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Comparative Study of the Transient Behaviour of the 80MWth LBE- and Gas-cooled XADS using TRAC/AAA

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ABSTRACT: A comparison of transient calculations is given for two 80-MWt MOX-fuelled Experimental Accelerator-Driven Systems (XADS), one cooled by lead-bismuth eutectic and the other by helium. Results obtained with the TRAC/AAA code are presented for protected and unprotected transient overpower, spurious beam trip, loss of flow, and loss of coolant accidents.

KEYWORDS: *transient, XADS, TRAC/AAA*

I. INTRODUCTION

Within the EU 5th Framework Programme, the Preliminary Design Study of an Experimental Accelerator-Driven System (PDS-XADS) project was primarily focused on the study of two 80 MWt design options for which the core was cooled either by lead-bismuth eutectic (LBE) [1] or helium [2], both cores being driven by a neutron spallation source, generated by a proton accelerator beam impacting an LBE windowless target. One of the Work Packages of the PDS-XADS Project was concerned with the assessment of the safety of the two 80 MWt designs [3] in regard to the following main objectives:

- to develop an integrated safety approach, common to both the LBE- and the gas-cooled concepts;
- to identify the main XADS safety issues, along with their phenomenology, and develop an evaluation methodology for both alternatives; and
- to perform transient analyses, with the aim of producing safety analysis reports identifying the design features needed to meet the XADS safety objectives.

A separate Work Package considered the design and safety of a third XADS system: the 50 MWt LBE-cooled MYRRHA concept.

In this paper, representative results of the transient analyses performed at PSI in relation to the PDS-XADS study are discussed. The list of transients considered includes protected and unprotected transient overpower, spurious beam-trip incidents, and loss of flow and loss of coolant accidents. The transients were simulated using the TRAC/AAA code [4], which is part of the FAST code system [5] being developed at PSI for the comprehensive safety analysis of advanced, fast-spectrum reactors. The TRAC/AAA code is based on the USNRC LWR transient analysis code TRAC, and includes a 3D (hydraulic) vessel component, generalised heat structure components to model the fuel rods, heat exchangers, environmental heat losses, etc., as well as models for all "normal" reactor components, such as pumps, valves, separators, turbines, etc. In addition, the AAA version has been modified by the US DoE and PSI for application to advanced fast reactor systems.

II. LBE- AND HE-COOLED XADS CONCEPTS

The main parameters of the 80 MWt MOX-fuelled LBE- and He-cooled ADS demonstration facilities, as developed by Ansaldo [1] and Framatome [2], are given in Table 1.

The core diagrams of the LBE and He systems are presented in Fig. 1a and Fig. 1b, respectively. The subcritical core (in each option with $k_{eff} \sim 0.97$) has an annular configuration. A spallation neutron source unit is inserted in the core central void region. This source unit has its own circuit, with circulating LBE acting both as coolant and target material.

The reactor layout arrangements of the LBE and He systems are shown in side view in Fig. 2a and Fig. 2b, respectively. The LBE-cooled system is a pool-type design (Fig. 2a), but does not use traditional mechanical pumps in the primary system. Instead, the natural circulation of the primary LBE is enhanced using gas lift pumps. The primary coolant flowing out of the core collects in the hot plenum, spreads out to the periphery, and enters the vertical pipes or risers, which are installed over the periphery of the upstand region. Argon, extracted from the cover gas above the LBE surface, is fed via a compressor into the bottom of each riser tube to create an upward two-phase (LBE/gas) flow stream. The resultant difference in fluid density between the riser and the downcomer generates the pressure difference needed to drive the natural circulation coolant flow.

Table 1: Main parameters of LBE/He XADS concepts.

Parameter	LBE	He
Nominal thermal power (MWt)	80	80
Multiplication factor k_{eff} at BOC	0.973	0.970
Number of FSAs	120	90
Number of pins per FSA	90	37
FSA flat-to-flat distance (mm)	138	120
Fuel type/ Fuel mass (t)	MOX/3.24	MOX/4.37
Plutonium content (%)	23	35
Core inner/outer diameter (m)	0.58/1.7	0.48/1.4
Fuel height (mm)	900	1500
Fuel pellet inner diameter (mm)	1.8	3.2
Fuel pellet outer diameter (mm)	7.14	11.5
Clad outer diameter (mm)	8.5	13
Pitch to diameter ratio	1.58	1.29
Average power rating (W/cm)	82	160
Peak power rating (W/cm)	130	256
Primary coolant/pressure (MPa)	PbBi/1	He/6
Inlet coolant temperature (ºC)	300	200
Outlet coolant temperature (ºC)	400	450
Peak fuel temperature (ºC)*	1047	1648
Peak clad temperature(ºC)*	494	541
Core mass flowrate (kg/s)	5460	61.6
Core pressure drop (kPa)	25	100

*calculated using TRAC/AAA

After exiting the risers, the flow direction of the primary coolant changes from upward to downward, and the gas separates at the interface with the cover gas, thus closing the gas loop. The resulting single-phase LBE flows downwards in the surrounding annulus or downcomer. The major part of the coolant flows through the intermediate heat exchangers (IHXs), installed in the downcomer, transferring heat to the secondary fluid. A small fraction, however, flows down through the IHX bypass, transferring heat through the gas gap between the reactor vessel and the guard vessel to the Reactor Vessel Air Cooling System (RVACS).

In comparing the transient response characteristics of the two 80 MWt XADSs, a number of issues require particular attention. The He-cooled XADS design has:

- a much lower heat transfer coefficient between cladding and coolant;
- a low thermal inertia in the active core region, as well as in the primary system, because of the low density of the gas coolant, thus providing a limited temporary heat sink (buffer) to the heat stored in the fuel;
- a relatively low natural convection flow rate, due to the low density of the coolant (natural convection at nominal conditions provides only about 7% of nominal flow rate, in comparison to the LBE-cooled system in which 30-40% of nominal flow is due to natural convection); and
- a linear power rating about twice as high as that of the LBE-cooled design, due to the higher fuel pin diameter in the gas-cooled core, and resulting in a steady-state peak fuel temperature about 600ºC higher than for the LBE system, while the average coolant temperature at core outlet, as well as the peak cladding temperature, are only about 50ºC higher (see Table 1).

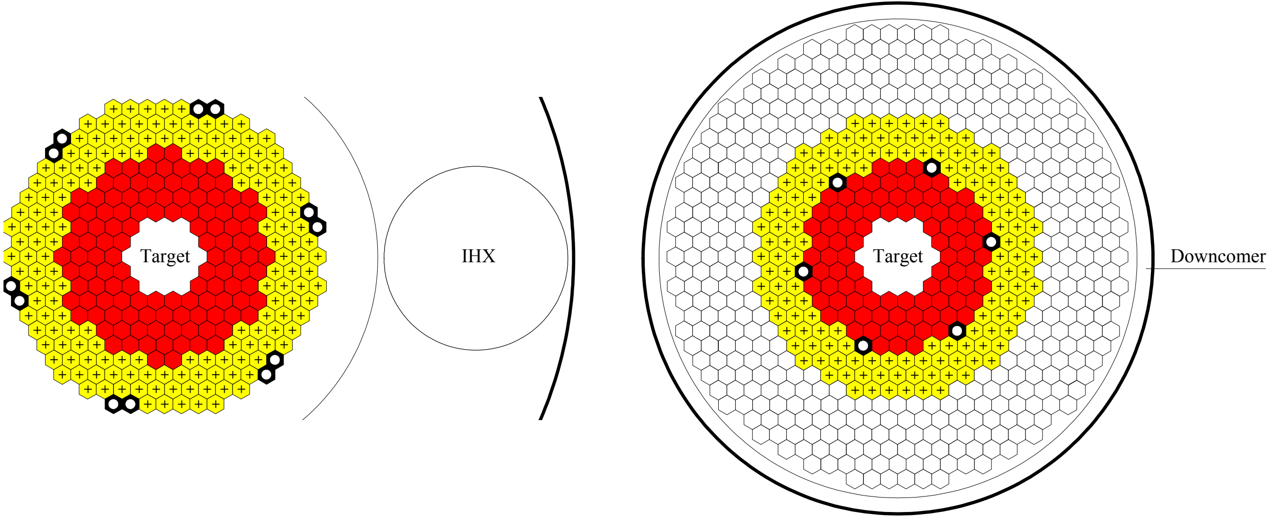
The combination of the above four factors makes the He-cooled XADS design rather sensitive to any perturbation to the balance between the heat generated in the fuel and the heat removed by the flowing coolant. The LOF and LOCA transients are particularly influenced, since a mismatch of heat generation and heat removal causes a brief core temperature overshoot during these events. This overshoot can be minimized by appropriate design measures in the core, subassembly and pin layout, in conjunction with the implementation of appropriate operational procedures.

III. TRAC/AAA REPRESENTATION (NODALIZATION DIAGRAMS)

Advantage was taken of the modelling capability of the TRAC/AAA code to develop a 3D representation of the primary vessel. An R-Z-θ TRAC/AAA vessel component was used for both the LBE-cooled and the He-cooled XADSs, while one-dimensional pipe components were used to simulate the channels of both the primary heat exchangers and the secondary circuits. The reactor core fuel rods, core diagrid, heat exchanger tubing and vessel wall were all represented using heat structure components. The core cooling was simulated with parallel channels representing groups (rings) of sub-assemblies.

The TRAC/AAA source-driven point kinetics model was used in the reactor power calculation, with the Doppler and coolant density reactivity feedbacks derived from static reactor calculations. In addition, the TRAC/AAA code was modified at PSI [6] to simulate the reactivity feedbacks due to fuel axial expansion and core-diagrid radial expansion. A separate heat structure, coupled to the relevant hydraulic volumes at the core inlet, was used to simulate the core diagrid. The ANS-79 decay-heat standard was used to estimate the decay-heat power. In the case of the LBE XADS, the equilibrium power generated in the coolant due to ^{210}Po α-decay was uniformly distributed in the primary coolant using a model unique to the TRAC/AAA code in which heat is deposited directly into the coolant.

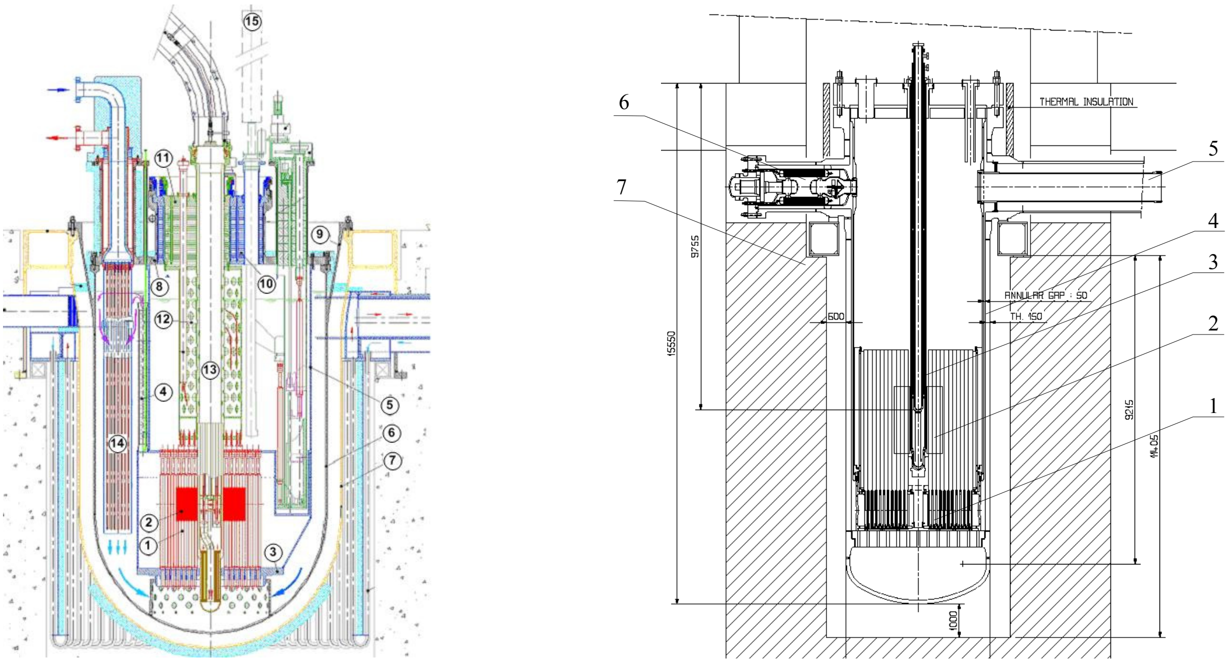
For the protected accidents, an accelerator beam trip was assumed to occur if the core outlet coolant temperature reached 420ºC for the LBE-cooled XADS, and 500°C for the He-cooled system. (These temperatures represent a 20% increase in the core heating.) The gas-cooled system also includes a number of other beam-trip signals, i.e. those based on “main blower status”, system pressure, etc.



a) LBE-cooled system

b) gas-cooled system

Fig. 1: Horizontal Sectional Views of the Two XADS Core Designs
⬢ – fuel assembly; ⊕ – reflector; ⭘ – control rod; ⬡ – shield.



1 – reactor core
2 – fuel zone
3 – diagrid
4 – riser channel
5 – inner vessel
6 – reactor vessel
7 – safety vessel
8 – reactor roof
9 – vessel support
10 – rotating plug
11/12 – above core structures
13 – target unit
14 – IHX
15 – transfer machine

a) LBE-cooled system

1 – core diagrid
2 – core
3 – target unit
4 – reactor vessel
5 – cross duct to PCS
6 – SCS unit
7 – reactor vault

b) He-cooled system

Fig. 2: Vertical Sectional Views of the two XADS System Designs.

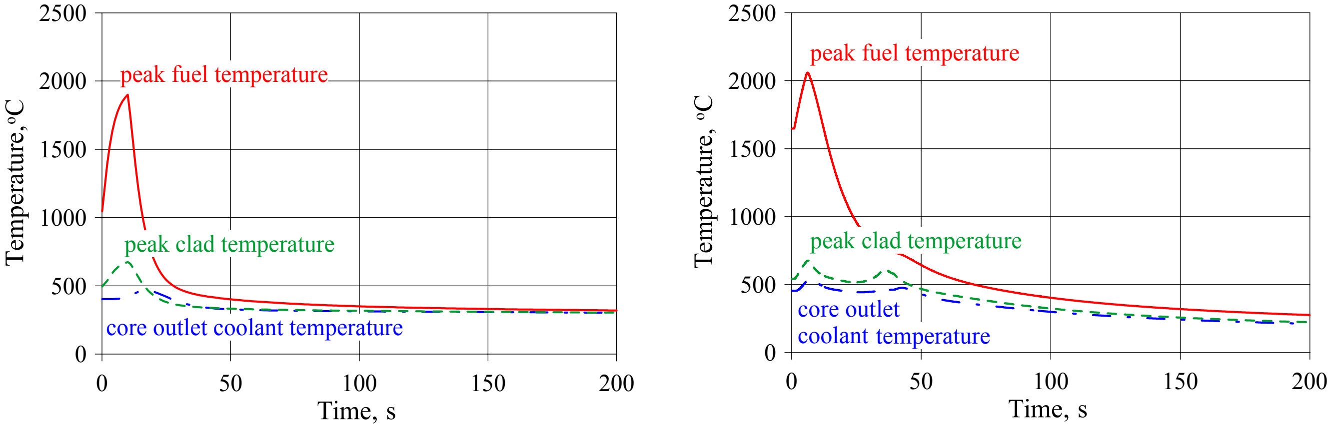
IV. RESULTS

Results are presented below for a number of protected and unprotected accidents, including transient overpower, spurious beam trip, loss of flow (LOF), and loss of coolant accidents (LOCAs).

1. Transient Overpower Accident (TOP)

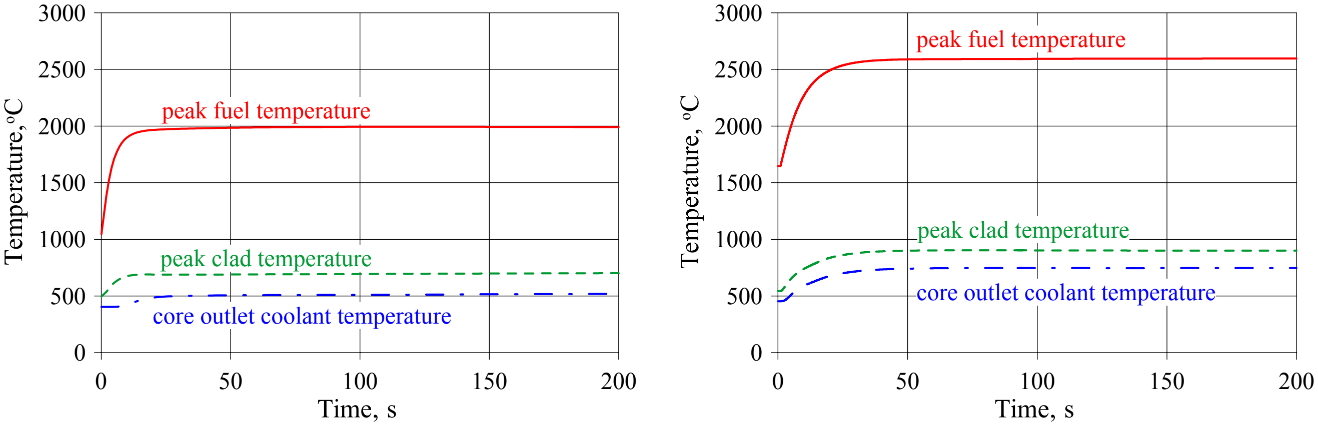
As a bounding (even if unrealistic) case, a TOP accident has been considered with an insertion of positive reactivity of 2000 pcm. It is to be expected (see below) that the consequences of such a transient will be relatively mild, since the subcriticality level of the two XADSs (k_{eff}~0.97) was chosen such that the reactor core remains subcritical for all credible reactivity insertions. Comparative results for the protected (PTOP) and unprotected (UTOP) accidents are shown in Fig. 3 and Fig. 4, respectively. For both the LBE-cooled and He-cooled XADSs, the reactor power at first increases rapidly, as a consequence of the reactivity insertion, but then slowly decreases due to the reactivity feedback resulting from the increase in core temperature. In the case of the protected accident, this feedback continues until the beam trip, which ultimately reduces the reactor power to the decay-heat level. The power reduction after the beam trip leads to a decrease in the core temperatures, resulting in an increase of reactivity due to temperature feedbacks.

The responses of the clad and coolant temperatures are very close for the two systems, while the peak fuel temperature in the He-cooled XADS is 160ºC higher for the PTOP, and 600ºC higher for the UTOP, compared to the LBE-cooled system, mainly because of the initial difference in peak fuel temperatures for the two systems.



a) LBE-cooled XADS b) He-cooled XADS

Fig. 3: Results for 2000 pcm Protected Transient Overpower Accident.

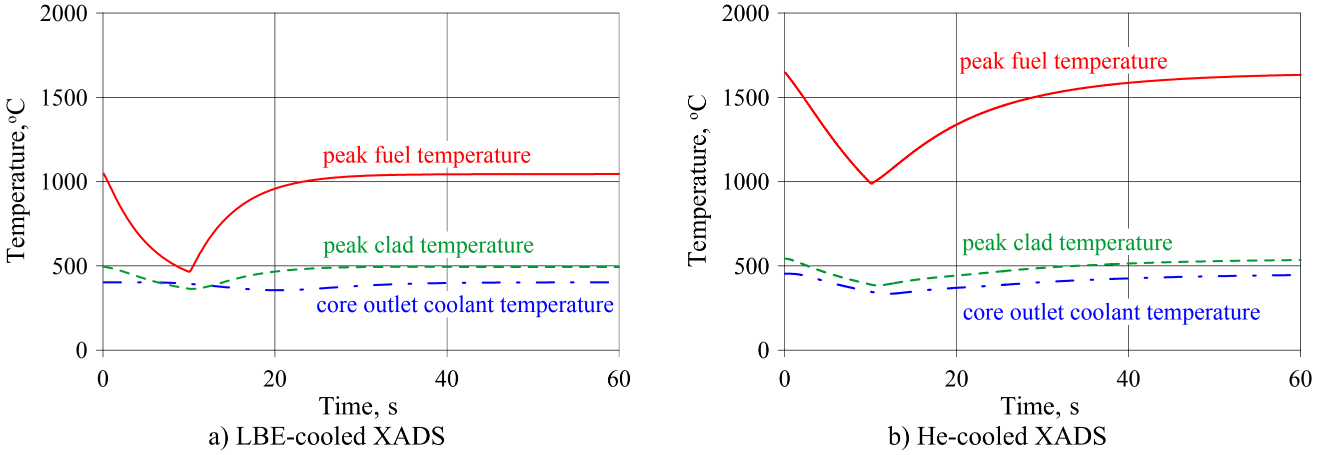


a) LBE-cooled XADS b) He-cooled XADS

Fig. 4: Results for 2000 pcm Unprotected Transient Overpower Accident.

2. Spurious Beam Trip (BT)

One of the current limiting factors for ADSs is the lack of reliability of the associated accelerators. It is therefore necessary to consider the systems response to beam-trip incidents. We present here results of a 10s beam trip (Fig. 5), i.e. for which the accelerator beam is tripped and then restarted after a delay of 10 s. All temperatures decrease following the beam-trip, but by different amounts, and on different time scales. After the beam is reactivated, temperatures return to their steady-state values. However, due to the fuel temperature reactivity feedback, the power slightly overshoots the steady-state value. The temperature responses are very similar for both systems, except that the initial peak fuel temperature for the gas-cooled XADS is 600ºC higher than that of the LBE-cooled system, and the recovery time is longer.



a) LBE-cooled XADS b) He-cooled XADS

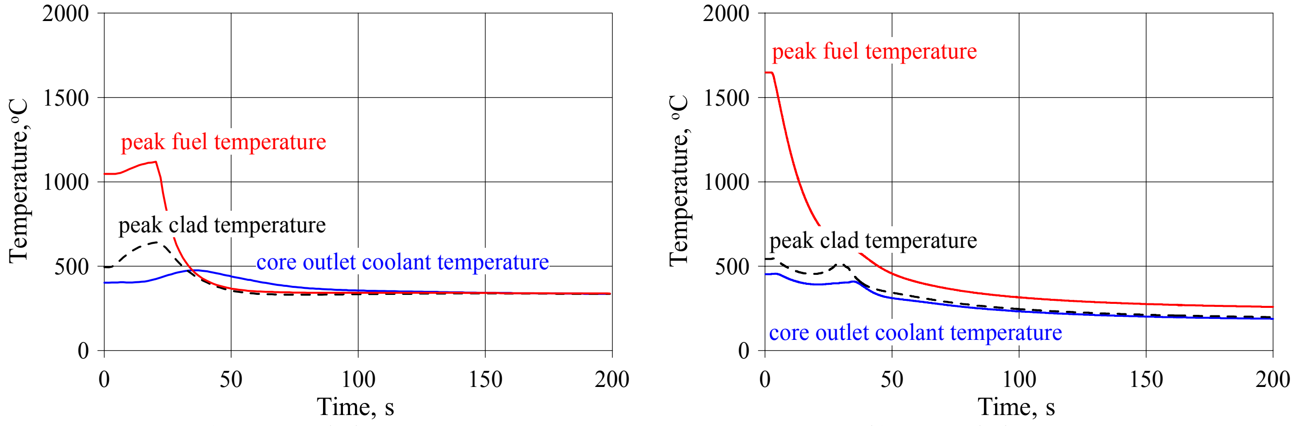
Fig. 5: Results for 10 s Beam Trip Incident.

3. Loss of Flow Accident (LOF)

For the LBE system, the LOF accident is simulated by interrupting the argon supply to the gas lift pumps. In contrast, for the He system, the accident is initiated by cutting off the primary blower, with the subsequent actuation of 2 of the 3 shutdown cooling system (SCS) units. The results of these calculations are shown in Fig. 6 and Fig. 7 for the protected and unprotected cases, respectively.

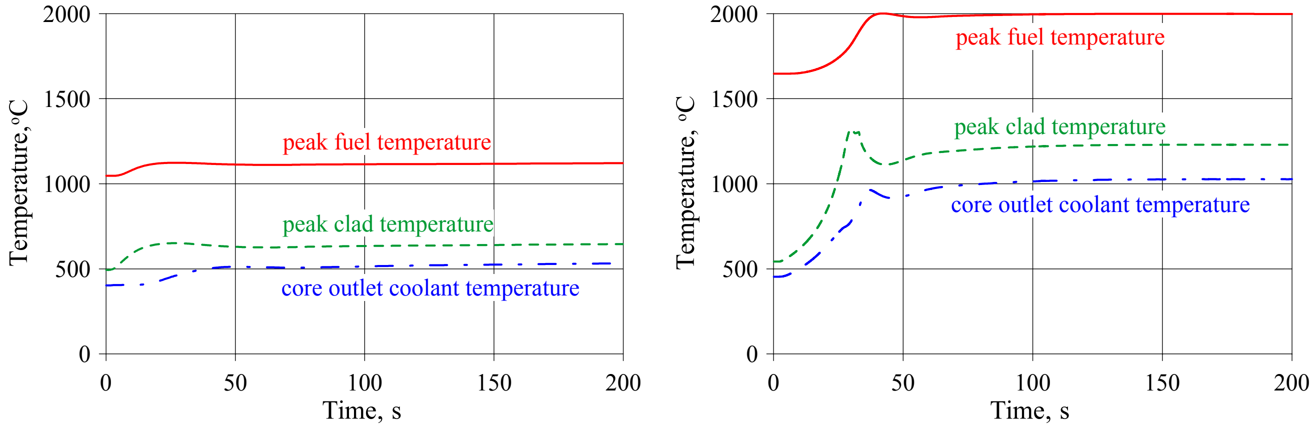
For the protected case, the beam trip for the He-cooled XADS (Fig. 6b) occurs at the beginning of the transient, using the "main blower status" as the triggering signal. As a consequence, all temperatures decrease monotonically thereafter. However, for the LBE case (Fig. 6a), there is initially a temperature increase (70ºC for the fuel and 150ºC for the cladding) until the coolant outlet temperature reaches 420ºC, at which time the beam-trip signal is generated.

For the unprotected case (Fig. 7), the temperature increase in the gas system is much higher than for the LBE system. This is because the natural-circulation contribution to the LBE coolant flowrate is very high (more than 40% at nominal conditions), and peak temperatures stabilize at 1120ºC for the fuel, and 640ºC for the cladding. For the gas system, however, the two SCS units provide a flow rate of only about 20% of the nominal value with the blowers in operation. As a consequence, the peak temperatures stabilize at much higher levels: 2000ºC for the fuel, and 1220ºC for the cladding.



a) LBE-cooled XADS b) He-cooled XADS

Fig. 6: Results for Protected Loss of Flow Accident.



a) LBE-cooled XADS b) He-cooled XADS

Fig. 7: Results for Unprotected Loss of Flow Accident.

4. Loss of Coolant Accident (LOCA)

For the LBE concept, which is an unpressurized pool-type system, the LOCA event was simulated using a leak valve at the bottom of the primary vessel. The coolant then drained from the vessel under gravity. For the He system (coolant pressure around 60 bar), the transient was modelled by opening a leak valve connected to the pipe between the main vessel and power conversion system. The break area was assumed to be 30 cm^2, and the outer pressure was set to 1 bar. The results of these calculations are shown in Fig. 8 and Fig. 9, for the protected and unprotected cases, respectively.

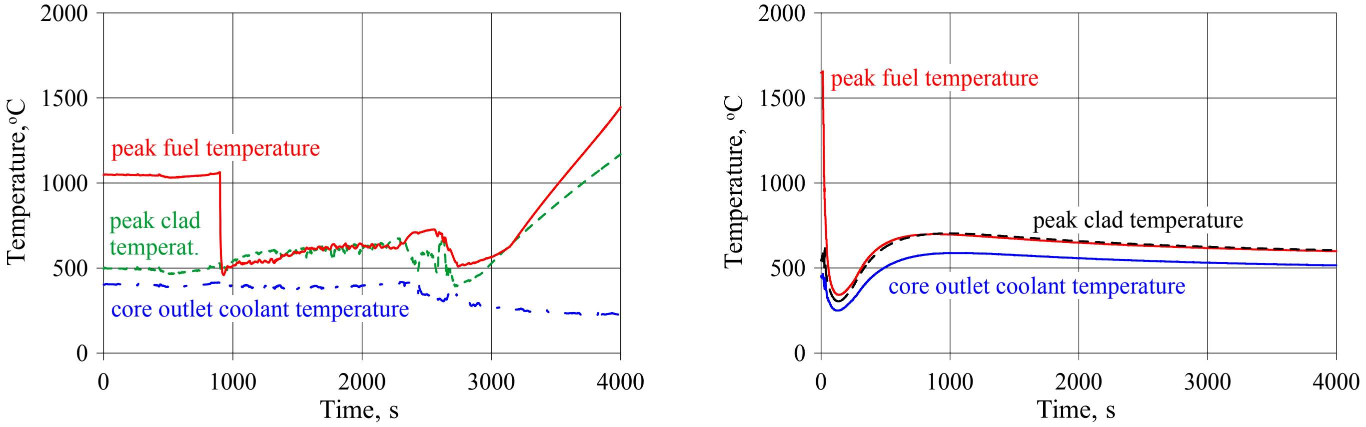
For the protected case, we assumed that all primary and secondary pumps of the LBE system stopped instantaneously at the moment of the beam trip. From Fig. 8a, we see that in the LBE system the reactor trip occurs at approximately 900s, at the time the reactor coolant level has fallen by about 2 m. Subsequently, the core flow rate falls to a low value, as a result of the tripping of all of the forced-circulation systems. The main circuit breaks, and natural circulation is established through a special orifice connecting the upper plenum with the IHX bypass. However, even after such a short time, the heat removed by the reactor vessel cooling system, together with the residual flow through the IHXs, is sufficient to match the decay heat, so that there is only a very slow increase in the primary system temperatures (Fig. 8a). This continues until about 2500s, when the coolant level has fallen to just above the top of the fuel. By this time, about 135 m^3 of coolant has been lost from the primary system. With continuing loss of LBE, the top of the core becomes uncovered, and core temperatures increase rapidly. The calculations predict that the temperature increase would lead to clad failure after 164 m^3 of coolant had been lost from the primary system. To avoid such severe consequences, the LBE coolant loss is designed to be limited to about 75 m^3 by collecting the lost LBE inside the safety vessel, thereby balancing the gravity head inside and outside the reactor vessel. Even if the safety vessel fails, the loss of LBE will be limited to about 135 m^3 due to collection inside the reactor cavity.

For the He-cooled XADS, the accelerator beam trip is initiated by a loss-of-pressure signal at 14 s into the transient (Fig. 8b). The primary blower is tripped following the accelerator beam trip, and the SCS blowers are actuated, providing, at atmospheric pressure, a forced mass flow of coolant at 2% of the nominal value. The clad temperature reaches 700ºC at 1000 s, but slowly decreases thereafter.

In the unprotected case, for the LBE system, all pumps were assumed to continue in operation following the beam trip. Calculation shows that the core flow rate continues at approximately its nominal value, even as the coolant is being lost from the reactor vessel. This means that all of the reactor power would continue to be removed through the IHXs to the secondary loops. The reason that the core flowrate is maintained, in spite of the loss of coolant inventory, is a consequence of the increase in void fraction in the riser as the pressure head decreases. This results in the two-phase level remaining above the top of the IHX inlets for an extended period, thereby maintaining the flow into the IHXs and around the reactor vessel (see Fig. 2a). After about 800 s, when the coolant level has fallen by about 2 m, the core flow rate begins to decrease. This continues until the level falls by more than 3 m (about 1400 s), at which time the coolant circulation flow path through the IHXs breaks down, and the heat removal capacity is strongly reduced, with the result that core temperatures increase rapidly, leading to clad failure (by melting) at 1500ºC. The loss of inventory at this point is about 75 m^3. This means that no severe consequences will ensue, provided the coolant remains inside the reactor safety vessel. In contrast, for the gas system (Fig. 9b), core temperatures rapidly increase. Clad failure occurs at 1500ºC, about 60 s after initiation of the accident, and the calculation stops at this time.

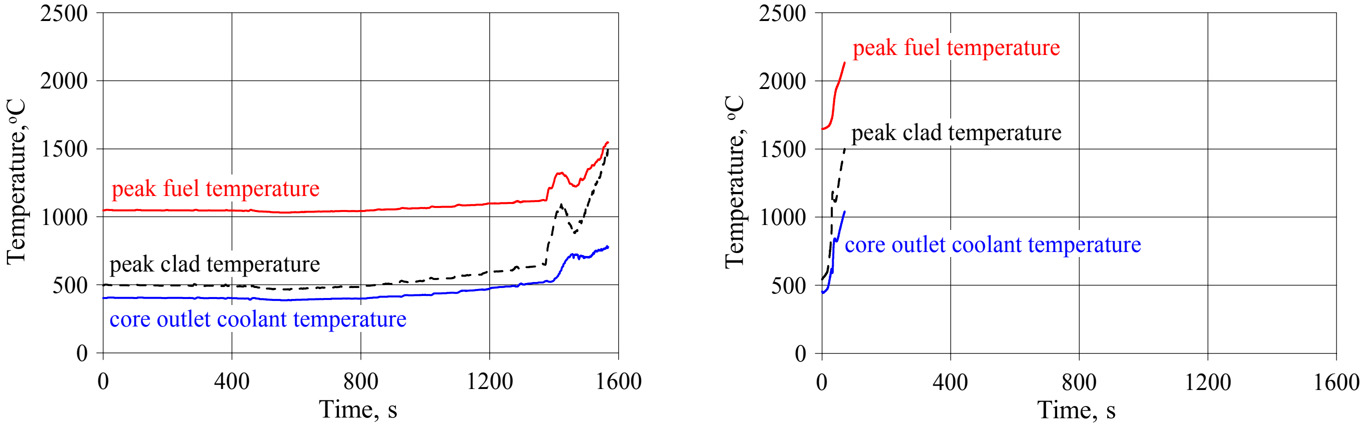
V. CONCLUSIONS

Analysis of a wide spectrum of accidents has been performed using the FAST code system for two 80 MWt MOX-fuelled XADSs, one cooled by LBE and the other by He. The results obtained have shown that the LBE-cooled XADS exhibit very wide safety margins (for both protected and unprotected transients) as a consequence of very favourable safety characteristics, including excellent heat transfer properties, the high boiling point of the coolant, favourable in-vessel and secondary system coolant natural circulation flow characteristics, and the large thermal inertia within the primary system due to the high LBE inventory (pool design).



a) LBE-cooled XADS b) He-cooled XADS

Fig. 8: Results for the Protected Loss-of-Coolant Accident.



a) LBE-cooled XADS b) He-cooled XADS

Fig. 9: Results for the Unprotected Loss-of-Coolant Accident.

For the He-cooled concept, the results demonstrate the importance of core heat transfer, the need for an adequate decay heat removal system (for both protected depressurization and loss of flow transients), and the availability of an appropriate time window for backup proton beam shutdown systems in the event of an unprotected transient.

For reactivity accidents, an envelope transient, with a reactivity insertion of 2000 pcm, was considered. As expected, the consequences of such transients have been found to be relatively mild, since the subcriticality level of both the XADSs ($k_{eff} \sim 0.97$) was chosen such that the reactor core remains subcritical for all credible reactivity insertions.

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