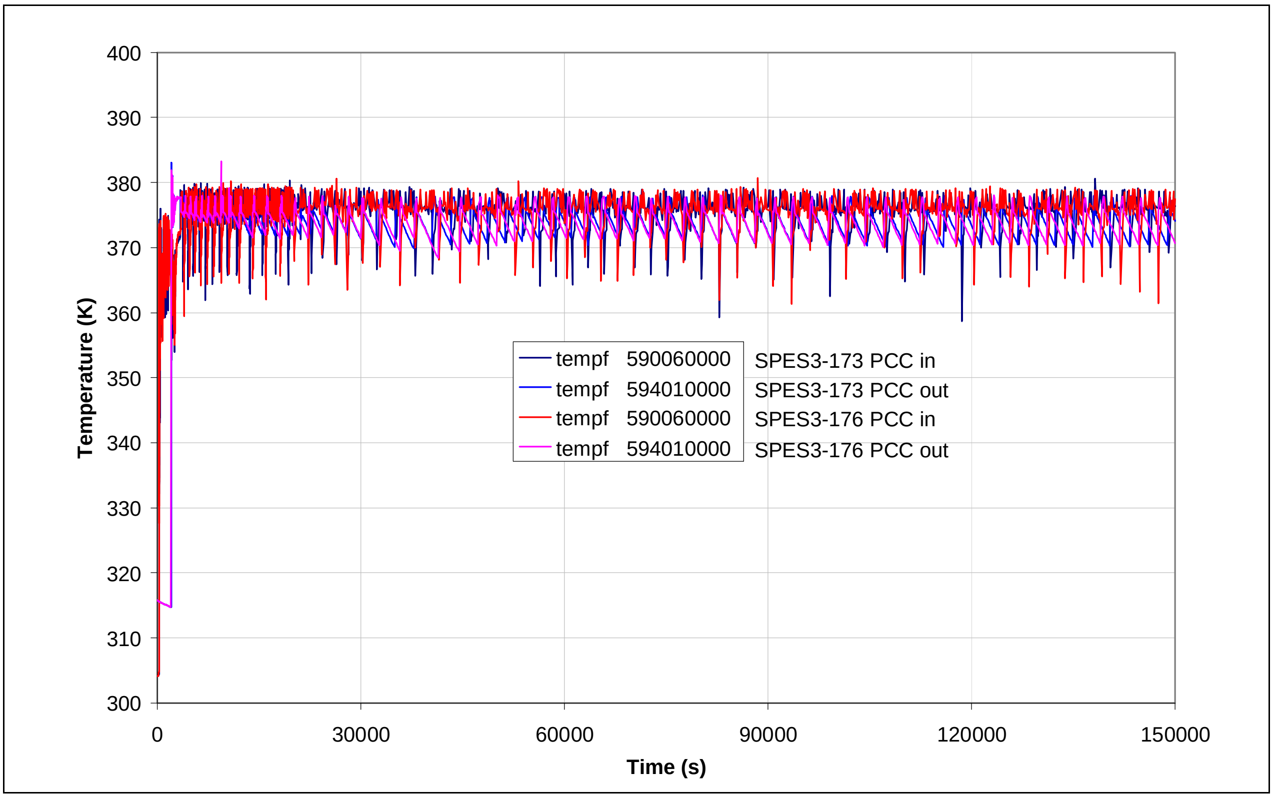


Fig.8. 78 – SPES3-173 and SPES3-176 PCC liquid void fraction (window)

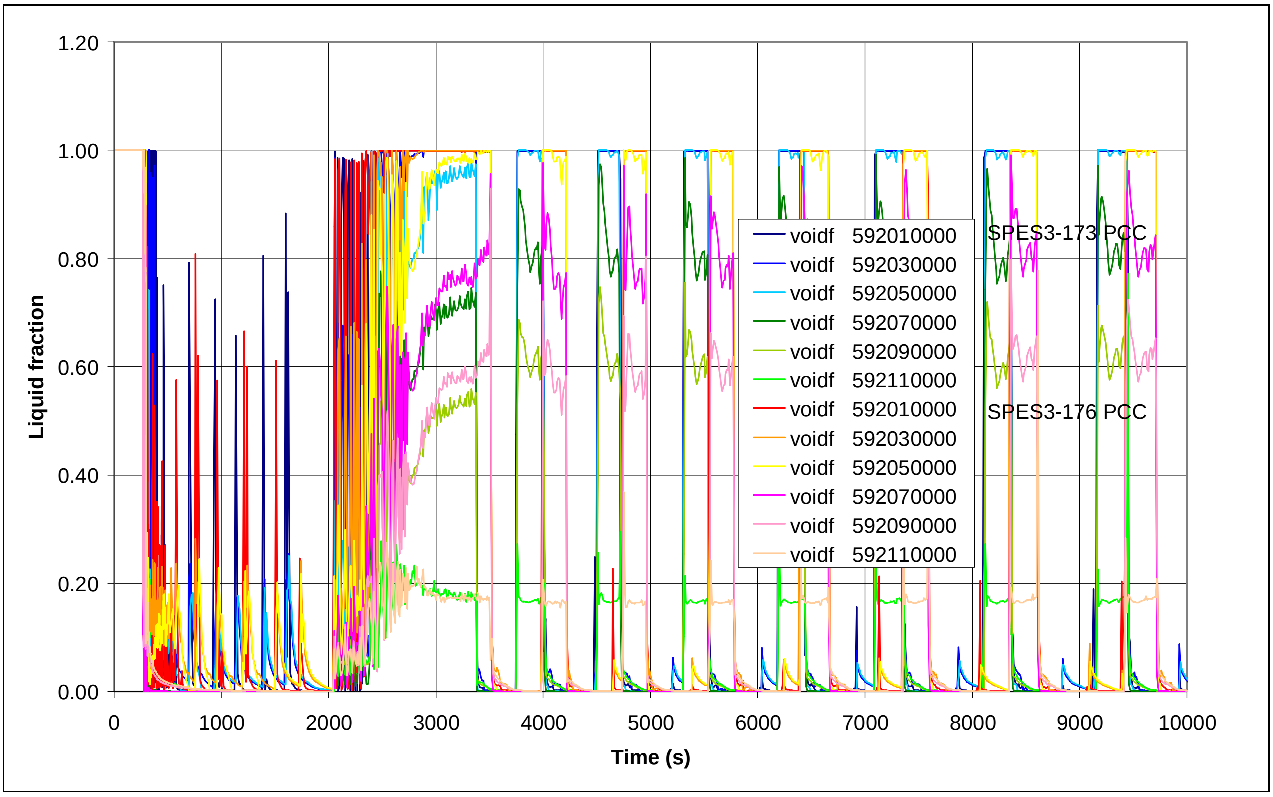


Fig.8. 79 – SPES3-173 and SPES3-176 PCC liquid void fraction

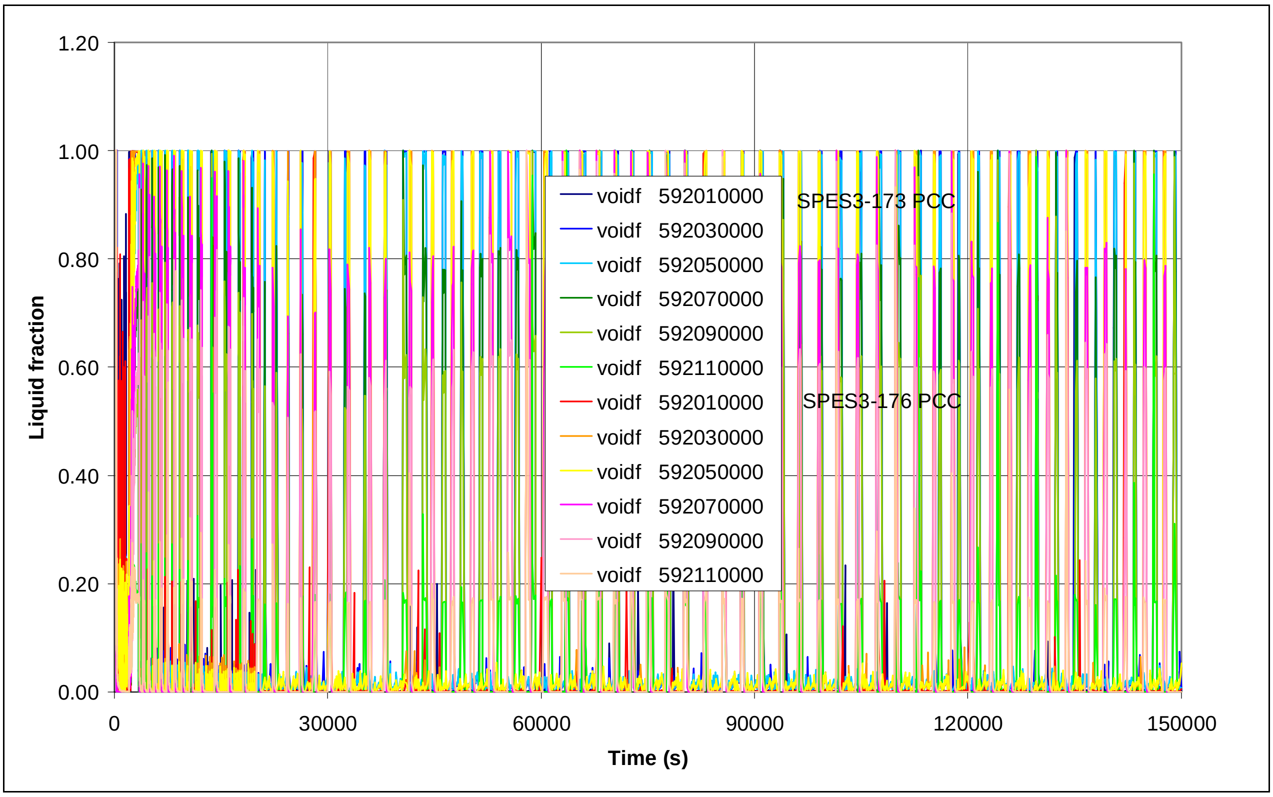


Fig.8. 80 – SPES3-173 and SPES3-176 LGMS level

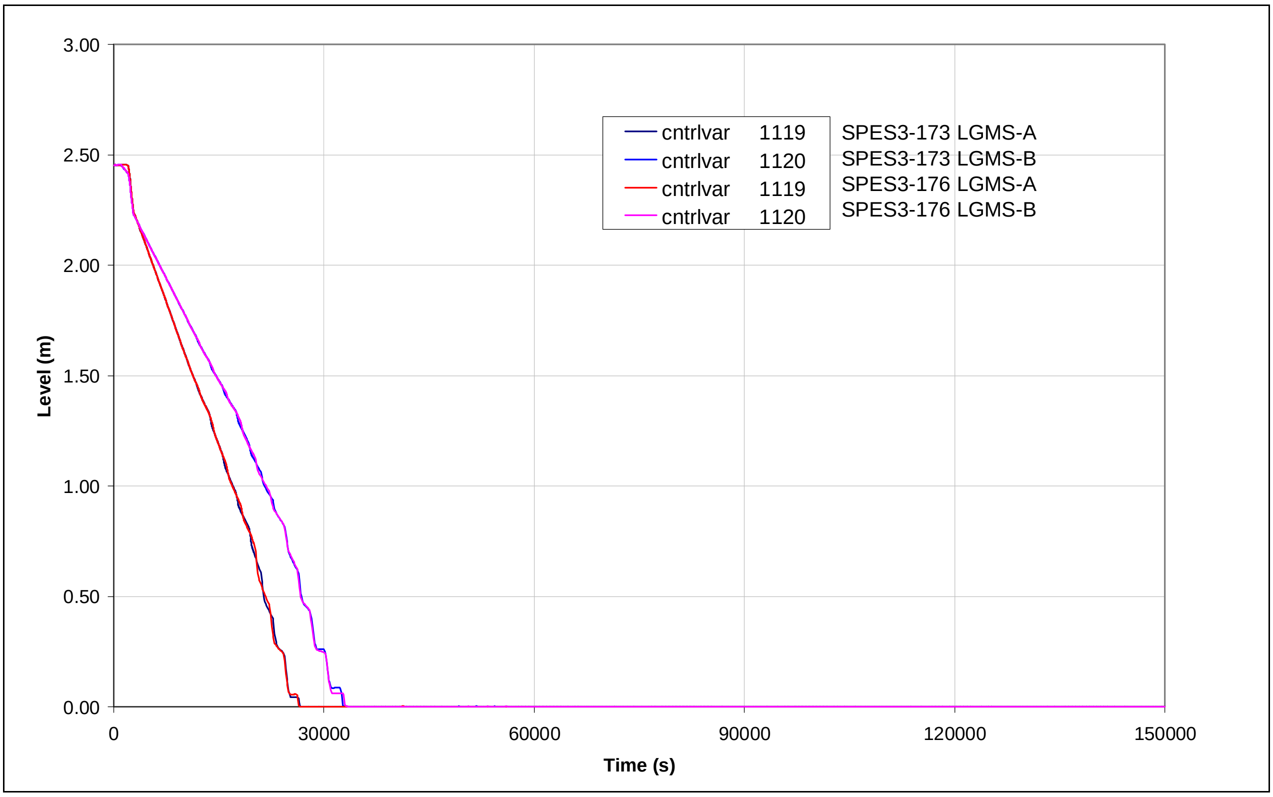


Fig.8. 81 – SPES3-173 and SPES3-176 LGMS mass

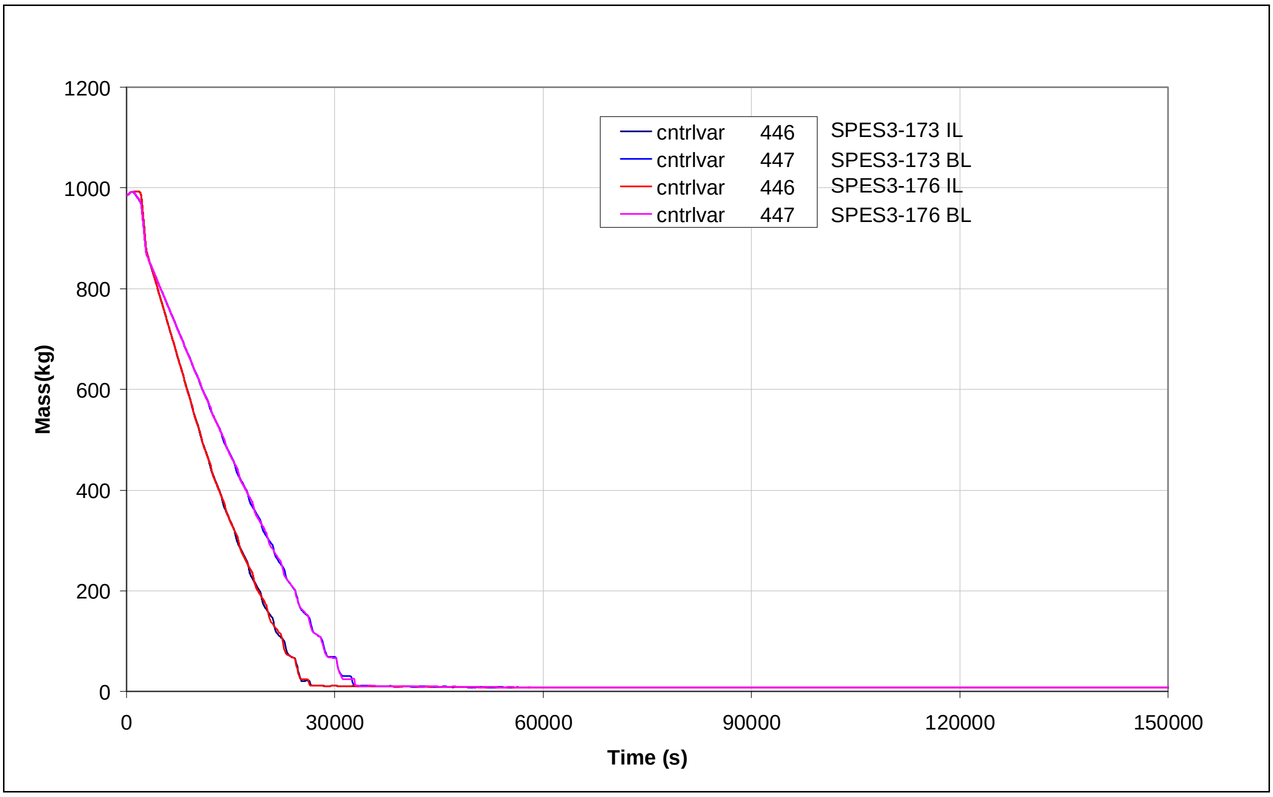


Fig.8. 82 – SPES3-173 and SPES3-176 LGMS and DVI pressure (window)

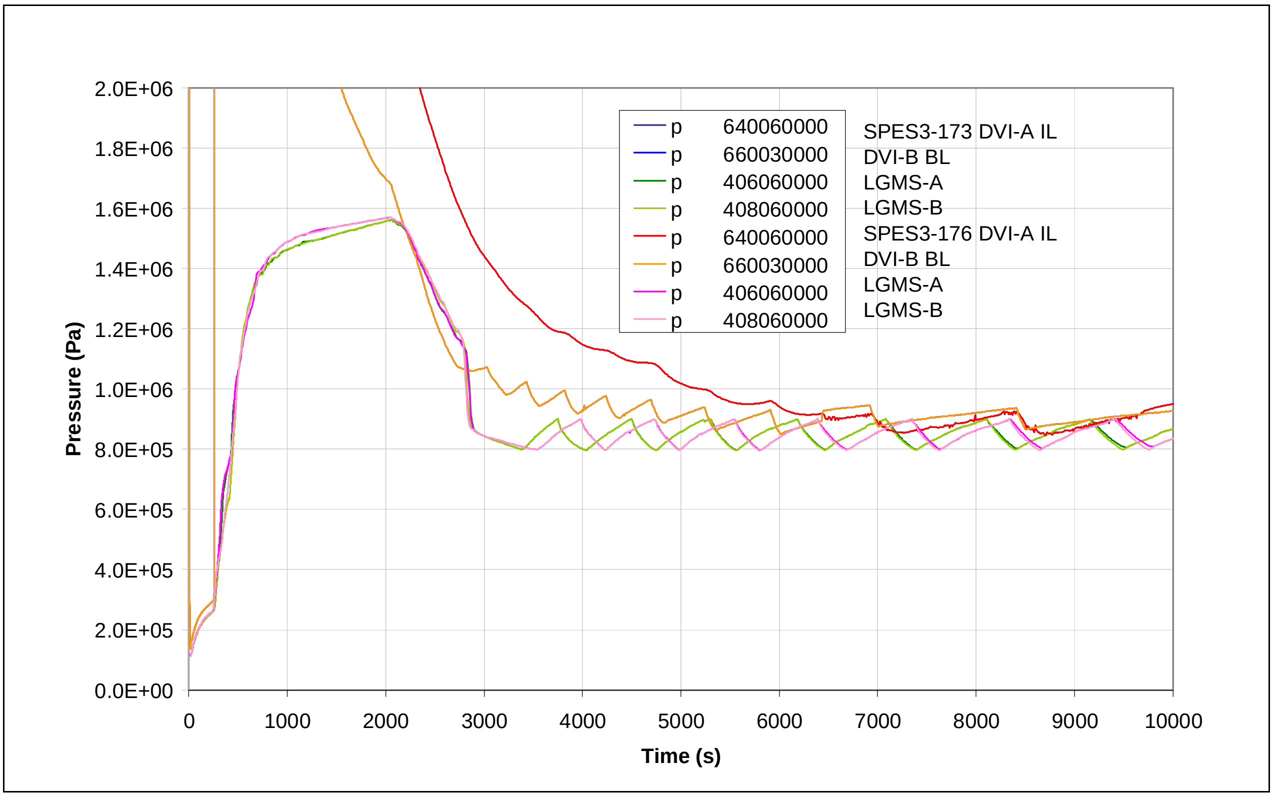
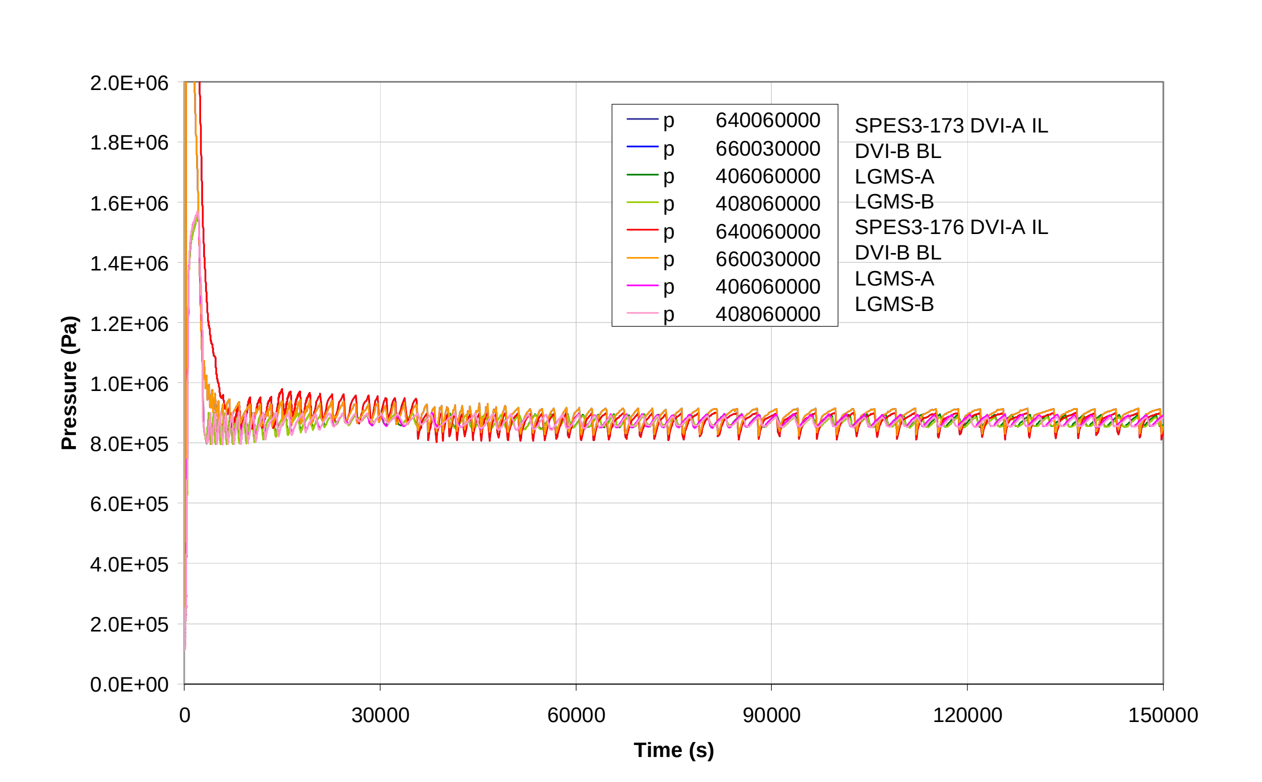


Fig.8. 83 – SPES3-173 and SPES3-176 LGMS and DVI pressure (window)



9. CONCLUSIONS

This document reports the results of the RELAP5 simulation of Design and Beyond Design Basis Events foreseen in the test matrix [1]. The DVI line DEG break is the analyzed transient, starting from 100% and 65% power with (DBE) and without (BDBE) EHRS availability.

A configuration of the facility, in terms of geometry and boundary conditions, was found suitable to simulate the postulated transients starting from 100% power and reduced power conditions.

Sensitivity analyses on PCC and ADS Stage-II intervention allowed to optimize the safety signal actuation sequence to cope with the most challenging transient of DVI line DEG break with all EHRS failure.

The comparison between full and reduced power transients, both for the DBE and BDBE DVI DEG break, showed a great similarity of results and finally led to affirm SPES3 reduced power simulations are fully representative of those at full power.

The present SPES3 nodalization for RELAP5 code will be the starting point for further simulations of transients included in the test matrix.

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11. ATTACHMENTS

The RELAP5 input deck files and results are provided for all cases described in this document.
The list of files and details are reported in Tab.11. 1.

Tab.11. 1 – Files attached to document

Case	File	Notes
SPES3-160	spes3-157_3.i	Steady state input-deck (10000 s)
	restart-160.i	Restart of spes3-157_3 since 10000 s
	spes3-160a.xls spes3-160a_1.xls spes3-160c.xls spes3-160c.xls spes3-160d.xls spes3-160e.xls spes3-160f.xls spes3-160g.xls spes3-160i.xls spes3-160l.xls	Results
SPES3-159	restart-159.i	Restart of spes3-157_3 since 10000 s
	spes3-159a.xls spes3-159a_1.xls spes3-159c.xls spes3-159c.xls spes3-159d.xls spes3-159e.xls spes3-159f.xls spes3-159g.xls spes3-159i.xls spes3-159l.xls	Results
SPES3-162	restart-162.i	Restart of spes3-157_3 since 10000 s
	spes3-162a.xls spes3-162a_1.xls spes3-162c.xls spes3-162c.xls spes3-162d.xls spes3-162e.xls spes3-162f.xls spes3-162g.xls spes3-162i.xls spes3-162l.xls	Results
SPES3-158	restart-158.i restart-158_2.i	Restart of spes3-157_3 since 10000 s Restart of restart-158 since 50000 s
	spes3-158a.xls spes3-158a_1.xls spes3-158c.xls spes3-158c.xls spes3-158d.xls spes3-158e.xls spes3-158f.xls spes3-158g.xls spes3-158i.xls spes3-158l.xls	Results

Case	File	Notes
SPES3-163	restart-163.i restart-163_2.i	Restart of spes3-157_3 since 10000 s Restart of restart-163 since 14100 s
	spes3-163a.xls spes3-163a_1.xls spes3-163c.xls spes3-163c.xls spes3-163d.xls spes3-163e.xls spes3-163f.xls spes3-163g.xls spes3-163i.xls spes3-163l.xls	Results
SPES3-164	restart-164.i	Restart of spes3-157_3 since 10000 s
	spes3-164a.xls spes3-164a_1.xls spes3-164c.xls spes3-164c.xls spes3-164d.xls spes3-164e.xls spes3-164f.xls spes3-164g.xls spes3-164i.xls spes3-164l.xls	Results
SPES3-165	restart-165.i	Restart of spes3-157_3 since 10000 s
	spes3-165a.xls spes3-165a_1.xls spes3-165c.xls spes3-165c.xls spes3-165d.xls spes3-165e.xls spes3-165f.xls spes3-165g.xls spes3-165i.xls spes3-165l.xls	Results
SPES3-166	restart-166.i	Restart of spes3-157_3 since 10000 s
	spes3-166a.xls spes3-166a_1.xls spes3-166c.xls spes3-166c.xls spes3-166d.xls spes3-166e.xls spes3-166f.xls spes3-166g.xls spes3-166i.xls spes3-166l.xls	Results

Case	File	Notes
SPES3-167	spes3-167.i	Steady state input-deck (10000 s) 100% power
SPES3-169	spes3-169.i	Steady state input-deck (10000 s) 65% power
SPES3-172	restart-172.i	Restart of spes3-167 since 10000 s
	spes3-172a.xls spes3-172a_1.xls spes3-172c.xls spes3-172c.xls spes3-172d.xls spes3-172e.xls spes3-172f.xls spes3-172g.xls spes3-172i.xls spes3-172l.xls	Results
SPES3-175	restart-172.i	Restart of spes3-169 since 10000 s
	spes3-175a.xls spes3-175a_1.xls spes3-175c.xls spes3-175c.xls spes3-175d.xls spes3-175e.xls spes3-175f.xls spes3-175g.xls spes3-175i.xls spes3-175l.xls	Results
SPES3-173	restart-173.i	Restart of spes3-167 since 10000 s
	spes3-173a.xls spes3-173a_1.xls spes3-173c.xls spes3-173c.xls spes3-173d.xls spes3-173e.xls spes3-173f.xls spes3-173g.xls spes3-173i.xls spes3-173l.xls	Results
SPES3-176	restart-176.i	Restart of spes3-169 since 10000 s
	spes3-176a.xls spes3-176a_1.xls spes3-176c.xls spes3-176c.xls spes3-176d.xls spes3-176e.xls spes3-176f.xls spes3-176g.xls spes3-176i.xls spes3-176l.xls	Results