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Lead-Bismuth Eutectic Cooled Experimental Accelerator Driven System: Windowless Target Unit Thermal-hydraulic Analysis

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ABSTRACT

A main concern related to the peaceful use of nuclear energy is the safe management of nuclear wastes, with particular attention to long-lived fission products. An increasing attention has recently been addressed to transmutation systems (Accelerator Driven System: ADS) able to "burn" the actinides and some of the long-lived fission products (High-Level Waste: HLW), transforming them in short or medium-lived wastes that may be easier managed and stored in the geological disposal, with the consequent easier acceptability by population. An ADS consists of a subcritical-core coupled with an accelerator by means of a target.

This paper deals with the thermal-hydraulic analysis, performed with STAR-CD and RELAP5 codes for the windowless target unit of Lead-Bismuth Eutectic (LBE) cooled experimental ADS (XADS), both to assess its behaviour during operational and accident sequences and to provide input data for the thermal-mechanical analyses. It also reports a description of modifications properly implemented in the codes used for the assessment of this kind of plants.

1 INTRODUCTION

The closure of the nuclear fuel cycle and, more generally, the disposal of the radioactive waste resulting from the industrial nuclear energy production (and from the nuclear weapons dismantling) represents a problem not yet fully solved, especially in terms of environmental and social acceptability.

The Deep Geological Repository, in which to store all the produced HLW, is considered at present as the most suitable technological solution to get rid of problems related to the fuel cycle closure. Nevertheless such solution, even if technically sustainable, still represents a hardly acceptable heritage for the next generations, apart from any economical issue. For this reason, since the end of the 1980's, research on transmutation of transuranics (TRU's) and selected long-lived fission products (LLFP's) using an ADS has increased all over the world, being a promising solution for reducing the long-term radio-toxicity and the amount of long-lived radionuclides to be disposed that is a fundamental requirement for Sustainable Development [1].

An ADS consists of a subcritical-core reactor coupled to an accelerator by means of a target unit. The subcritical core is not able to sustain by itself the neutron chain reaction, but it needs an external neutron source that is produced by the interaction of the ion-beam coming from the accelerator with a heavy metal target located inside the subcritical core, via spallation reactions. The target unit is the functional and physical interface between the accelerator and the sub-critical system. Its function is to supply an external neutrons source to the ADS sub-critical core. Subcritical systems do not rely on delayed neutrons for control or power change; they are only driven by spallation neutrons produced by the accelerator ion beam. Control rods and reactivity feedback have very little or no importance: sub-critical systems are decoupled from the external neutron source [1].

The development of Nuclear Energy has followed different patterns in different countries, mainly in relation to the cycle closure. Although reprocessing facilities have been in successful operation for many years, not all the countries have decided to recycle the spent nuclear fuel. Several countries still have the so-called once-through cycle, where the spent fuel is safely stored but not treated in any way. Moreover, current fuel recycling is done in LWR reactors, which are not well suited to take advantage of the energy content of the spent fuel. Breeder reactors would be the right choice for it, but they are not an actual option for the moment. However, they could be considered in a futuristic scenario of full deployment of Nuclear Energy, and ADS could be an additional tool in this scenario to help minimizing the long-term radio-toxicity of the waste. Of course practicability of transmutation at industrial scale requires to be demonstrated by an experimental ADS (XADS).

A great amount of R&D and engineering activities have been and are being performed in Europe to demonstrate separate basic aspects of the ADS concept and to define conceptual plant reference configurations. Several different technological and design options have been considered and studied. Taking into account that fast neutron spectrum is the optimised solution for transmutation purpose, the R&D efforts were focused on liquid metal-cooled ADS and gas-cooled ADS. The preliminary design studies developed in different European Union member countries, were concentrated mainly on three concepts for the nuclear reactor part: a LBE-cooled concept and a gas-cooled concept of approximately 80 MW thermal, and a small LBE-cooled concept (~30 MW thermal) [1, 2].

In this context, the European Community is promoting in the framework of the PDS-XADS project studies on the feasibility of experimental demonstration sub-critical plants (XADS) that use different coolants (gas or Lead-Bismuth Eutectic alloy: LBE) for the primary system [2]. Three options are investigated for the target unit: a window target for the gas-cooled XADS and both a window and a windowless target for a LBE-cooled XADS. The latter is the reference solution chosen for this plant. In the windowless target the proton beam impinges directly on the redirected LBE flow in the lower part of the beam tube at core centre (spallation zone). Cooling is achieved by forced circulation inside the target unit.

In the LBE-cooled XADS concept not only the reactor core is cooled by LBE, but also the target unit. Two flows of LBE are kept separated to limit the pollution of the primary system by spallation products produced in the target unit [3].

This document deals with the thermal hydraulic results of the calculations performed with STAR-CD and RELAP5 for studying the behaviour of the windowless target unit during normal condition (steady state) and some off-normal operating conditions (beam trips). It also reports a description of modifications properly implemented in the codes used for the assessment of this kind of plants.

2 GENERAL LAY-OUT OF SPALLATION ZONE

The target unit has a vertical orientation and penetrates the reactor vessel cover plate and the core from the top by a non-axial central channel [3].

LBE is used in the target unit both as target and as a mean to transfer the heat deposited by the impinging proton beam to the heat sink placed about 1 m beneath the core region. Because of the basic conception of the windowless target, natural circulation is inherently hindered, being the cold source at lower position with respect to the hot one. Therefore, a continuous flow of LBE from the free surface towards the heat exchanger can only rely on forced circulation assured by two mechanical propeller pumps, which thrust it upwards into the spallation zone, where it is heated up in the transversal duct, and then downwards through the heat exchanger located under the fuel core.

The proton beam footprint is shaped very thin in the flow direction, about 1 cm thickness, and a little smaller than the channel width in the other direction (8 cm).

A sketch of the geometry is given in Figure 1 and Table 1 summarizes the main process parameters.

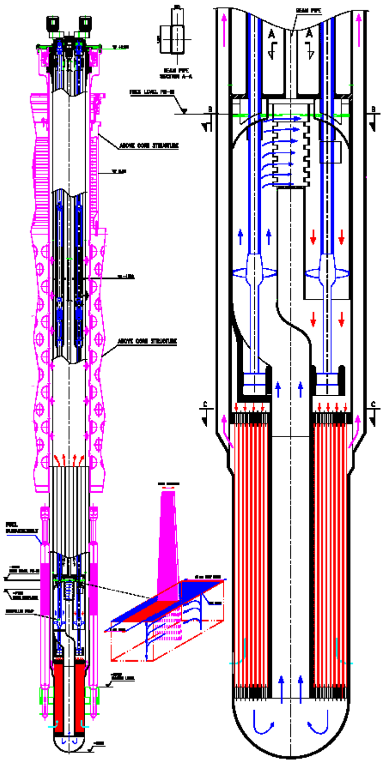

Figure 1: Target unit sketch

Table 1: Main process parameters

Power of sub critical core	P = 80 MW_{th}
Max. proton energy	E = 600 MeV
Max. proton beam intensity	I = 6mA
Max. target power/beam power	P = 2.6 / 3.6 MW_{th}
Current density profile of the beam spot	Bivariate Gaussian (TBD)
LBE Temperature Target inlet Target outlet Secondary inlet Secondary outlet	 335 °C ≈ 440 °C 300 °C 380 °C
Target LBE velocity Flow average Maximum at the flow surface	 0.5 m/s ≤ 2,0 m/s

3 THERMAL-YDRAULIC ANALYSIS IN NORMAL AND OFF-NORMAL CONDITIONS

This analysis was oriented to assess the behaviour of the target unit and to provide a set of boundary conditions for allowing 3-D calculations for the spallation zone during Design Basis Conditions (DBCs) and Design Extension Conditions (DECs) in order to define enveloping conditions to be used for the thermo-mechanical verifications.

The list of the analysed off-normal conditions is shown in Table 2, but only the results of the first off-normal condition are described in the paper.

Table 2: List of off-normal conditions

Event Description	Event classification
Beam trips of different length	DBC category II
1 (out of 2) target propeller pump trip	DBC category II
1 (out of 2) target propeller pump trip without Proton beam shut-off	DEC
1 target propeller pump trip without Proton beam shut-off followed by the second pump trip	DEC and Residual risk situations

3.1 Target unit thermal-hydraulic models

Two codes were used for studying the behaviour of the windowless target unit during normal and off-normal operating conditions: STAR-CD and RELAP5.

STARC-CD code [4] was used to study the stability and the thermal-hydraulics of LBE flow in the transversal duct at the spallation zone and to simulate the thermal behaviour of the target above the two propeller pumps. The model includes the pump shafts, the duct walls and the horizontal plate placed in the downcomer channel at an elevation higher than the propeller pump outlet, which allows a little fluid recirculation in the upper part to limit temperature difference between inside and outside the spallation zone. It has 384000 fluid cells and 181000 solid cells and it is parametrized so that the mesh density and the position of the characteristic points can be easily modified.

RELAP5 mod3.2 beta version [5] was used for assessing the thermal-hydraulic behaviour of the target unit and the sub-critical system during the DBCs and some DECs considered critical for this plant. As some results of these calculations were needed for STAR-CD simulations, the dimensions of volumes of the spallation zones and the rising and descending channels were chosen in order to reduce as much as possible the errors related to the transfer of the data from RELAP5 model to STAR-CD one.

Figure 2 shows the RELAP5 nodalization of the XADS primary circuit and target unit. From the thermal-hydraulic point of view the Target is simulated with two main flow paths:

- the Target circuit, which circulates the LBE through the spallation zone and drives it to a straight pipe Heat Exchanger for power rejection to the primary system. It mainly consists of a rising channel (202, 205, 206, 207, 216) with a propeller pump (204), the spallation zone (208, 209, 210), a descending channel (218, 213, 212, 217, 222-02 to 03) with a further propeller pump (214), a heat exchanger (222-04 to 08) and a downcomer (220-01 to 03, 222-01);
- the Cooling channel that circulates the primary LBE outside the heat exchanger pipes from the reactor lower plenum up to the quasi-stagnant region above the core. It consists of a rising channel (226) that drives the LBE from the lower plenum (vol. 100) through the HX pipes shroud, through the fuel elements bypass around the core, up to enter the primary side into the quasi stagnant volume above the core (dead volume 170).

The primary system is simulated with two main flow paths: the above-mentioned cooling channel and main coolant circulation path, which consists of: a) lower plenum (node 100), core (node 110), upper plenum (node 120), risers (node 144), downcomer uppermost region (nodes 172 and 162), IHXs region (nodes 181 or 182), downcomer lowermost region (node 102), lower plenum (node 100), core bypass via the dummy assemblies (node 106) and the region encompassed between the dummy assemblies and the inner vessel (node 104); the upper and lower downcomer (physical region outside the IHXs heat transfer area; nodes 152, 142, 132, 122 and 112); b) the quasi stagnant region above the core (node 170); c) the two risers necessary to allow a small LBE circulation filling the region above the core (nodes 148 and 146).

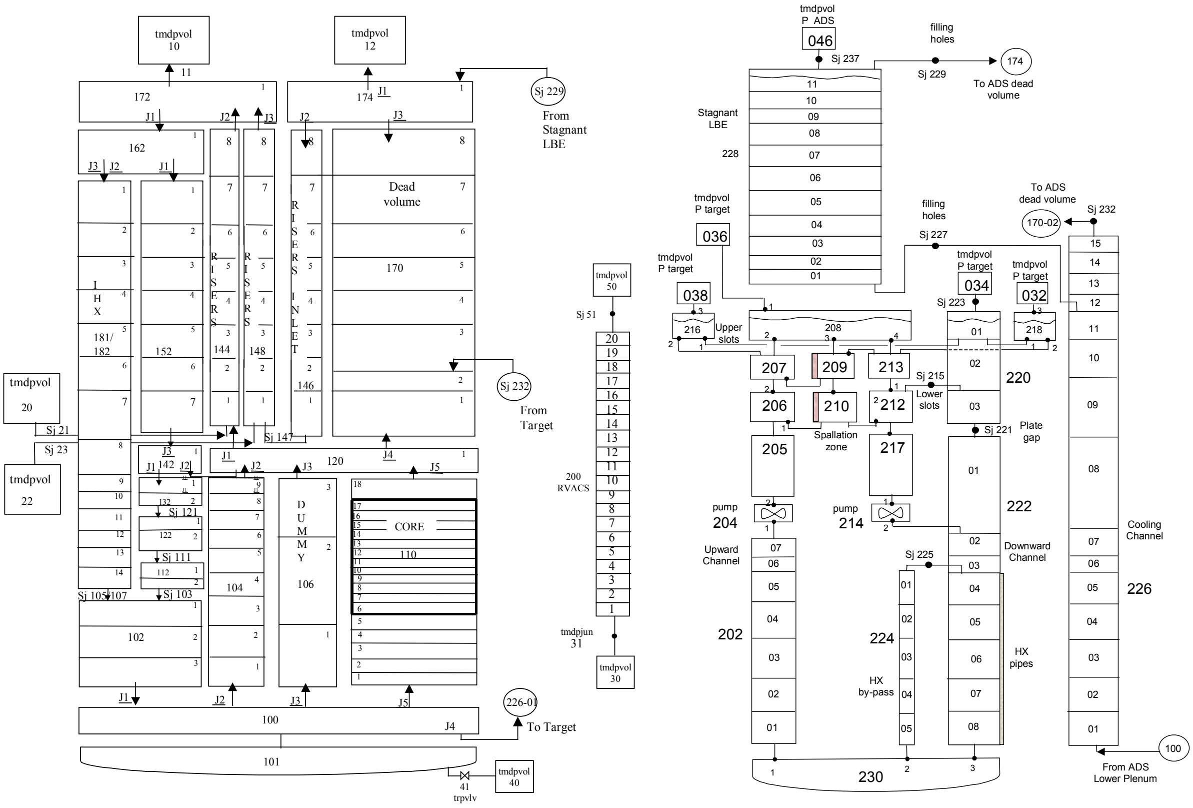

Figure 2: Primary System (left) and Target unit (right) nodalizations

Relevant modifications have been made in the code to use LBE as working fluid: development and implementation of thermodynamic properties (enthalpy, etc.) and other physical properties (thermal conductivity, surface tension and viscosity); implementation of heat transfer correlations and development of the finned tube heat exchanger model.

3.2 Steady state analysis

The main results of the STAR-CD simulation are summarized in Table 3. The needed boundary conditions were provided by RELAP5 1D calculations for the state at full power, such as mass flow rate, inlet temperature in the spallation zone, bulk temperature of LBE under and over the downcomer plate at different elevations.

Table 3: Steady state results

Quantity	Value	
Maximum bulk temperature	492.7	C
Maximum fluid surface temperature	450.8	C
Maximum duct wall temperature	427.0	C
Maximum shaft temperature	490.0	C
Spallation zone mean pressure drop	6100	Pa

Figure 3 deals with the trace of beam deposition, whereas the temperature profile on the fluid is reported in Figure 4. It may be noted that the recirculation zone at the bottom of the channel produces a local maximum of the temperature. The velocity magnitude on the symmetry plane is shown in Figure 5.

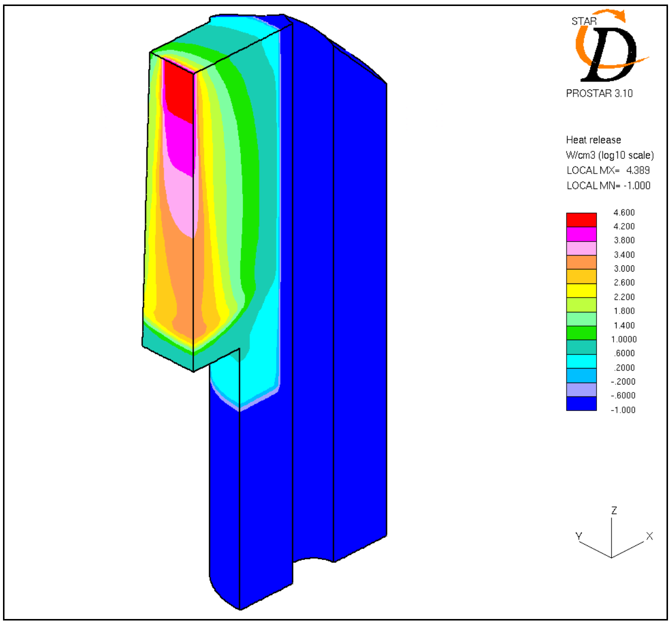

Figure 3: Beam energy distribution (in log scale)

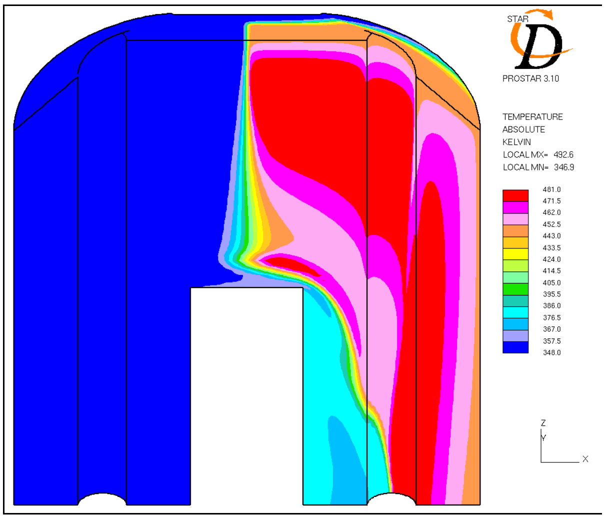

Figure 4: Temperature field of the fluid

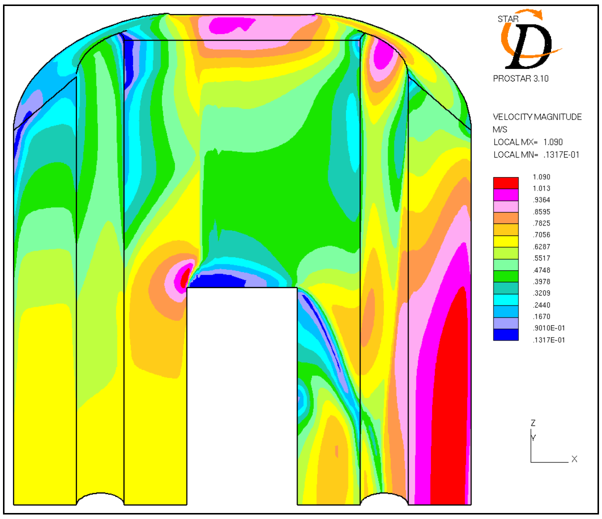

Figure 5: Velocity magnitude

A sensitivity analysis was performed for a simplified geometry without and with a vertical flow diverter to demonstrate the need of flow diverter for shaping and stabilizing the flow in the spallation zone.

The analysed duct geometry is a 2-D U-shaped channel. It may be noted how the flow diverter modify the velocity profile at the vertical centre-line. Without flow diverter (Figure 6), the velocity is low at the top, it increases to its maximum at 80% of the depth and presents a noticeable re-circulation close to the bottom. With the flow diverter (Figure 7), the maximum velocity is reached close to the top and it decreases towards the duct bottom, without relevant re-circulation at the bottom. This latter flow profile is almost unchanged in presence of beam heat deposition (Figure 8).

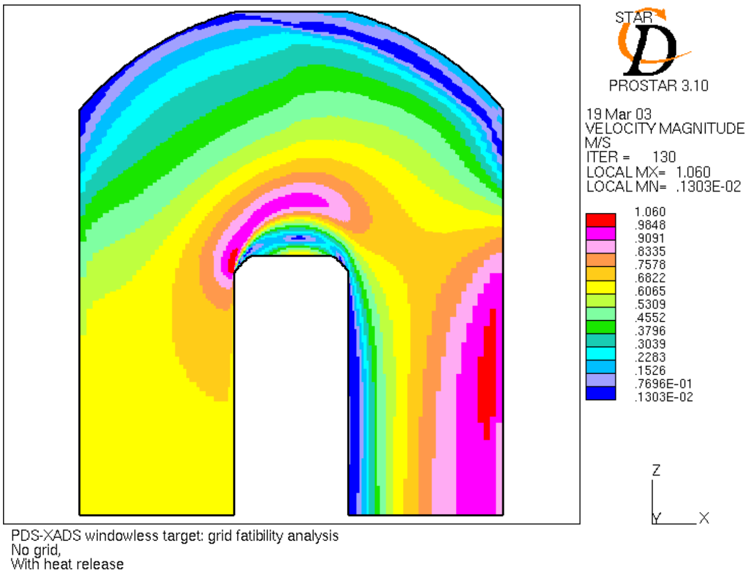

Figure 6: Velocity fields without diverter

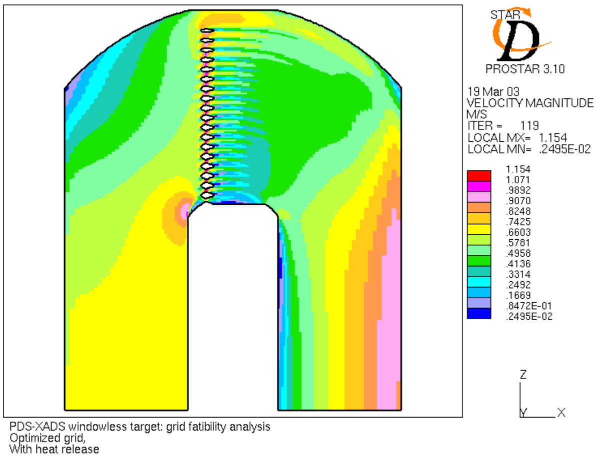

Figure 7: Velocity fields with flow diverter and without beam heat deposition

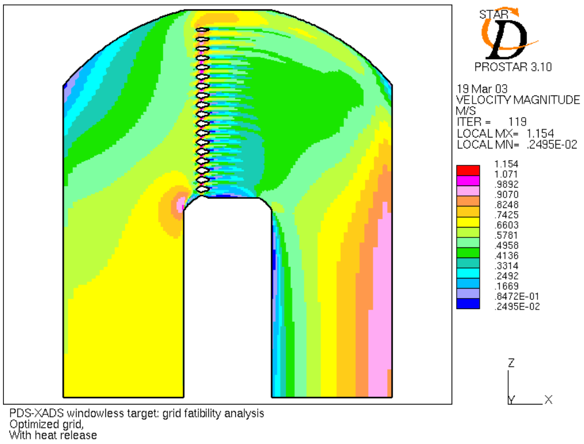

Figure 8: Velocity fields with flow diverter and with beam heat deposition

3.3 Beam trips analysis

A series of beam trip of different length (0.5, 1. 10, 20, 30 and 60 s) and a definitive trip were imposed and power was restarted after all the trips, except for the definitive trip. The transient, simulated with RELAP5 code, starts from steady conditions at full power and after any trip of stated length the plant reaches again steady conditions at full power. After the definitive trip, only the core decay power is provided and the XADS control system adjusts the air cooler air flow rate in order to remove it.

The core power curves are shown in Figures 9 for all the transient.

The core inlet and outlet temperatures are shown in Figure 10. It is possible to observe that for 0.5 s and 1 s beam trips, minimum temperature variations occur at the core inlet and a maximum variation of 10 K occurs at the core outlet. For the other analysed beam trips, the core outlet temperature variations are stronger and it tends to equalise the inlet temperature. After the definitive beam trip, the core inlet and outlet temperatures slowly decrease according to the decay power curve and difference of about 2 K establishes between them.

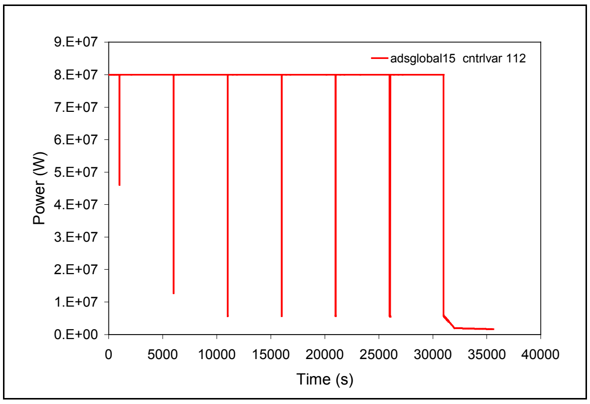

Figure 9: Core power

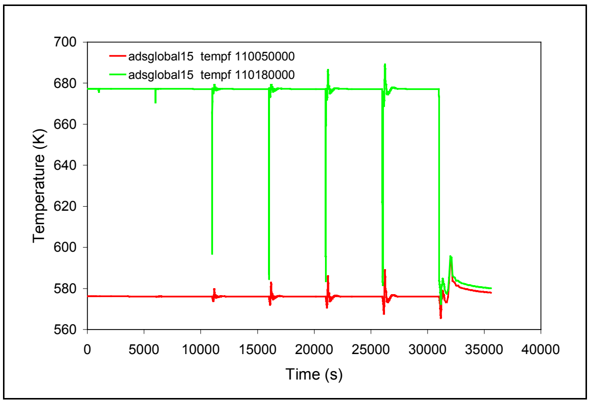

Figure 10: Core inlet and outlet temperatures

The core flow rate is shown in Figure 11. As for the core inlet and outlet temperatures, the 0.5 s and 1 s beam trips almost does not modify the flow rate value, i.e. the thermal inertia of the system and the fact that power is soon restarted are sufficient to limit the fluid condition variations. More important flow rate variations are observed after the other beam trips. Strictly related to the LBE temperature and density, the more the beam trip lasts, the more the liquid level in the spallation zone decreases down to about 3 cm after the definitive trip, see Figure 12.

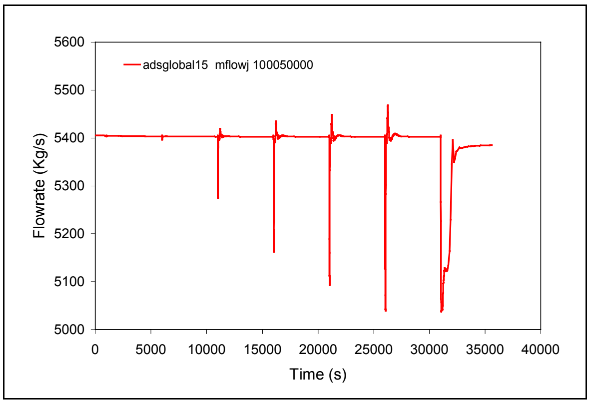

Figure 11: Core flow rate

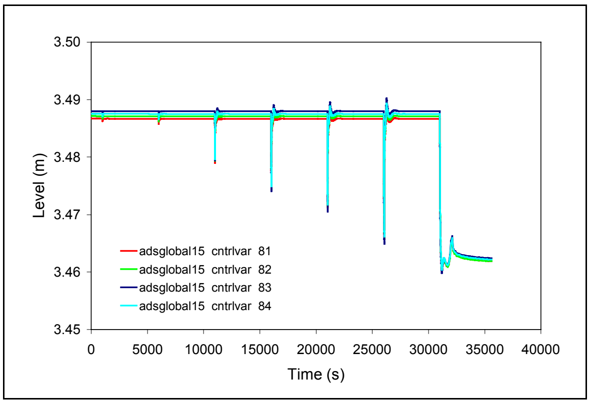

Figure 12: Target spallation zone levels

The spallation zone inlet and outlet temperatures undergo a relevant variation to start from the 10 s length beam trip, Figure 13. Also the HX inlet and outlet temperatures follow the spallation one trend and the outlet temperature changes are less than half the inlet temperature ones. After the definitive trip, the temperatures equalize and tend to the cold regime conditions, Figure 14.

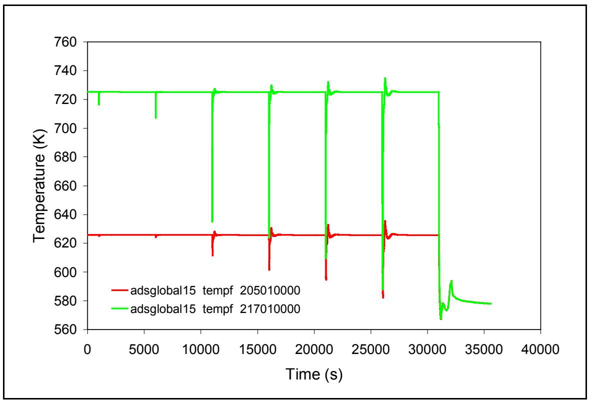

Figure 13: Target spallation zone inlet and outlet temperature

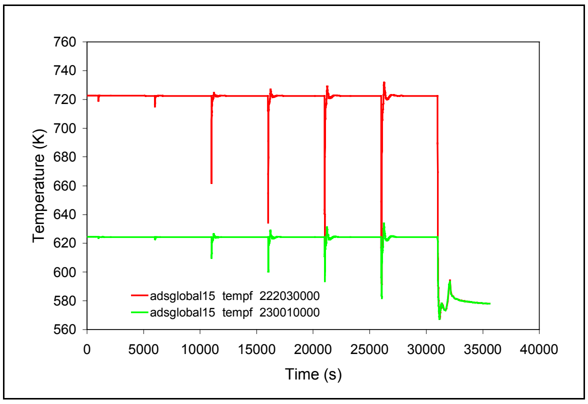

Figure 14: Target HX inlet and outlet temperature

4 CONCLUSIONS

A deep thermal-hydraulic analysis of the XADS windowless Target unit was performed in the frame of the European PDS-XADS project.

Two thermal hydraulic codes, RELAP5 (properly modified for LBE) and STAR-CD, were utilised for the following respective goals:

- to analyse the general primary to target unit coupling response to normal and off-normal conditions;
- to investigate in detail the target spallation zone both from the thermal-hydraulic and geometrical point of view.

The STAR-CD analyses put in evidence the need of a flow diverter in order to shape and stabilize the LBE flow. Of course, the shape of such diverter should be experimentally verified and optimized.

The RELAP5 analyses showed that: 1) the beam trip lasting 0.5 s and 1 s are short enough not to affect the plant temperatures (fluid and wall) and liquid flow rates. After these trips the plant power could be restarted without thermal stress on the system; 2) longer beam trips instead affect the fluid and system structures and the proton beam must not be turned on to avoid heavy thermal stress on the walls; 3) the length of 1 s is not really a design limit for the windowless solution.

ACKNOWLEDGMENTS

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