LOSS OF FLOW ASSESSMENT IN A LBE-COOLED XADS CONCEPT

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Abstract

The Experimental Accelerator-driven System (XADS) is a proposed 80 MW_{th} Lead-Bismuth-cooled pool type facility coupling a proton accelerator and a sub-critical fission core by means of a spallation target. A cascade fission reaction is sustained by the spallation neutrons. The facility primarily aims to demonstrate the operability of the whole complex and, subsequently, also the capability to reduce the inventory of Pu, Minor Actinides and selected long-lived fission products. It was conceived by a team of Italian organisations led by Ansaldo and including ENEA (the National Research Organisation for Alternative Energies), INFN (the National Institute for Nuclear Physics) and CSR4 (a Research Institute based in Sardinia), with contributions from selected Universities; he feasibility analyses aiming to define its reference configuration were performed. The effort was sponsored by the Italian Ministry of the University and of the Scientific and Technological Research. The 80 MW_{th} Lead-Bismuth-cooled design is currently being assessed, versus a gas-cooled concept, in the frame of a contract with the Commission of the European Communities.

The paper, after a brief description of the LBE-cooled XADS concept, focuses on the assessment of its response to loss of flow events affecting both the whole core and a single fuel assembly. While the former are originated from the postulated malfunction or loss of the peculiar gas injection system employed to enhance primary coolant circulation, the latter may derive from significant flow blockages at a fuel assembly inlet. The results of the performed analyses show the excellent natural circulation capability of the system, specifically in an accident scenario with the assumed simultaneous failure to trip the proton beam, and highlight the indeed peculiar heat removal mechanisms from a fuel assembly in case the associated coolant flowrate drops to very small values.

1. Introduction

The transmutation of transuranics (TRU's) and selected long-lived fission products (LLFP's) using an accelerator-driven system (ADS) is a promising solution for reducing the amount of long-lived radionuclides to be disposed. Its usage could be tailored to the different nuclear policies of the European Union members. Its practicability on an industrial scale requires to be demonstrated by an eXperimental ADS (XADS).

Following a preliminary design developed in 1998, which was based on the Energy Amplifier concept proposed by CERN, [1] the Reference Configuration [2,3] of a Lead-Bismuth Eutectic-cooled Experimental ADS (LBE-XADS) was worked out in the period 1999-2001 by a group of Italian organisations led by Ansaldo, with the aim of assessing the feasibility of a small-sized (80 MW_{th}) ADS. The Italian consortium (Ansaldo, ENEA, INFN, CRS4, CIRTEN, SIET and SRS) design activities were performed under the aegis of MURST (the Italian Ministry of University and of the Scientific-Technological Research); two main tasks were funded, the first addressing the design of the target unit and the sub-critical multiplier and the second the accelerator system.

The activity is now progressing within the 5^{th} Framework Programme of the European Commission, in the context of the research on Fission Reactors Safety, with funding to a project named PDS-XADS (Preliminary Design Studies of an Experimental Accelerator-driven System) with a three-year contract involving the participation of 25 partners (industries, research organisations and universities). The European Project focuses on the comparative assessment of the above mentioned Pb-Bi-cooled and a gas-cooled ADS concept. It is the first major step of a consistent European effort that, as a key-milestone, will allow to design in detail an XADS for the transmutation technology demonstration. The main objective of this experimental facility will be to demonstrate the technological feasibility of coupling the accelerator with the nuclear reactor. The Experimental ADS will be designed to demonstrate first the feasibility and safety of coupling an accelerator with a sub-critical reactor and, later on, the feasibility of transmutation of Transuranics (Plutonium and Minor Actinides, according to different countries strategies) and LLFP's transmutation, this being the anticipated mission of the follow-on programme on the eXperimental Accelerator-driven Transmuter (XADT).

In the meantime, in Italy, MURST continues to fund the development of the lead-bismuth technology in the large-scale CIRCE experimental facility. [4]

2. The Lbe-cooled xads

The LBE-cooled XADS [2,3] can be schematically divided into some conceptual blocks: the spallation target, the sub-critical core, the primary loop, the secondary loop and the auxiliary systems.

The target

Two design solutions, "window" and "windowless", are studied for the target, each with LBE acting both as spallation target and cooling fuid, separate from the primary eutectic by a retrievable mechanical structure, the target unit, which is centred inside a core cavity to evenly deliver the source spallation neutrons to the surrounding fuel.

The window target configuration consists of a mechanical barrier of material fairly transparent to neutrons and protons, engineered to withstand pressure and thermal loads. The LBE flows by natural circulation as it is heated up by the proton beam in the lower part of the target unit, centred at the core mid-plane, while it is cooled down in the upper part where the heat is evacuated through a heat exchanger by means of a diathermic fluid.

In the "windowless" target configuration (see next Figure 1) an LBE free surface is directly exposed to the proton beam pipe vacuum, balanced by about 1 m LBE head. The beam impinges directly on the eutectic free surface producing a small foot print of rectangular shape (50, 120 mm). The LBE coolant is forced to circulate by means of pumps downwards to the bottom part of the target unit, where the heat is evacuated through a heat exchanger cooled by the primary LBE coolant.

The windowless target is currently viewed as the more attractive configuration because it allows to avoid some relevant technological and design problems. In fact, in this case, there is no need to develop proper materials able to withstand high proton and neutron fluxes, as well as mechanical and thermal loads; also the neutron streaming phenomenon, which impacts the reactor roof accessibility for refueling or other operator intervention, is limited due the possibility to adopt a small beam pipe.

The sub-critical core

The fuel core (see next Figure 2) consists of an annular pattern of 120 fuel assemblies, for a total of 3,65 tons of MOX fuel, which surrounds the inner target cavity. The assemblies are all alike, each loaded with 90 fuel pins which have the same radial dimensions and fuel MOX composition as the standard Superphénix reload fuel but with slightly higher enrichment (23,25% Pu, to set an operational $k_{eff} = 0.97$ at nominal power and BOL). The fuel pin cluster is enclosed into an hexagonal wrapper; the lattice is about 40% larger while the active fuel length is slightly shorter (87 vs 100 cm) than SPX.

The fuel core is surrounded by a buffer region of 174 non-fuelled dummy elements filled-up by LBE, whose purpose is softening the hard neutron spectrum to relieve the fast fluence on the fixed structures around the core.

The buffer region adds up LBE thickness to the coolant flowing in the downcomer of the primary loop: a substantial core reflector is thus available for improving the overall neutron economy by a sort of diffusive neutron cloud around the core. The core boundary neutron leakage is so minimised to as low as 1 - 2% without need of specific reflector structure which is on the contrary requested in FRs based on different coolants. The LBE is in fact a highly diffusive and fairly transparent (slowly-lethargising and low-absorbing) means for neutrons which undergo thousands of collisions against Pb-Bi nuclei while slowly relaxing from fast down to thermal energies. The long wandering neutrons tend to be kept and attenuated inside the LBE volume whereas they would rather escape, while rapidly slowing down, in light, low-A liquids, or gas coolants.

A practical result of such a higher neutronic sustainability in LBE (survivability with high energy spectrum) directly reflects the possibility of making substantially wider fuel pin lattice in LBE-cooled systems: due to reduced friction losses, this also helps sustaining natural circulation regimes and diminishes pressure head requirements when assisted pumping or natural circulation enhancement is needed.

Moreover, the core buffer allows a very flexible management for irradiation testing of prototypical FAs containing different kind of fuels or LLFPs and for positioning neutron absorbers to lower $k_{eff} < 0.95$ before starting the core refuelling outages.

Figure 1. **The LBE-cooled XADS windowless target**

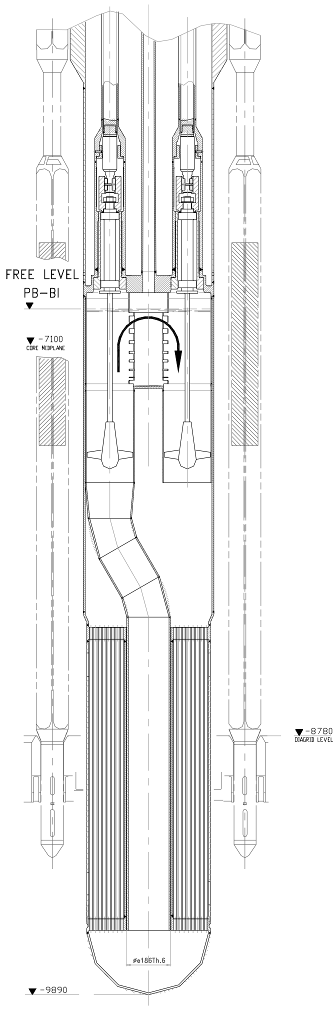
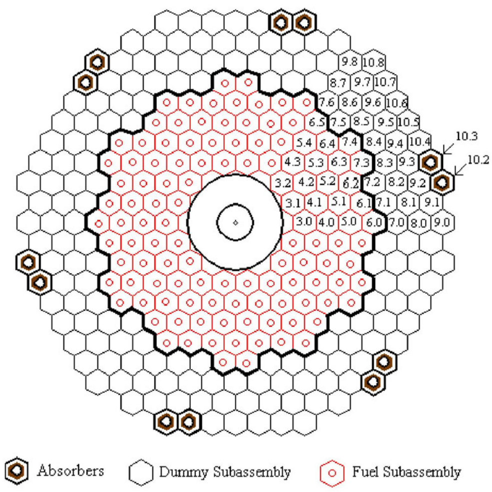


Figure 2. **The LBE-cooled XADS core cross-section**



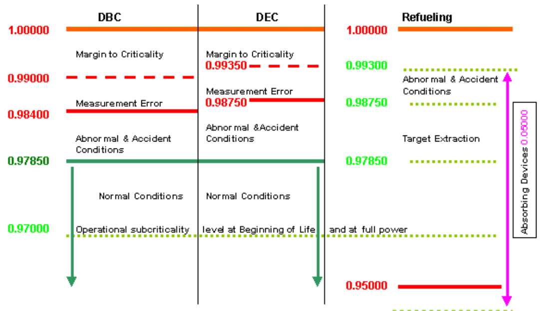
The core sub-criticality level

A core multiplication factor of 0.97 (at core rated power, BOL) is considered sufficiently low to ensure the safe operation of the LBE XADS without need of shutoff rods. It has been determined by an approach balancing the accelerator system demanded performances and the design goal to have margin from criticality in all normal and accident Design Basis Conditions – (DBC) and Design Extension Conditions (DEC). The approach adopted for the determination of the operational sub-criticality level includes evaluation and appropriate combination of the relevant reactivity effects and proper consideration of specific design features (e.g. absence of shutoff rods). [5]

In particular, allowances for a safety margin of $\Delta k=1\%$ (i.e. approximately 3$) and for k measurement error (0.6%, i.e. approximately 2$) are applied with respect to criticality ($K_{eff}=1$), so that the actual upper limit for the multiplication factor becomes k = 0.984 for normal operation and DBC's. Core cooling from operation at full power down to ambient temperatures plus target-beam pipe flooding by LBE or geometrical variation from earthquake loading (inserting a total reactivity estimated approximately 1.4% including Doppler, coolant density and thermo-structural effects) accounts for the widest reactivity insertions predictable under DBC conditions for the LBE-cooled XADS. The core multiplication factor limit for normal operation at full power and BOL is thus set at $k_{eff} = 0.984 - 0.014 =$ 0.97 (i.e. a sub-criticality margin of $\rho_o \sim -3\%$, Figure 3). Accidents like those involving larger core compaction may be ascribed to Design Extension Conditions (DEC); based on the core and fuel assembly design, the associated reactivity effect may be worth about 0.5÷0.6%, so that it still allows the system to remain sub-critical, though with a reduced safety margin.

Concerning refuelling, the requirement of a K_{eff} <0.95 implies the need to use neutron absorbing devices (the ones located far from the core in Figure 2) worth approximately 5 000 pcm and manually moved close to the core before starting refuelling operations.

Figure 3. **Sub-criticality: conceptual approach**



The Primary Loop (PL) configuration

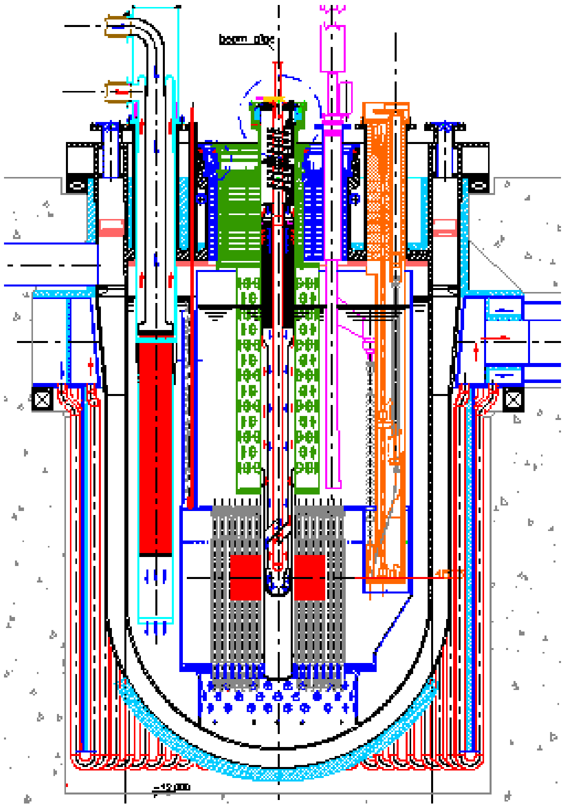
The use of lead-bismuth eutectic in the XADS allows retaining neutronic properties similar to lead, but its remarkably lower melting point consents to operate at moderate temperatures. Some experience on the LBE corrosion chemistry and protection methods for the structural steels is already known and can be more readily developed in out-of-pile testing facilities like the large scale CIRCE experimental loop. [4]

Nevertheless, the major drawback of using the LBE eutectic is the formation of the 138 days T½ α-emitter ^{210}Po from bismuth.

The PL configuration is the pool-type (Figure 4), rather than the loop-type, as this design allows to pool within the main vessel all the primary coolant with the spallation target and the core structures, as well as the four intermediate heat exchangers (IHX). Conversely, a loop-type option with LBE coolant is hardly practical as this would involve quite huge and heavy piping, complex and costly design and seismic problems. The pool-type is also the preferred solution for large sodium-cooled reactors and the design experience gained with them can be suitably transferred to LBE.

As the highly diffusive, low-lethargising neutronics exploitable with the LBE allows making large fuel pin lattice, with pitch-to-pin diameter ratios in the range $1.5 \div 2$ vs ~1.2 of FRs, the coolant pressure drops across the core can be kept below a few tenths of bar, i.e. an order lower than sodium-cooled FRs.

Figure 4. **The LBE-cooled XADS PL cross-section**



The prerequisite of developing a substantial cooling by natural circulation can be hence readily met (thanks also to the small XADS power) as a pool-type loop configuration can provide inherently large flow area with simple design of the primary system.

However moderate, the flows developable by natural circulation can be in any case sufficient for evacuating the XADS residual power and are besides suitable for limiting the LBE corrosion-erosion on structural materials.

The space saved from the lack of a cumbersome pumping mechanics can be made available on the roof of the primary loop for components which are specific adds-on of the XADS, like the beam-pipe and the spallation target structure.

The exploitation of a completely natural circulation in the primary coolant would conversely present some demanding design requirements and constraints, which refrain from fully undertaking such a design philosophy: 1) a substantial reactor vessel height for developing enough head to drive purely natural circulation, which would add distance between the bending magnet and the spallation target; 2) an attentive minimisation of pressure losses through the core and the IHX, impacting on optimal performaces; 3) an inherently poor controllability of the LBE flow-rate limiting the flexibility of operating conditions.

As a result of mediating between the countervailing merits and drawbacks of natural vs forced circulation, while keeping as a safety requirement the removal of the core residual heat by natural convection alone, it has been decided to design a flow enhancement system based on the injection of a few percent volume of PL cover gas into the bottom of the riser above the XADS core. The PL design then includes 24 risers where the reduced density lifting thrust of the two-phase LBE - gas mixture is added to that of the core heating to the LBE upstream flow. The admixed gas is stripped into the PL cover atmosphere when the LBE flow turns down at the pool surface. The total head is the natural buoyancy of the hot LBE stream above the core added by the gas injection density lightening, as weighted against the single-phase cold flow in the PL downcomer at the PL vessel wall after the IHX.

During normal operation the natural convection head is a 20% of that assisted by the gas injection, but the natural circulation alone is more than sufficient, after power shutdown, to cool the core.

On the other hand, exploitation of higher natural heads for more moderate LBE temperature increments would require rising the height of the hot head a few times and/or enlarging the core size. These measures, besides hindering the operating flexibility, would make the PL and the whole XADS facility huger and costly, very disproportional compared to the aims an experimental facility is expected to accomplish.

As for the beam, an extended distance of the spallation zone, centred at the core mid-plane, from the beam controlling optics located above the PL cover top, would make the necessary beam spot precision more difficult to achieve.

The secondary system – BOP configuration

The two loops secondary system is thermally coupled to the PL through four IHX's so to transfer the operational core heat to the outer environment.

Each secondary loop, besides two IHXs, includes three heat exchangers arranged in series for rejecting heat to the external atmosphere via finned tubes and is operated through a circulation pump. The thermal cycle temperatures, 280-320°C cold-hot leg, are consistent with the synthetic diathermic fluid used as the coolant for this circuit. While assuring good compatibility with the hot LBE in case of leaks from the IHX (no fast chemical reactions are foreseen), this choice allows to keep high enough temperature levels in the SS without pressurisation due to the low vapour pressure of the organic fluid. In spite of the lower thermal properties, the overall heat transfer capability of the SS fluid is comparable to that of LBE. The much lighter, non-corrosive, organic fluid can be in fact pumped at high speed and its comparably high heat capacity allows a 50 times lower mass compared to that required for cooling also the SS by LBE.

Conversely, the largely different coolants thermal property and the much longer SS flow path, compared to the PL, may require quite slow ramp-rates, during beam start-up/shut-down transients, for controlling temperature mismatches between the two loops, giving rise to oscillations in the SS due to its much larger thermal time constant.

3. Loss of LBE flowrate accidents

Depending on the particular malfunction or failure occurred in the plant, loss of flow events can affect the whole core or a single fuel assembly. In particular, a failure causing the termination of the argon injection in the plant risers used to enhance the LBE natural circulation (the argon gas compressor trip in the present report) will cause a reduction of the primary and hence core flowrate.

On the contrary agglomeration of particles (Pb oxides) from various part of the system as well as failure of fuel or of other structural components within the core can lead to partial flow obstruction or blockage in a localised region of the reactor core.

In this paper the total loss of argon injection initiating event is analysed both crediting the protection system which actuates the trip of the proton beam as the plant heats up (DBC) and assuming its failure. The latter event, referring to an anticipated abnormal occurrence associated with the failure to "trip" the reactor, is defined as a Anticipated Transient Without Proton Beam Trip event (ATWPBT) in analogy with the practice of the critical nuclear power plants where the failure to shut down the reactor following a frequent initiating event is called an Anticipated Transient Without (reactor) Scram or ATWS.

In both cases the postulated events lead to a core power removal by primary coolant in natural circulation mode.

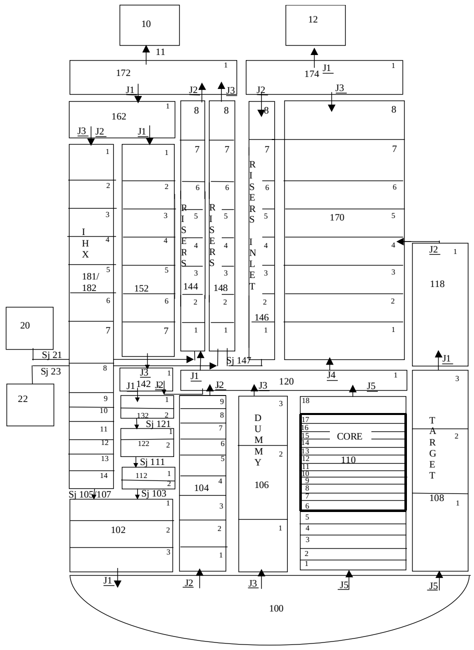
The postulated partial obstruction of a single fuel assembly causes flowrate reduction more and more significant as the residual cross area available to the flow reduces. The local LBE, clad and fuel temperature increase depends from the residual heat removal capability of the affected fuel assembly flowrate and of the bypass coolant flowrate in the interspace between this fuel assembly and the adjacent ones. Due to the mixing phenomena, the obstruction of 1 out of 120 channels produces only localised effects and does not substantially affect the total core flowrate and the outlet core temperature.

4. Computer code, plant models & data

RELAP5/MOD3.2.2 Beta [6] has been chosen for use in the XADS safety analyses due to the capabilities and flexibility which make it capable to adequately represent the main characteristics of this innovative design. However, in order to use it in the XADS safety analyses it has been modified [7] to include specific features of the XADS, such as:

- the use of lead-bismuth as primary coolant and target material;
- the use of gas injection to enhance primary coolant circulation;
- the use of an organic diathermic oil as secondary coolant;
- the rejection of generated heat from the secondary coolant to the external atmosphere via finned heat exchangers (with external air in forced circulation).

Figure 5. **The LBE-cooled XADS PL RELAP5 model**



The RELAP5/MOD3 programme, modified as above, has then been tested:

- against experimental results for lead-bismuth eutectic two-phase flow (experiments performed by Solmecs, Israel, courtesy of ENEA to Ansaldo);
- against producer data for heat transfer calculations for the secondary diathermic organic oil;
- against Russian codes calculations for heat transfer calculations for the primary lead-bismuth coolant.

The XADS model developed for Relap5 code represents all the major primary, secondary and passive safety systems and components of the plant.

The primary system model, reported in Figure 5, essentially simulates the region inside the main vessel. Most of its volume constitutes the primary coolant circulation flow path with only minor fractions of it being filled with quasi stagnant lead-bismuth.

In particular, the main circulation flow path includes:
lower plenum (node 100) → core (node 110) → upper plenum (node 120) → risers (node 144) → downcomer uppermost region (nodes 172 and 162) → IHX region (nodes 181 or 182) → downcomer lowermost region (node 102) → lower plenum (node 100).

Nodes 106 and 104 represent core bypasses via dummy assemblies and through the gap between dummy assemblies and inner vessel. Also, nodes 108 and 118 represent the target.

The two secondary coolant loops of the plant are separately modelled. The model of one secondary loop is reported in Figure 6.

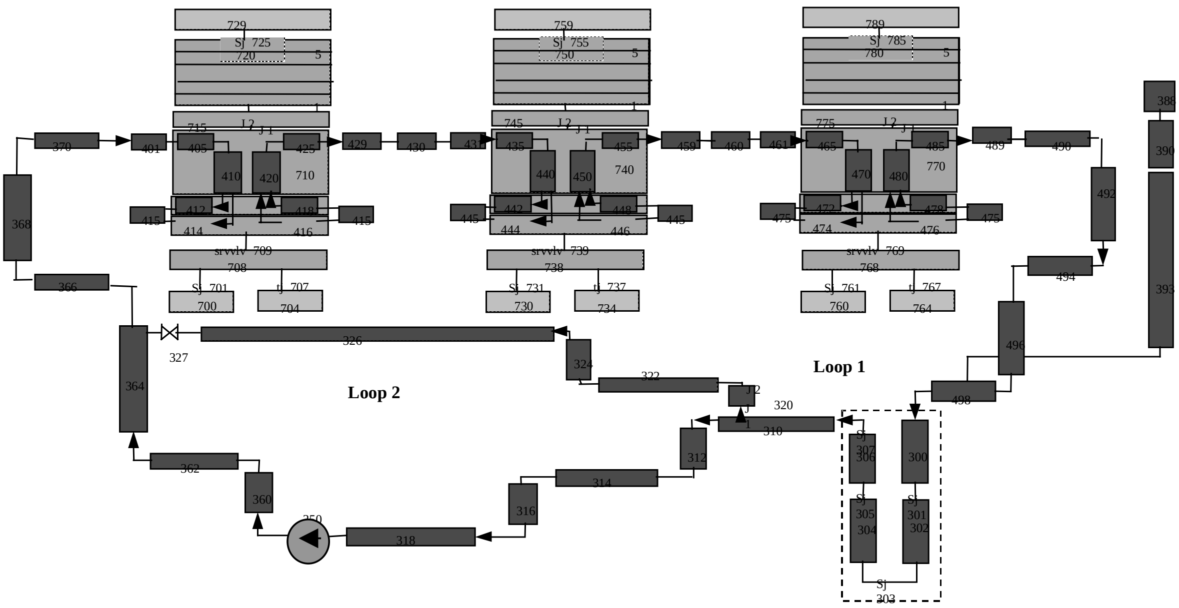
It includes: pump (node 350), pump bypass line (nodes 320 to 326, check valve 327), one IHX, one Air Coolers train, piping (the remaining nodes and junctions) as well as expansion the tank (388).

An Air Coolers Train includes three units each characterised by chimney, fan and regulating devices. In particular the first AC chimney is represented by nodes 700 and 704 (1st air cooler inlet), node 729 (1st air cooler outlet), nodes 730 and 734 (2nd air cooler inlet), node 759 (2nd air cooler outlet), nodes 760 and 764 (3rd air cooler inlet), node 789 (3rd air cooler outlet) represent the external environment.

Each AC is provided with two different inlet flow paths which are employed to simulate the air delivery to each air cooler under natural and forced circulation (namely junctions 701 and 707 for 1st air cooler). It is underlined that primary and secondary coolant temperatures in the XADS are maintained within the established operational range acting on the Air Coolers regulating devices (inlet and outlet louvers, modulating dampers, fans). The control strategy is based on providing the required heat rejection capacity with air flowing, to the extent possible (that is for low operating power levels), in natural circulation; fans are then progressively switched on, as appropriate, for increasing operating power levels.

Consistent with this strategy and starting from hot standby (zero power) operation, the Air Coolers control system thus begins to open the movable dampers of one Air Cooler, moving to the next Air Cooler only when their are completely open. The fan of the first Air Cooler is switched on when the movable dampers of the three Air Coolers are completely open; then its velocity is increased up to the maximum. The fans of the second and then of the third Air Cooler are switched on (and their velocity increased up to the maximum) in sequence.

Figure 6. **The LBE-cooled XADS secondary system RELAP5 model**

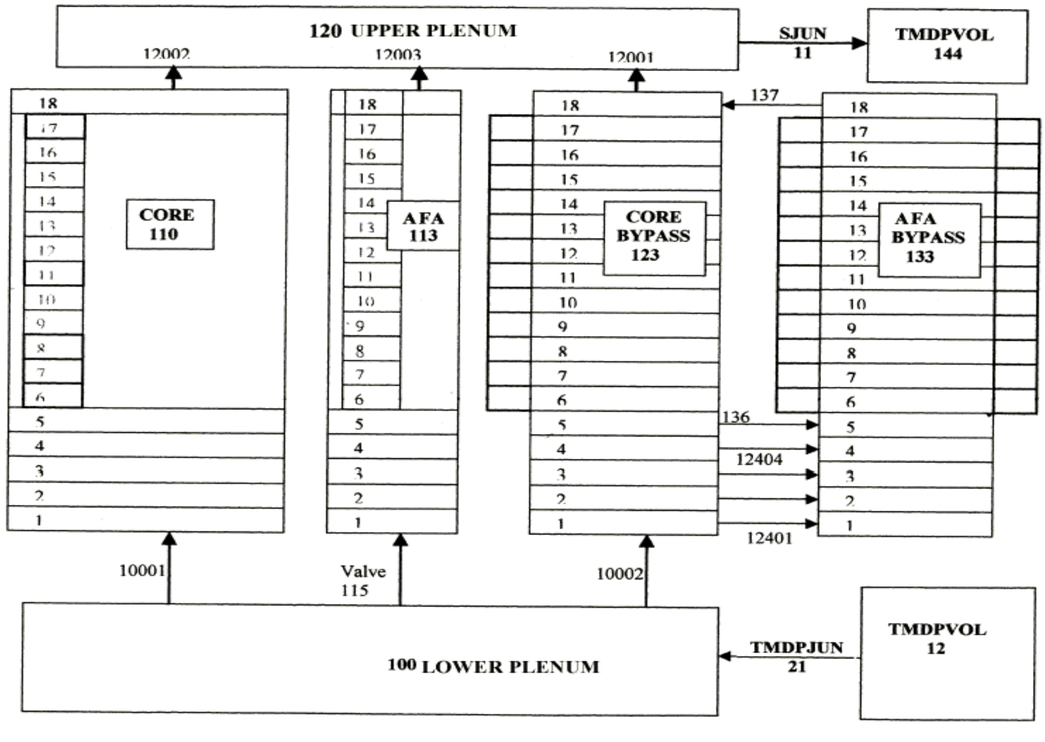


The described Air Coolers control system strategy is implemented in RELAP5 by means of a suitable series of control variables.

The full plant model in Figures 5 and 6 has been used to simulate the total loss of argon injection; while for the single channel flowblockage analyses a simplified scheme was set up (see next Figure 7, [8]) due to the local nature of the relevant thermal hydraulic effects. Indeed only the primary system has been taken into consideration.

Moreover the system components upstream and downstream the core have been collapsed in only two different time dependent volumes (volumes 12 and 144 in Figure 7) in which appropriate values of the pressure and temperature have been imposed. These parameters are kept constant during all the transient. A slightly more detailed nodalisation has been used for the core schematisation. This consists, besides in lower and upper plenums volumes (volumes 100 and 120, respectively), in four additional pipes: the first one, which collapses 119 out of 120 fuel assemblies, represents the whole core fuel assemblies (CORE, pipe component 110) but the affected one; the second represents the fuel channel affected by flow area reduction (AFA, pipe component 113). As for the remaining two pipes, one of them conveys the bypass coolant flowing through the interspace between the affected assembly and the adjacent ones (AFA bypass, pipe component 133), whereas the other conveys the flow rates pertaining to all the remaining fuel assemblies interspaces (CORE bypass, pipe component 123). In order to account of possible effects due to transverse flows involving the affected channel bypass and the unaffected core bypass, these pipes have been connected to each other by cross flow junction placed at suitable location along their axial length. A time dependent junction supplies the lower plenum volume with the nominal flow rate (5 460 kg/s). A motor valve, choking in 10 s to a prescribed flow area, is introduced between lower plenum and affected fuel channel, to make possible the simulation of the channel flow area restriction. Finally, various thermal structures were introduced in order to simulate the heat transfer processes taking place among the core elements schematised as above.

Figure 7. **The LBE-cooled XADS RELAP5 model for flowblockage transients**



The main T/H plant data at nominal operating power are reported in Table 1.

Table 1. **Plant and Core Parameters**

Fission power, MW	80
Proton beam current (at rated power): beginning of cycle, mA end of cycle, mA	 3 6
Reactor pressure (cover gas region), MPa	0.11
Primary coolant flow rate, kg/s	5 961
Core flow rate, kg/sec	5 471
Core inlet temperature, °C	300
Core outlet temperature (at rated power), °C	400
Argon flow rate,	120 N-litres/s
Secondary system pressure (at expansion tank), MPa	0.155
Secondary coolant flow rate (per loop), kg/s	413
Secondary coolant inlet temperature, °C	280
Secondary coolant outlet temperature (at rated power), °C	320
Ambient air flowrate (at rated power), kg/s	750

5. Analysis of results

Argon gas compressor trip with successful proton beam trip

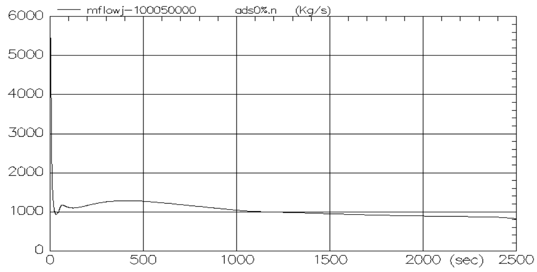
Figures 8 to 12 refer to the transient LBE-cooled XADS response after a gas compressor trip postulated at time=0. s which causes a total loss of the argon mass flow rate injected into the plant risers. In the analysis, no credit has been conservatively given to the Air Coolers Control System which otherwise could mitigate the plant heating up before the proton beam is tripped as well as stabilise the plant conditions following proton beam shutoff.

As a consequence of the initiating event a sudden decrease brings the core coolant mass flow rate from the nominal value of 5 471 kg/s down to a value of 980 kg/s (18% of nominal, Figure 8) due to the transition from forced to natural circulation. Hence the core outlet primary coolant temperature suddenly increases (Figure 9) reaching the proton beam trip set point of 420°C at 6.5 s. After a delay of 2.5 s, the proton beam shutdown takes place determining the generated power to set to decay values. As a consequence the core outlet temperatures quickly decrease; later on the mismatch between the power removed by the secondary system and the generated power causes the decrease of the PbBi core inlet temperature also, which, due to the primary coolant low flowrate, sets after about 200 seconds of delay.

The plant cooldown has been calculated until t=2 500 s time at which the simulations ends.

As referred by Figures 10 and 11, which show the temperature evolution in the lowest, middle and highest portion of the hot rod fuel and clad (short term), the maximum value 1 160 K (887°C) and 780 K (507°C) respectively) is attained at about 10 s. In the following the temperature decreases continuously till the end of the transient. The reactor vessel wall inner temperatures (Figure 12) does not experience any increase with respect to the nominal values as a consequence of the coolant temperature distribution along the path flow. In any case no significant challenges are experienced by the safety related physical barriers (actually there is no overtemperature transient at all for the vessel and only a minor over-temperature for a short time interval for the cladding).

Figure 8. **Gas compressor trip – core flowrate**



It is important to note that the plant cooldown operated by the secondary system causes LBE freezing inside the IHXs at about t=2 300 s (Figure 12) which will prevent freezing of the coolant in the remaining portion of the PL. Owing to the absence of mechanical barriers in the downcomer, natural circulation of the LBE establishes between core and downcomer allowing the decay power removal on the IHXs skirt.

Figure 9. **Gas compressor trip – core inlet and outlet temperature**

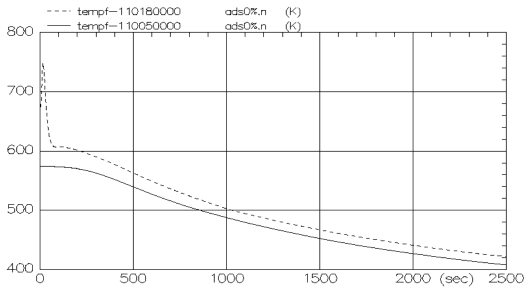


Figure 10. **Gas compressor trip – hot rod fuel temperature (short term)**

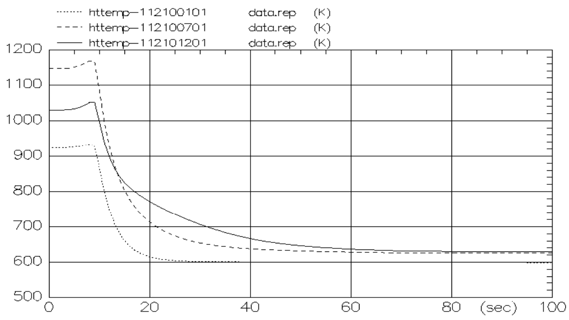


Figure 11. **Gas compressor trip – clad temperature (short term)**

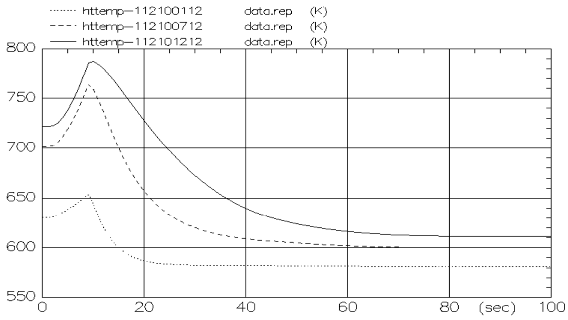
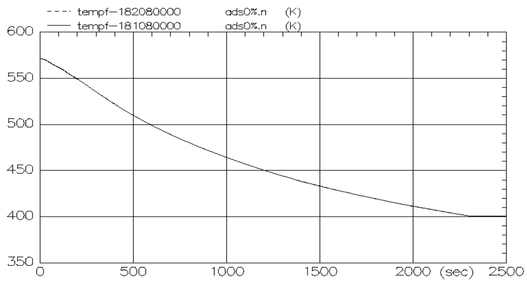


Figure 12. **Gas compressor trip – IHX outlet temperature**



Argon gas compressor trip with failure to trip the proton beam

In the second analysed scenario it is assumed that, in spite of the fact that at t=6.5 s a high lead-bismuth temperature at core outlet is reached, the associated proton beam trip is not actuated. The XADS response to the postulated scenario is illustrated in Figures 13 to 16.

As a consequence of the postulated total loss of argon gas injection into all the risers, assumed instantaneous, the lead-bismuth flowrate in the core rapidly decreases to a minimum of about 1 530 kg/s (28% of the nominal value, Figure 13); then, as the temperature distribution in the main vessel changes, it stabilises at approximately 50% of the nominal value. Consistent with the core flowrate history, Figure 14 shows a rapidly increasing core outlet temperature, peaking for a short while at about 900 K (627°C), then decreasing and stabilising at around 765 K (492°C) (note that the power generated in the core has been assumed to remain constant rather than changing according to the reactivity feedbacks). The LBE temperature increase across the core, after peaking, stabilises at about 190°C. This is consistent with the practically halved lead-bismuth flowrate. From Figure 14, it can be observed that the LBE temperature decrease across the IHX stabilises at around 127°C.

The hot rod cladding (see Figure 15, highest clad portion) and fuel maximum temperatures vary according to the coolant temperature and the (constant) generated power.

The main vessel wall temperatures close to and right below the lead-bismuth free surface also increase, up to approximately 70 K, reaching a maximum of about 743 K (470°C, Figure 16).

Hence the safety related physical barriers (fuel clad and vessel wall) temperatures stabilise at values only moderately higher than nominal values at full power.

Figure 13. **Gas compressor trip with no proton beam trip – core flowrate**

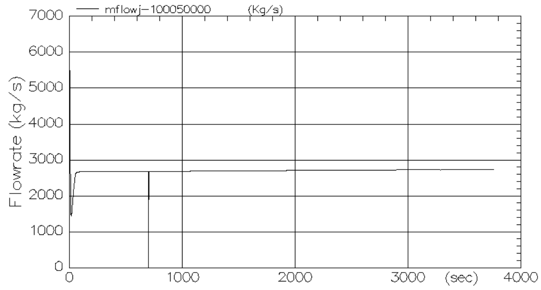


Figure 14. **Gas compressor trip with no proton beam trip – core & IHXs inlet and outlet temperature**

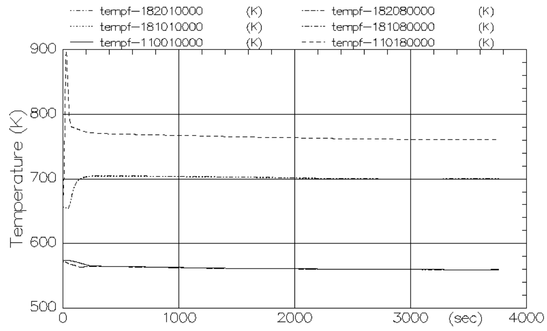


Figure 15. **Gas compressor trip with no proton beam trip – hot rod clad temperature**

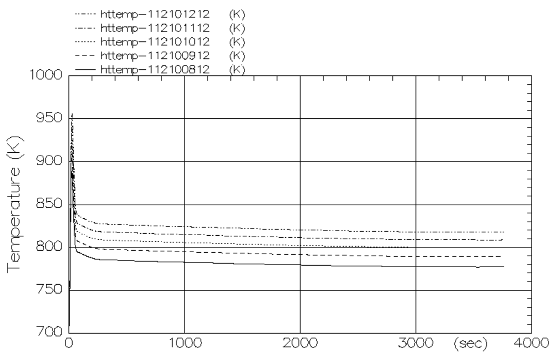
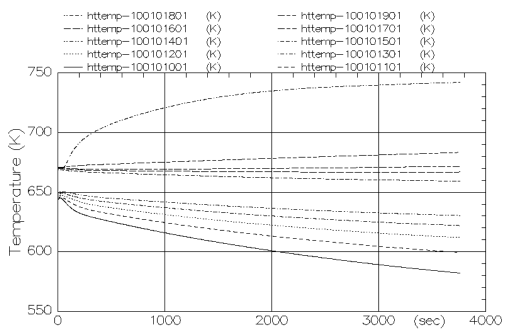


Figure 16. **Gas compressor trip with no proton beam trip – main vessel wall temperature**



Flow reduction in a single fuel assembly

With respect to the single fuel assembly flowblockage transients, in order to consider the worst conditions, it is hypothesised that the flow area reduction takes place at the hottest channel, all other components being however well working.

Different simulations have been performed in which the hottest fuel assembly inlet flow area was reduced by 10% per simulation. When reaching 80% flow area reduction, smaller reduction steps have been used, until the total flow blockage was reached. No proton beam trip is simulated.

Two series of analyses, performed adopting two different values (k=0, k=3) for the loss coefficient in the cross flow junctions between the bypasses, have been carried out. In each simulated transient, after 400 s steady state calculation with the plant at nominal conditions, within 10 s the hottest fuel assembly inlet flow area is reduced down to the established residual cross-sectional flow area. Due to the partial obstruction, the mass flow rate decreases in the affected channel and, consequently, it increases in the relevant bypass. We note that, as there isn't substantial difference between the results of the above said two series of simulations, it isn't worth to report both of them. Therefore, only the second series of results will be illustrated in the following.

As one can see in Figure 17, where the maximum temperatures of coolant, clad and fuel in the affected channel are reported as function of the fractional residual flow area, up to approximately 65% flow area reduction (A/Ao = 0.35), the clad temperature increase is indeed small (less than 80°C) so that even a non coated material is not likely to experience failure. For reduced residual flow areas (A/Ao<0.35) the maximum clad temperature rises faster and faster; however the clad fusion temperature (1 473 K) is predicted only when the affected channel flow area reduces to about 2% of its nominal value. Note that in this case an amount of about 60% of the AFA generated power (860 Kw) is removed radially. Fuel melting as well as coolant boiling is never predicted.

In Figure 18 the affected channel flow rate decrease as function of the progressive flow area reduction is reported. In the same figure the corresponding increase of the flow rate through the relevant bypass is also reported. Figure 19 shows the power exiting radially from HFA (Hot Fuel Assembly), the power removed by AFA (Affected Fuel Assembly) bypass coolant, the power transferred to adjacent FAs coolant; up to 65% area reduction the fuel element bypass substantially receives power from both the HFA coolant and other FAs coolant. For larger area reduction, the HFA bypass coolant begins to remove an increasing amount of power from the HFA and deliver part of it to adjacent FAs. Finally, as a further illustration of the flowblockage transient progression, in Figures 20 through 22 the axial hot channel temperature distributions in the cases: A/Ao = 1, normal condition; A/Ao = 0.35, A/Ao = 0.03, just before clad melting are reported.

It has to be outlined that the predicted cladding melting in case of AFA A/Ao <0.03 should be avoided if the crediting of a LBE fuel element high outlet temperature signal would actuate the proton beam trip. In this case in fact, also assuming a total AFA flowblockage, the removal of the decay power (less than a 10% of the nominal value) through the adjacent FAs would establish, avoiding excessive cladding temperature increase.

Figure 17. **Flow blockage – maximum temperature as function of normalised residual flow area in AFA**

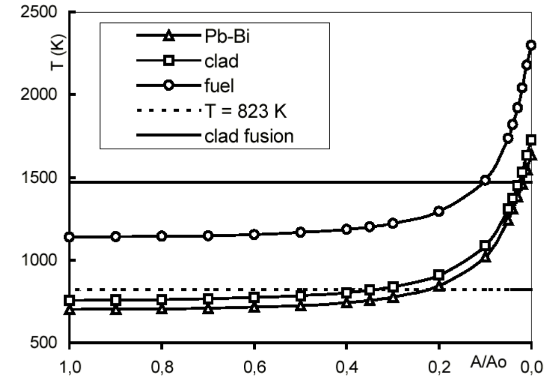


Figure 18. **Flow blockage – Pb-Bi flow rates in the affected fuel channel and in the relevant bypass**

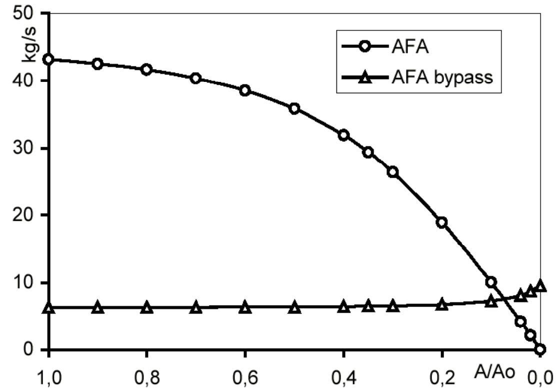


Figure 19. **Flow blockage – (°) Power exiting radially from HFA, (Δ) power removed by AFA bypass coolant, (□) power transferred to ajacent FAs coolant**

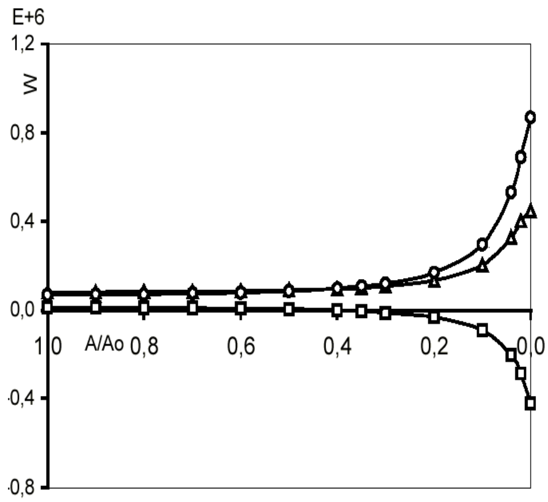


Figure 20. **Flow blockage – AFA axial temperature distribution for A/A0 = 1**

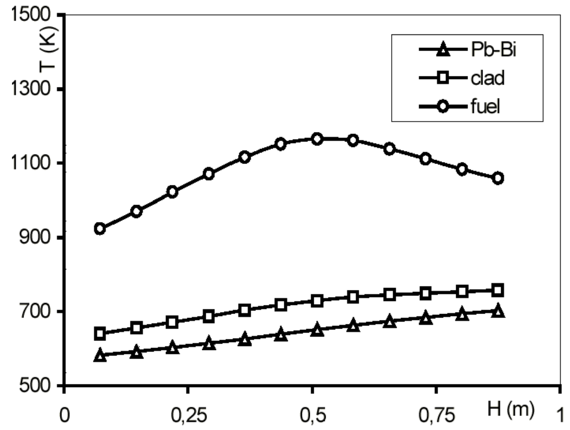


Figure 21. **Flow blockage – AFA axial temperature distribution for A/A0 = 0.35**

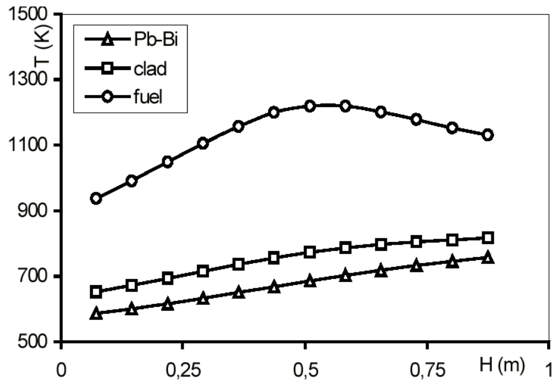
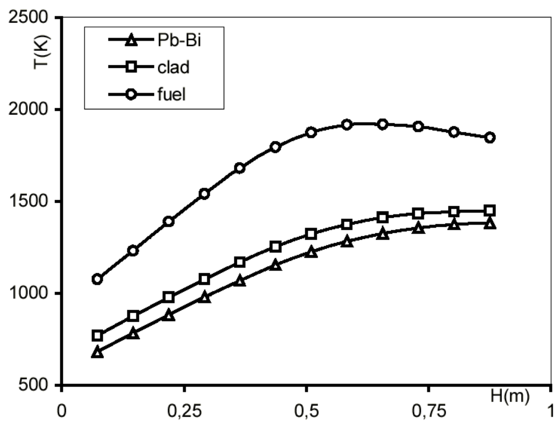


Figure 22. **Flow blockage – AFA axial temperature distribution for A/A0 = 0.03**



The above results indicate that:

- the LBE-cooled ADS is very tolerant to flowblockage (no significant temperature effects up to a 65% fuel assembly flow area reduction);

- for higher flowblockage a peculiar heat transfer mechanism rejecting an increasing amount of heat radially to the coolant flowing outside the affected fuel assembly establishes; this prevents coolant boiling and fuel melting also assuming the plant at full power;
- the complete flowblockage will be tolerated without any significant clad and fuel temperature increase crediting the proton beam trip on a LBE fuel element high outlet temperature protection signal.

6. Conclusions

The reported results of some loss of primary flow events in a Pb-Bi-cooled XADS indicate that:

- following a loss of primary flow originated by a postulated total loss of argon injection to enhance it, the primary coolant mass flowrate decrease promptly causes higher differential temperature across the core which readily actuates the plant protection system (proton beam trip) as the high core outlet coolant temperature setpoint is attained. No significant challenges are experienced by the safety related physical barriers (actually there is no over-temperature transient at all for the vessel and only a minor over-temperature for a short time interval for the cladding).

- a moderate increase of the primary temperatures is caused by the total loss of argon injection without proton beam trip. The hot rod cladding and fuel maximum temperatures vary according to the coolant temperature and the (constant) generated power. While the coolant temperature increase across the core moves from 100°C to 190°C, the main vessel wall temperatures close to and right below the lead-bismuth free surface increases up to approximately 70 K. In any case the safety related physical barriers (fuel clad and vessel wall) temperatures stabilise at values only moderately higher than nominal values at full power. The residual primary lead-bismuth flowrate of approximately 50% indicates that the primary system geometry, as currently designed, allows a significant degree of natural circulation in case of total loss of argon injection without proton beam trip

- In case of accidental obstructions of the hot fuel channel inlet flow area up to total flowblockage, the affected fuel element coolant mass flow rate decrease causes the coolant temperature increase. Simulations results indicate that:
  - the LBE-cooled ADS is very tolerant to flowblockage (no significant temperature effects up to a 65% fuel assembly flow area reduction are predicted);
  - for higher flowblockage a peculiar heat transfer mechanism rejecting an increasing amount of heat radially to the coolant flowing outside the affected fuel assembly establishes; this prevents coolant boiling and fuel melting melting also assuming the plant at full power;
  - the complete flowblockage will be tolerated without any significant clad and fuel temperature increase crediting the proton beam trip on a LBE fuel element high outlet temperature protection signal.

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