Accident analysis of the Windowless Target System

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Abstract

Transmutation systems are able to reduce the radio-toxicity and amount of High-Level Wastes (HLW), which are the main concerns related to the peaceful use of nuclear energy, and therefore they should make nuclear energy more easily acceptable by population.

A transmutation system consists of a sub-critical fast reactor, an accelerator and a Target System, where the spallation reactions needed to sustain the chain reaction take place. Three options were proposed for the Target System within the European project PDS-XADS (Preliminary Design Studies on an Experimental Accelerator Driven System): window, windowless and solid.

This paper describes the constraints taken into account in the design of the windowless Target System for the large Lead-Bismuth-Eutectic cooled XADS and deals with the results of the calculations performed to assess the behaviour of the target during some accident sequences related to pump trips.

KEYWORDS: Transmutation, PDS-XADS, Accelerator Driven System, Target, Accident analysis

1. Introduction

In the 5th Framework Programme the European Commission (EC) funded the PDS-XADS project, mainly devoted to the demonstration of the feasibility of the coupling between an accelerator and a sub-critical core loaded with standard MOX (Mixed Oxide) fuel through a Target system and to preliminary investigate the possibility of enhancing the transmutation rate for achieving values suitable for an Industrial Scale Transmuter.

The XADS (eXperimental Accelerator Driven System) subcritical core, likewise any other Accelerator Driven System (ADS), 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 accelerator proton beam with heavy metal nuclei. Moreover it cannot rely on delayed neutrons for the control or power change, but it can be only driven by spallation neutron source. Therefore control rods are unnecessary and reactivity feedback have very little or no importance.

Thanks to subcriticality an ADS can: 1) be safely operated with any fuel (also with a high concentration of Minor Actinides (MA)); 2) take advantage of the nuclear properties of the LBE alloy, used as coolant, for effectively burn nuclear waste; 3) facilitate tasks that would be difficult or inefficient in critical systems.

Within the above-mentioned project the attention was focused on three concepts: two large plants of

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approximately 80MWth, cooled by Lead-Bismuth Eutectic alloy (LBE) and gas (He), respectively and a small LBE-cooled plant of 50 MWth (called MYRRHA). In all these plants the target material is kept confined within the target system in order to limit the pollution of the primary system by the spallation products (Polonium, etc.). Moreover to enhance the effectiveness of the spallation neutron source the target system is placed in the core central void.

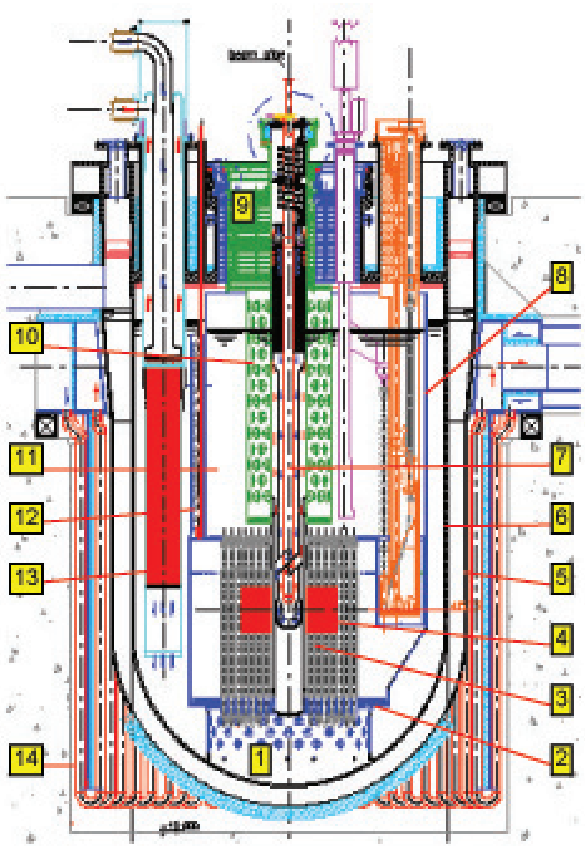
Three solutions were studied for the target system: window, windowless and solid. The window target option is the reference solution for the gas-cooled XADS and the reserve one for LBE-cooled XADS. The solid option is, instead, considered an alternative to the reference liquid LBE target of the gas-cooled XADS, as it simplifies the design and reduces the activation of the target cooling circuit. The windowless option is the reference solution for both the large and small LBE-cooled XADSs allowing to overcome the above-mentioned issues related to material resistance that influence the target life, in particular of the window one.

This paper describes the constraints taken into account in the design of the windowless Target System for the large Lead-Bismuth-Eutectic (LBE) cooled XADS and deals with the results of the calculations performed to assess the behaviour of the target during some accident sequences related to pump trips.

2. Target design and primary system description

The large LBE-cooled XADS, shown in Fig. 1, is a pool-type design [1].

Figure 1: Reactor assembly reference configuration



Legend

1 Lower plenum
2 Diagrid
3 Reactor core
4 Fuel zone
5 Safety vessel
6 Reactor vessel
7 Target system
8 Inner vessel
9 Above core structure (upper)
10 Above core structure (lower)
11 Dead volume
12 Riser
13 IHX
14 RVACS heat exchanger

The primary coolant flowing out of the core collects in the hot plenum, enters the riser pipes, then flows from upward to downward in the lower plenum and enters the core as well as the target system. The major part of the coolant flows in the downcomer through the IHX (Intermediate Heat eXchanger), transferring heat to the secondary fluid. A small fraction of the coolant flows down through the IHX bypass, transferring heat to the RVACS (Reactor Vessel Air Cooling System), which removes ~260 kW of power under nominal conditions and it is also able to assure the decay heat removal in the event of the unavailability of both secondary loops.

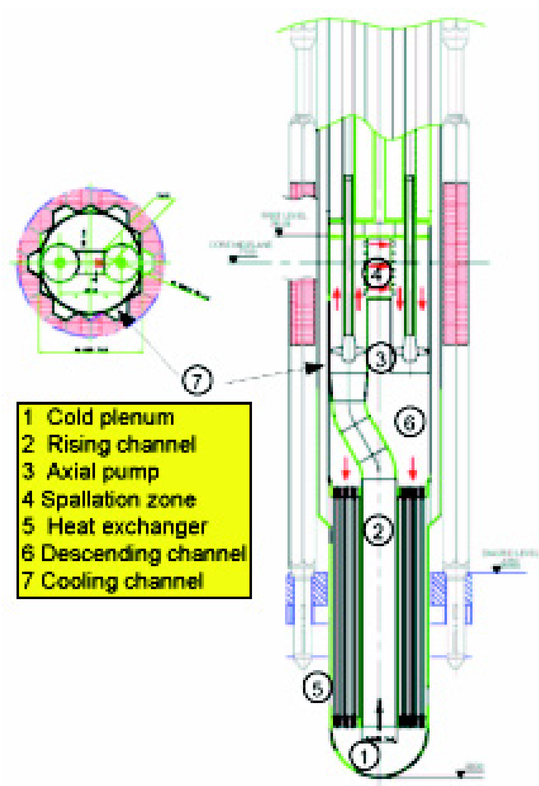
The primary LBE circulation relies on natural circulation enhanced by injection of argon gas fed by a compressor into the bottom part of the 24 vertical riser pipe installed on the periphery of the quasi-stagnant region located above the core. Due to the adopted design solutions, such as high fuel pin pitch-to-diameter ratio, absence of mechanical pumps and low coolant velocities, the hydraulic resistance of the primary circuit is very low (about 30KPa), thus a high level of natural circulation is assured even in the absence of the gas-lift pumps.

The subcritical core has an annular configuration around the target and consists of 120 MOX fuel assemblies (SAs), 168 dummy reflector SAs and twelve absorber SAs. Each fuel SA contains 90 fuel pins with an outer diameter of 8.5 mm. The core is characterized by a low power rating with average and peak values of about 82 and 130 W/cm, respectively [1].

The heat generated in the core (80MWth) and target (up to 3MWth) is transferred to the environment by two secondary loops thermally coupled to the primary system through four IHX. As no electric power production is envisaged in the XADS, the organic oil cooled secondary system dissipates power in atmosphere by means of air coolers.

The windowless target system, shown in Fig. 2, has a vertical orientation and is placed in the core central void covering the equivalent of the central position and the inner two assembly rows. It is supported at the reactor vessel top and horizontally guided at the elevation of the core diagrid, Fig. 1 [2].

Figure 2: Target system sketch



Because of the basic conception of the windowless target, the proton beam impinges directly on the free LBE surface and no structural material is exposed to the direct proton irradiation. LBE is used both as target and as a means to transfer the heat deposited by the impinging proton beam to the heat sink placed about 1 m beneath the core region.

The 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 pumps, which thrust LBE upwards into the spallation zone, where it is heated up, and then downwards through the heat exchanger located under the fuel core.

The in-series arrangement ensures that, in case one pump fails, the other one is able to supply enough flow avoiding abrupt heating of LBE in the spallation zones. One propeller alone is in fact able to supply half flow for a maximum LBE temperature around 823 K, which is not a major issue for the target system performance apart the transient rise of the spallation exhaust release in the beam tube.

The maximum LBE flow speed at the free surface is kept high enough for lessening both temperatures and LBE evaporation in the beam tube.

The heat exchanger is a classical tube shell HX, with the target LBE flowing down through the tube assembly and LBE from the primary system, flowing out the assembly tubes from the core feed up to the quasi-stagnant region above the core. An inner duct drives back LBE from the lower plenum to the spallation region. The HX is placed at the bottom of the target system fitting in the central core cavity.

The heat removal is determined by the feed of primary LBE at the core inlet temperature and by the target LBE flow (~0,5m/s) from the two propellers.

The proton beam tube, housed inside the target system up to the plate placed above the free level, has a cross section that ranges from 12*5cm^2 at the bottom to 5*4cm^2 at the top in order to reduce the streaming inside the beam tube itself.

In the spallation region, the beam footprint is shaped as a rectangle of 10*80mm^2 (10mm in the flow direction and 80mm in other direction). Consequently, the spallation volume is roughly bounded to a slab 8cm wide, one beam spot thick (~1cm) and 30cm deep into the target LBE.

The main performance data of the windowless target system are reported in Table 1.

Table 1: Main Target System process parameters

Max. proton energy (MeV)	**600**
Max. proton beam intensity (mA)	**6**
Max. deposited power/beam power (MW)	**2.6/3.6**
LBE Temperature (K)	
- Target inlet	**608**
- Target outlet	**~713**
- Secondary inlet	**573**
- Secondary outlet	**653**
Target LBE velocity (m/s)	
- Flow average	**0.5**
- Maximum at the flow surface	**≤2.0**
Max LBE temperature at free level (K)	**723**
Max target structures temperature (K):	
- with coating	**808**
- surface alloying with Al	**823**
Target critical component life time	**about one fuel cycle**

3. Target design constraints and criteria

The size of the windowless target is based on a balanced optimisation among neutronic aspects (neutronic efficiency is affected by the proton energy and the maximum subcritical level at which to operate the core), material properties (physical and chemical), thermo-hydraulic constraints resulting from the high value of beam energy released in a reduced spallation volume, the maximum target LBE flow velocity that affects pumping and corrosion aspects and temperature variations, which influences the thermo-mechanical loading.

From the neutronic point of view the target physics and its conversion rate is basically defined once the energy of impinging proton beam has been fixed.

A 600MeV proton beam energy was considered as a good compromise for both practical considerations and the costs linked to the accelerator technology development, even if the overall efficiency is somewhat penalized.

The neutronic source was thus evaluated so as to achieve the nominal core power output of 80MWth. The core being loaded with MOX fuel, the reactivity along the cycle decreases and the proton current needed to feed the core has to be increased to compensate for the fuel burnup. The current at EOC (End Of Cycle) is, however, lower than the maximum value (see Table 1). In any case the proton current values are higher than usually available and high performance accelerators have to be developed. In fact the current research accelerators working at the frontier of high energy physics ask for high accelerating voltage and are much less demanding about the current level (lower than 2mA).

The alternative approach of operationally running a constant proton current requires either to adjust the effectiveness of the spallation neutron source as burn-up occurs or to define a core configuration where the k_{eff} is constant or nearly constant along the cycle.

The effectiveness of the spallation neutron source could be exploited by moving the spallation zone from the top to core centre or increasing the energy of the neutron source. Both solutions are not applicable for engineering reasons.

A constant or almost constant k_{eff} may be reached with new MA-dedicated fuel and with an appropriate choice of the neutronic parameters (power, rating, volume of different enrichment zones, core size (height and diameter, fuel isotopic vector, etc.) in core loaded with high quantity of MA. Also this solution is not applicable, as it requires the availability of new MA-dedicated fuel and fuel cycle facility.

The high intensity requirements that must characterize the spallation neutron source are inherently linked to the basic prerequisite for the XADS core to remain subcritical under any foreseeable occurrence pertaining either to Design Base Conditions (DBC) and Design Extension Conditions.

The choice of the structural material was based on the neutronic properties (low capture cross section), radiation and corrosion resistance capability, and mechanical properties (tensile strength, fracture toughness, Ductile Brittle Transition Temperature: DBTT, etc.). Assuming adequate limits on maximum LBE flow speed (2m/s) and temperature level (723 K), normal austenitic and ferritic-martensitic steels may be used to prevent the enhancement of LBE corrosion phenomena. Of course ferritic-martensitic is usually the preferred steel for the lower impact on the core neutronics.

From the thermo-hydraulic point of view the constraints considered in the design are related to the power released in the spallation volume; the maximum target material flow velocity and temperature distribution.

For a 600MeV proton beam, the energy released as heat is about 72% of the total: the rest is shared between the particles escaping the system and the binding energy of target nuclei.

Therefore the heat that needs to be evacuated by the target cooling system is 2.6MWth, which corresponds to an average density power of 12.5 KW/cm^3, considering the spallation zone a sort of flat slab 8x30cm wide,1 cm thick. At an average flow speed of 0.5 m/s the LBE temperature increases of about 440K when crossing the spallation slab.

The peak temperature inside the LBE bulk in the spallation volume was kept quite below the LBE boiling point in order to avoid massive boiling and disruption of the spallation cooling configuration. The possible onset of limited hot spots or local bubbling boiling in superheated thin flow fillets was investigated in order to verify that they do not rise buoyancy thrust and extinguish inside the LBE bulk while flowing downstream towards the heat exchanger.

The potential LBE boiling due to a high concentrated power of the beam spot impinging in the bulk was avoided by a simple scanning of beam along a fixed line segment. Moreover the effects of possible beam spotting superposition at the scanning edges, where the beam motion is reversed, was considered to avoid potential LBE local over-heating and to fix the beam scanning frequency.

The maximum LBE flow speed at free surface of the spallation zone was kept high enough in order to limit the maximum LBE surface temperatures and the related evaporation rate enhancement of LBE (as well as of other volatile spallation products) into the vacuum beam pipe. Conversely the LBE potential corrosion drawbacks ask for limiting the maximum flow speed, thus a maximum flow velocity of 2 m/s was considered adequate for keeping corrosion low while providing enough cooling. Also the flow velocity profile inside the LBE depth, along the beam range, was chosen so that to assure that massive LBE hot spots do not result from poor match of beam spallation peaking with locally reduced flow speed.

The temperature levels of the structures that are not in contact with LBE and then are not directly cooled by it have to be maintained below the limits that are compatible with the assumed target life extension (see Table 1).

4. Accident analysis

Once defined the spallation zone configuration for the steady state conditions that takes into account the above-mentioned issues, the assessment of the target system behaviour was also performed against a set of abnormal conditions, which are reported in Table 2.

Table 2: List off-normal conditions

Event	Classification
Beam trip of different length	DBC cat. II
Trip of one pump with proton beam shut-off	DBC cat. II
Trip of one pump without proton beam shut-off	DEC
Trip of one pump without proton beam shut-off followed by the second pump trip	Residual Risk Situation

The initiating events were identified by constructing a top-level logic model (Master Logic Diagram approach), because of the lack of plant specific data as well as of operating data and of peculiar characteristic of the XADS plant. The top event considered was “Pressure or Temperature variation”.

The accidents were classified using the European Utilities Requirements (EUR) that categorizes the events in: Design Basis Conditions (initiating events covering the whole range of faults from those that are likely to occur several times within the plant life to those whose occurrence is highly unlikely but the consequences must be evaluated with conservative rules), Design Extension Conditions (low frequency events considered in the design with the respect to the application of defence-in-depth principle and corresponding generally to multiple failures) and Residual Risk Situations (events with severe consequences that have not to be analysed in the design, but it is necessary to demonstrate that the prevention measures regarding their occurrence are sufficient).

The accidents were also classified in protected and unprotected transients, depending on the condition if proton beam shut-off takes places or not upon a request following an initiating abnormal event.

For the protected incidents, a beam shut-off was assumed to occur when the core outlet temperature reached 693K, which corresponds to a 20% of temperature increase across the core.

The assessment of the thermo-hydraulic behaviour of the target system during these accidents was performed with RELAP5 mod3.2 beta version [3]. This code required relevant modifications to use LBE as working fluid, such as development and implementation of thermodynamic properties (enthalpy, etc.) and other physical properties (thermal conductivity, surface tension and viscosity); implementation of heat transfer correlations for liquid metals and development of the finned tube heat exchanger model for the air coolers [4].

The model of the target system simulates the cold plenum, the rising channel, the first pump, the spallation zone (vol. 208, 209, 210 from top to bottom), the descending channel with the further pump, the HX and the downcomer. It is thermally and hydraulically coupled to the primary system by means of the target cooling channel that drives the primary LBE from the XADS lower plenum to the dead volume above the core [5].

In the paper only the results of the calculations performed for the protected and unprotected accidents related to the trip of a pump are described.

Both transients start from a full power steady state condition and refer to a beam power of 3 MW. At time 1000s the pump located in the rising channel was tripped and the speed of the pump was brought to zero in 3 s.

4.1 Trip of one pump with proton beam shut-off

In the protected transient, characterized by the accelerator shut-off, the beam trip was supposed to occur just after the pump trip start and the beam power was set to zero in 0.001 s.

After the beam trip, the core decay power is provided to the subcritical system and the XADS control system adjusts the air cooler flow rate in order to remove it. A primary flow rate decrease of about 300 kg/s is observed for about 900 s due to the air flow rate regulation by the control system, then the flow rate increases and tends again toward the steady value. Also the target flow rate is soon reduced after the pump trip and it passes from 207.8 to 143.1 kg/s. The core outlet temperature falls down and after a series of oscillations, the core inlet and outlet temperatures slowly decrease according to the decay power curve and a difference of about 2 K establishes between them, Fig. 3. The target spallation zone inlet and outlet temperatures and the HX inlet and outlet temperatures equalise just after the beam trip and they tend to the cold regime condition ones, Fig. 4. The spallation zone temperatures reach the same value after the beam trip, Fig 4. The primary LBE flow rate cooling the HX undergoes a little reduction of about 6.4 Kg/s and its trend is strictly related to the primary LBE temperature, Fig. 4.

The analysis of this accident shows that the target and the primary system, after some temperature and flow oscillations linked to the XADS control system, reach quasi-steady state conditions following the decay power curve

Figure 3: HX, Cooling channel and core temperatures

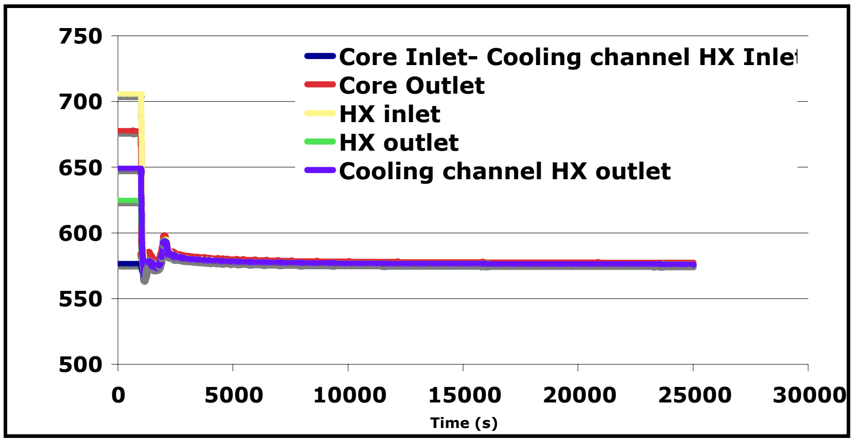
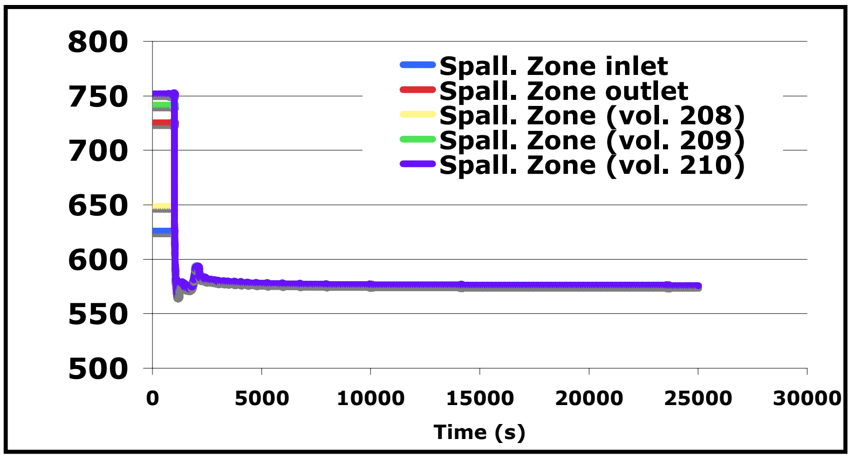


Figure 4: Spallation zone temperatures



4.2 Trip of one pump without proton beam shut-off

In the unprotected transient, the temperature in the target system increases and it converges toward a new steady condition characterized by a thermal stratification in the spallation zone, due to the flow rate reduction. The reached temperature leads to the calculation interruption at time 2197 s. The core inlet and outlet temperatures remain at their original value, as no flow regime modification occurs in the XADS primary circuit consequently to the first target pump trip. The target flow rate is instead quickly reduced after the first pump trip from 208.8 kg/ s to 130 kg/s. It is worth underlining that the target flow rate reduction is larger than that occurring in the case of pump trip with the accelerator shutdown. This is due to the natural circulation driving force opposition to the fluid circulation driven by the pump, because the heat source is at the top of the circuit. The target spallation zone inlet and outlet temperatures decrease and increase, respectively. The temperature increase at the outlet is due to the beam power deposition in a reduced LBE flow rate. The temperature decrease at the inlet depends on the Heat Exchanger power rejection rate. With a reduced flow rate, the power rejection rate to the primary circuit is maintained by increasing the temperature difference between HX inlet and outlet, Fig. 5. The spallation zone temperatures are shown in Fig. 6. The primary flow rate, cooling the heat exchanger, undergoes a little variation, then it establishes at a constant value of 266.7 Kg/s. The primary HX inlet and outlet temperatures are shown in Fig. 6. The inlet temperature is always constant, whereas the outlet one re-establishes at the initial value after a little decrease just after the pump trip.

The analysis of this accident shows that the target and subcritical system can be largely impaired by the thermal stratification occurring in the spallation zone due to the flow rate reduction and the power supply in the high zone of the circuit.

Moreover it is worth underlining that the calculation interruption was not observed reducing the beam power from 3 to 2.6 MW [6]. In the first calculation the fluid temperature in the upper part of the rising channel reached a value equal to the saturation temperature corresponding to the partial pressure calculated by RELAP5, thus the code stopped being not suitable to solve two-phase problems with liquid metals. In the second calculation, this situation did not verify and the calculation was not interrupted.

Figure 5: Figure 3: HX, Cooling channel and core temperatures

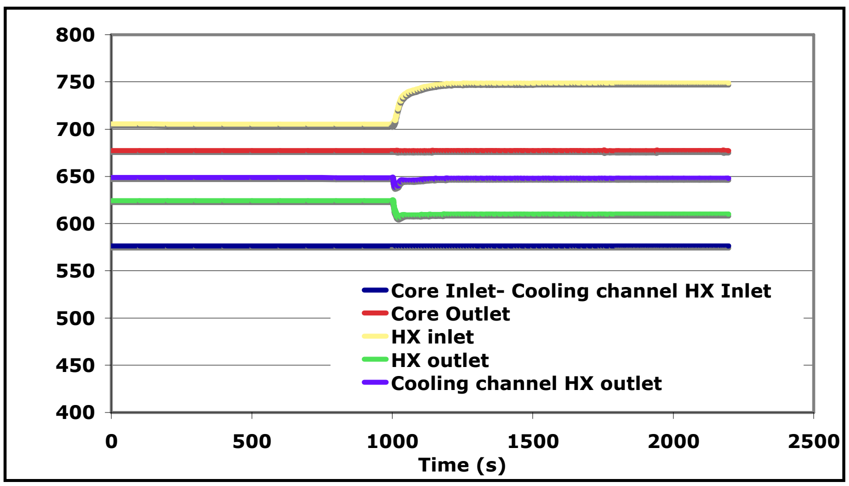
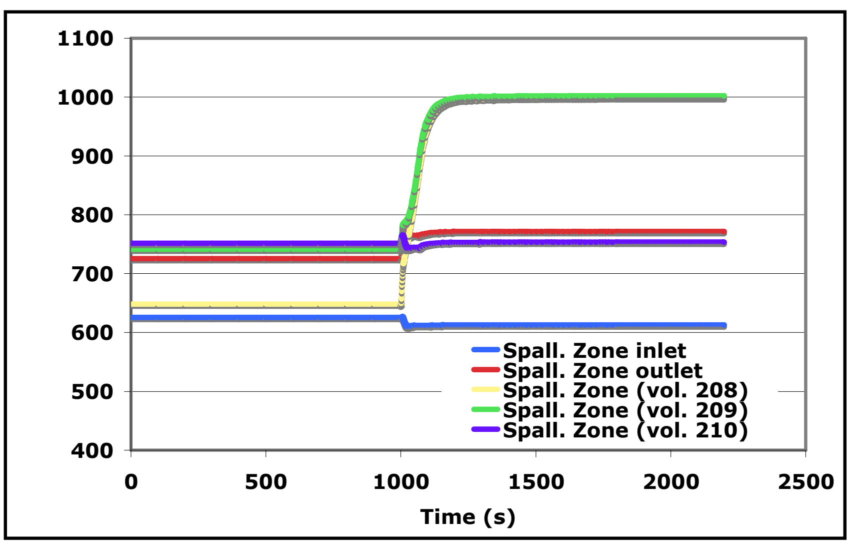


Figure 6: Spallation zone temperatures



5. Conclusion

The windowless target system was proposed to overcome mechanical limitations inherent to a window, whose lifetime ranges from 3 to 6 months maximum.

The thermo-hydraulic design in steady state conditions shows flow velocity, pressure and temperature profiles with sufficient margin to the specified design limits and the absence of hot spots or buoyancy effects.

Also in accident conditions the thermo-behaviour is acceptable except for the trip of one pump without beam shut-off, where a thermal stratification occurred due to the flow rate reduction and the power supply.

The calculations show that the need of further modifications to the code or LBE properties in order to improve the already performed changes and to avoid the code running problems.

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References

1) F. Bianchi, P. Meloni and F. Mattioda, "accident analysis of an Experimental accelerator System", Proc. Int. Conf. on Nuclear Engineering, ICONE13, Beijin, China, May 16-20, 2005, ICONE13-50553
2) L. Cinotti, A. Negrini, et al., "Design of a windowless target unit for the XADS Lead-Bismuth coolant system", Proc. Int. Workshop on P&T and ADS Development, Mol, Belgium, Oct. 6-8, 2003, A80 (2003)
3) S. A. Shich, et al., "RELAP5/MOD3 Code Manual Volume II: User's Guide and Input Requirements", NUREG/CR-5535, 1998
4) F. Bianchi, W. Ambrosini, et al., "Natural circulation of Lead-Bismuth in a one-dimensional loop: experiments and code prediction", Proc. Int. Conf. on Nuclear Engineering, ICONE10, Arlington, VA, USA, April 14-18, 2002, ICONE10-22356
5) F. Bianchi, et al., "Lead-Bismuth Eutectic cooled Experimental Accelerator Driven System: Windowless Target Unit Thermal-hydraulic Analysis", Int. Conf. on Nuclear Energy for New Europe 2004, Portoroz, Slovenia, Sept. 6-9, 2004
6) F. Bianchi, R. Ferri and V. Moreau, " Transient thermo-hydraulic analysis of the windowless target system for the Lead Bismuth Eutectic cooled Accelerator Driven System", Proc. Int. Conf. on Nuclear Engineering, ICONE14, Miami, Florida, USA, July 17-20, 2006, ICONE14-89212