COMPARATIVE TRANSIENT ANALYSIS OF Pb/Bi AND GAS-COOLED XADS CONCEPTS

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Abstract

In the field of waste management incorporating a transmutation option, accelerator-driven systems (ADS) represent an important alternative to conventional reactors due to their higher safety level when minor actinides (such as neptunium and americium) are loaded into the core. The Preliminary Design Study of an Experimental Accelerator-driven System (PDS-XADS) is being performed within the European Union's Fifth Framework Programme. The main goal of PDS-XADS is to demonstrate the feasibility of an ADS and to compare different coolant (Pb/Bi and gas) and power (50-80 MWth) options. At this stage, all options use MOX fuel. Comparative safety analyses were performed using the TRAC/AAA code for the 80 MWth Pb/Bi and gas-cooled designs. The analyses covered reactivity increase (as an example of perturbations of the core), transient overcurrent (as an example of perturbations of the source) and loss of coolant (as an example of transients coming from faults in the primary and secondary coolant systems).

Introduction

In the field of waste management incorporating a transmutation option, accelerator-driven systems (ADS) represent an important alternative to conventional reactors due to their higher safety level when minor actinides (e.g. neptunium and americium) are loaded into the core. Within the European Union Fifth Framework Programme (FP5), several ADS-related projects are being performed, one of which is the Preliminary Design Study of an Experimental Accelerator-driven System (PDS-XADS). The main goal of PDS-XADS is to demonstrate the feasibility of an ADS and to compare different coolant (Pb/Bi and gas) and power (50-80 MWth) options. At this stage, all options use MOX fuel.

Comparative safety analyses were performed using an adapted version of the TRAC/AAA code [1] for both the 80 MWth Pb/Bi and gas-cooled designs. The analyses presented in this paper cover reactivity increase (as an example of perturbations of the core), transient overcurrent (as an example of perturbations of the source) and loss of coolant (as an example of transients coming from faults in the primary and secondary coolant systems).

A detailed evaluation of reactor safety depends on a wide range of considerations, including possible initiating events, response of the reactor core, reactor coolant and mitigating effects, e.g. shutdown mechanisms, decay heat removal, etc. Many of these features are design specific, so that a simple one-to-one comparison between the two systems is very difficult. For example, the safety of a given XADS concept is a mixture of the response of the plant system (which would be similar to that in the corresponding critical reactor case and thus is unrelated to the subcritical nature of the ADS) and the response of the reactor core (where the individual core design and level of subcriticality are important). This is highlighted by comparing both system and core-initiated transients for the two XADS concepts.

Pb/Bi and He-cooled XADS concepts

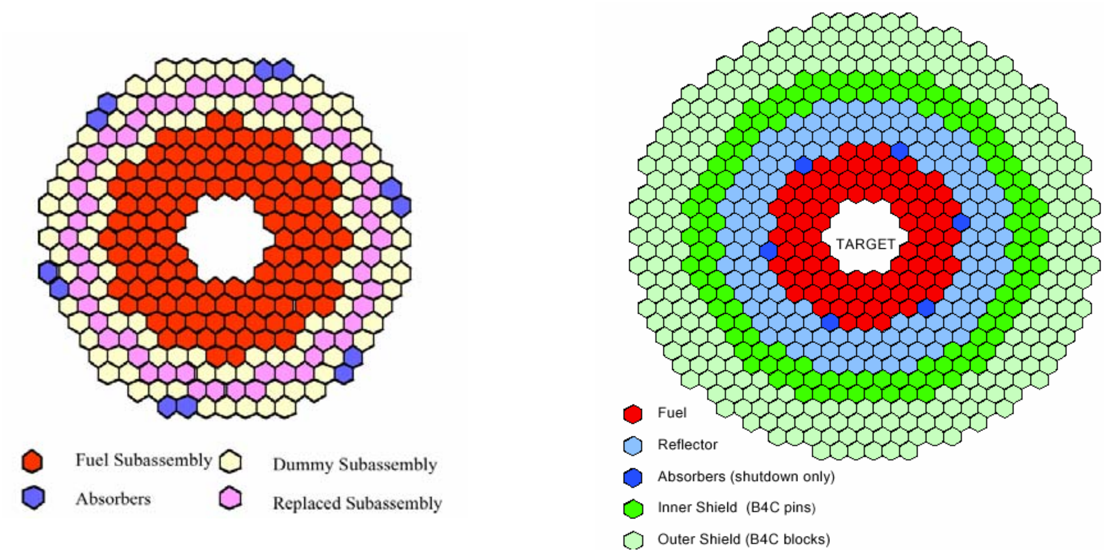
The main parameters of 80 MWth MOX-fuelled Pb/Bi and gas (He) cooled ADS demonstration facilities developed by Ansaldo [2,3] and by FRAMATOME [4] are given in Table 1.

Table 1. Main parameters of Pb/Bi and He-cooled XADS systems

Parameter	Pb/Bi	He
Nominal thermal power, MW	80	80
Multiplication factor k_{eff} at BOC	0.973	0.954
Number of FSAs/fuel pins per FSA	120/90	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	1 500
Fuel pellet inner/outer diameter, mm	1.8/7.14	3.2/11.5
Clad outer diameter, mm	8.5	13
Pitch-to-diameter ratio	1.58	1.29
Average/peak power rating, W/cm	82/130	160/256
Primary coolant/pressure, MPa	PbBi/1	He/6
Inlet/outlet coolant temperature, ºC	300/400	200/450
Core mass flow rate, kg/s	5 460	61.6
Core pressure drop, kPa	25	100

Diagrams of the two systems' core designs are presented in Figure 1(a) and 1(b). The subcritical core in both options has an annular configuration. A spallation neutron source unit is inserted in the core central void. In both cases, this source unit has its own circuit with circulating Pb/Bi eutectics used as a coolant and a target.

Figure 1. Diagrams of the Pb/Bi (a) and He (b) XADS core designs

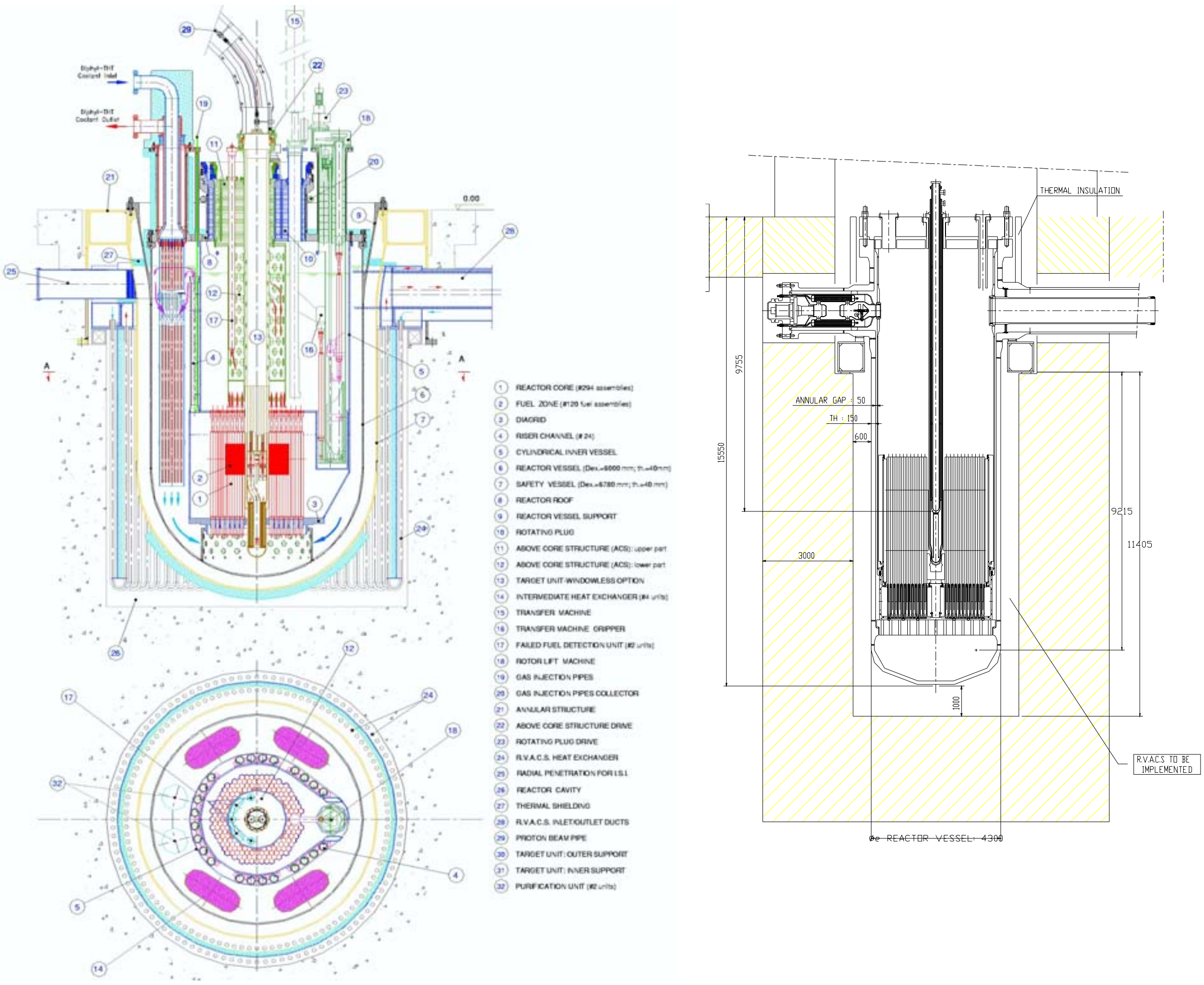


(a) (b)

Diagrams of the two systems are shown in Figure 2(a) and 2(b). In the Pb/Bi option, the primary system does not use traditional mechanical pumps. Instead, the natural circulation of the primary Pb/Bi is enhanced with gas lift pumps. Due to the high fuel pin pitch-to-diameter ratio in the core, absence of mechanical pumps and low coolant velocities, the hydraulic resistance of the Pb/Bi primary circuit is very low (~0.3 bar), providing a high level of natural circulation in case of pump trip. This along with a low core power rating, positive Pb/Bi properties (especially, high thermal inertia, chemical inertness and low neutron absorption), use of the passive decay heat removal system and the external neutron source provide a sound basis for a high level of safety with the Pb/Bi system.

In the gas-cooled option, the coolant (at ~60 bar pressure) flows out of the core [Figure 2(b)] and into the large upper plenum volume, then through the inner part of a concentric pipe to the power conversion system (PCS), which consists of a heat exchanger and blower unit. The secondary side of the heat exchanger is water-cooled. The blower drives the coolant along the outer region of the concentric pipe, into the reactor vessel downcomer and then to the lower plenum and core inlet. The gas-cooled XADS has a more compact core compared to the Pb/Bi-cooled system and, in particular, has a smaller number of thicker fuel pins per assembly with the result that the core average and peak linear ratings are about twice those of the Pb/Bi-cooled concept. For the gas-cooled XADS, the decay heat removal system consists of two out of three heat exchangers [Figure 2(b)], each with a nominal heat removal capacity of 2 MW, connected directly to the pressure vessel and placed at the same elevation as the connection to the PCS. The heat exchangers have a natural circulation secondary side water coolant flow and are designed to operate on the primary side under natural circulation conditions at full reactor pressure. However, the heat exchangers include blowers to circulate the primary coolant flow under low pressure (LOCA) conditions. An other important feature of the decay heat removal system is that a valve is located just upstream of the cold side PCS connection to the pressure vessel, which for a loss of coolant accident when closed prevents coolant flowing directly out of the break without first flowing through the core.

Figure 2. Diagrams of the Pb/Bi (a) and He (b) XADS system designs



(a) (b)

TRAC/AAA models

The TRAC/AAA [1] code version was specially developed at Los Alamos National Laboratory (USA) on the basis of the standard TRAC-M code to simulate transient behaviour of fast spectrum reactor systems, in particular to simulate additional working fluids (including liquid metals and helium), to add liquid metal and gas heat transfer correlations, to simulate fluid power in the working fluid and to simulate conduction within the working fluid (important for liquid metal coolants). Further code developments have been performed at PSI, including the integration of the FRED [5] fuel model to better capture reactivity feedback effects due to the fuel and core structure thermal expansion.

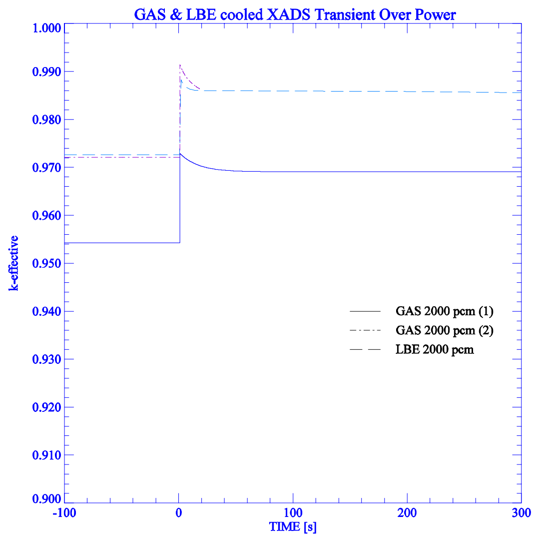
A three-dimensional (3-D) R-Z-θ representation with some 1 440 computational cells was elaborated for the TRAC/AAA simulation of the Pb/Bi primary vessel. The secondary and tertiary circuits of the Pb/Bi system were simulated using 1-D components. For the gas-cooled concept, a 1-D noding scheme of the pressure vessel, PCS and secondary coolant system (SCS) was used. A full set of plant protection controls and trips was included to control the accelerator beam trip, main blower trip, PCS isolation valve trip, opening of the SCS isolation valve and startup of the SCS blower.

Transient overpower (TOP) in Pb/Bi and gas-cooled systems

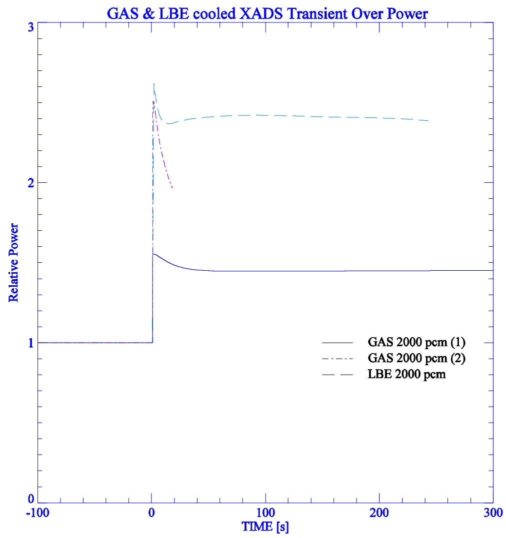
The results obtained for an unprotected (no beam trip) transient overpower accident (hypothetical addition of 2 000 pcm of reactivity) in the subcritical gas and Pb/Bi-cooled reactors are shown in Figure 3. Results [curves (2) for gas] are shown to provide a comparison of calculations for the two systems, beginning from the same subcriticality level of ~0.97 (chosen for the Pb/Bi-cooled system). The power jump to approximately 2.5 · nominal was the same in both systems. However, due to the higher power rating in the gas-cooled system and the low thermal inertia of the coolant, the clad and fuel temperatures increased to much higher values. In fact, for this transient the calculation terminated as soon as fuel melting occurred. Curves (1) for the gas-cooled system show that this transient is mitigated when the initial (operating) reactivity level is reduced. In this calculation, the nominal value of ~0.954 for the gas-cooled design was used.

Figure 3. Calculation results for unprotected transient overpower in Pb/Bi and gas-cooled systems

(a) K-effective, (b) relative reactor power, (c) clad surface temperatures



(a)



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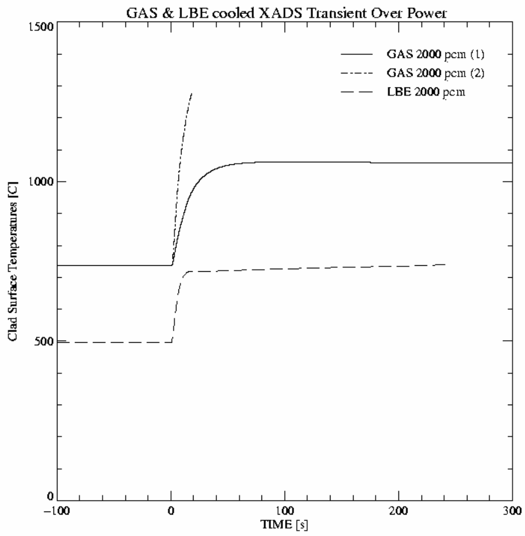


(c)

Beam overcurrent in Pb/Bi and gas-cooled systems

Since it is important in the analysed ADS for the beam current to be able to vary by over at least a factor of two to accommodate the reactivity swing expected during a reactor cycle, one transient that must be considered is the accidental increase in beam current to the maximum that the accelerator can deliver. Therefore, in order to examine this accident, the consequence of a beam overcurrent by a factor of two was considered.

The results obtained for three transients are presented in Figure 4. The transients examined are an unprotected beam overcurrent for the gas-cooled XADS, a protected beam overcurrent for the gas-cooled XADS and an unprotected beam overcurrent for the Pb/Bi-cooled XADS. The beam overcurrent transients were initiated from the design values of k_{eff}, i.e. the gas-cooled XADS transients start from a k_{eff} of ~0.954 and the Pb/Bi-cooled XADS from a k_{eff} of ~0.973.

For all transients, the 2 · beam overpower resulted in a rapid increase of the core power to ~1.8-1.9 of the initial value. The increase in core power produced an increase in the fuel and clad temperatures with the result that for the unprotected gas-cooled XADS transient [curves GAS (1) in Figure 4], clad melting occurred after ~20 s resulting in the termination of this calculation. This is similar to the situation for the TOP transient reported earlier with a k_{eff} value of 0.973 for the gas-cooled XADS, i.e. for the GAS (2) curves in Figure 3. (It should be noted that the initial peak cladding temperature for the gas-cooled system was lower in this calculation than that reported for the TOP transient. Also in this calculation the influence of increased clad to coolant heat transfer as a consequence of roughening the fuel pin surface was taken into account.) The effects of a subsequent trip of the accelerator are shown in the second gas transient [protected beam overcurrent, curves GAS (2) in Figure 4]. For this calculation, the accelerator was assumed to trip on high coolant (core exit) temperature. For this transient, as a consequence of the rapid reduction in the core power to the decay heat level, and the fact that at least initially the PCS blower and heat exchanger continue to operate, the clad and fuel temperatures fell rapidly.

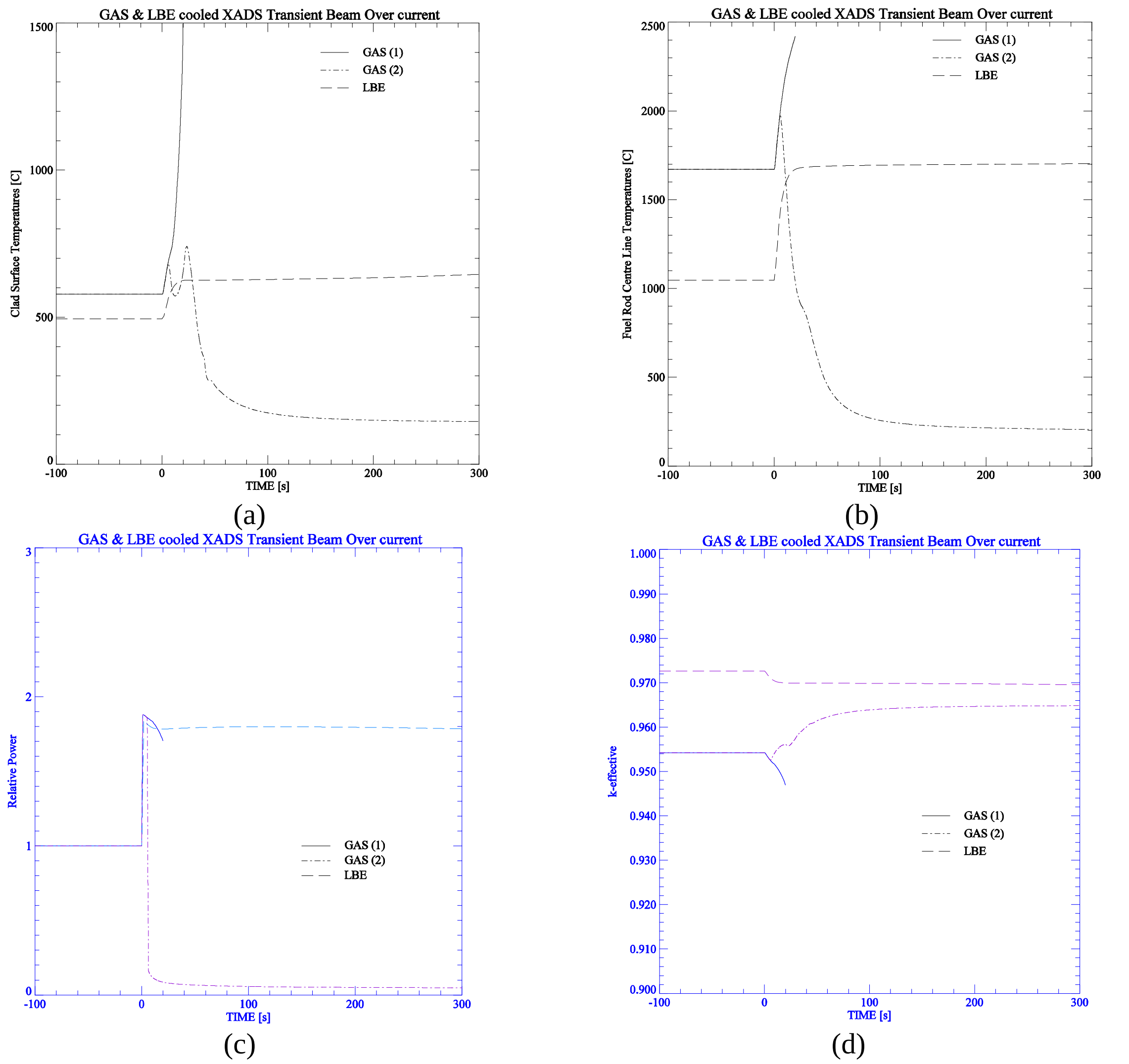
The response of the Pb/Bi-cooled reactor was similar to that for the TOP accident, except with the beam overcurrent transient where the power jump was approximately 1.9 · nominal compared to 2.5 · nominal for TOP. Figure 4 shows that for the unprotected Pb/Bi-cooled reactor, due to the much greater thermal capacity of the coolant, there are only modest increases in the peak clad and fuel centre line temperatures.

Another interesting difference between the two reactor systems is shown in Figure 4. Due to higher peak linear rating and larger fuel pin diameter of the gas-cooled concept, normal operation fuel centre line temperature was significantly higher, making it more sensitive to "overpower" transients.

A general conclusion from the two overpower transients presented above (i.e. TOP and beam overcurrent) is that although the power increase is dependent upon the subcriticality of the system, the response of the reactor to this power increase is more related to the general design of the reactor (e.g. power level, linear rating) and the choice of coolant.

Figure 4. Calculation results for beam overcurrent accident in Pb/Bi and gas-cooled systems

(a) Clad surface temperature, (b) fuel centre line temperature, (c) relative reactor power, (d) k-effective

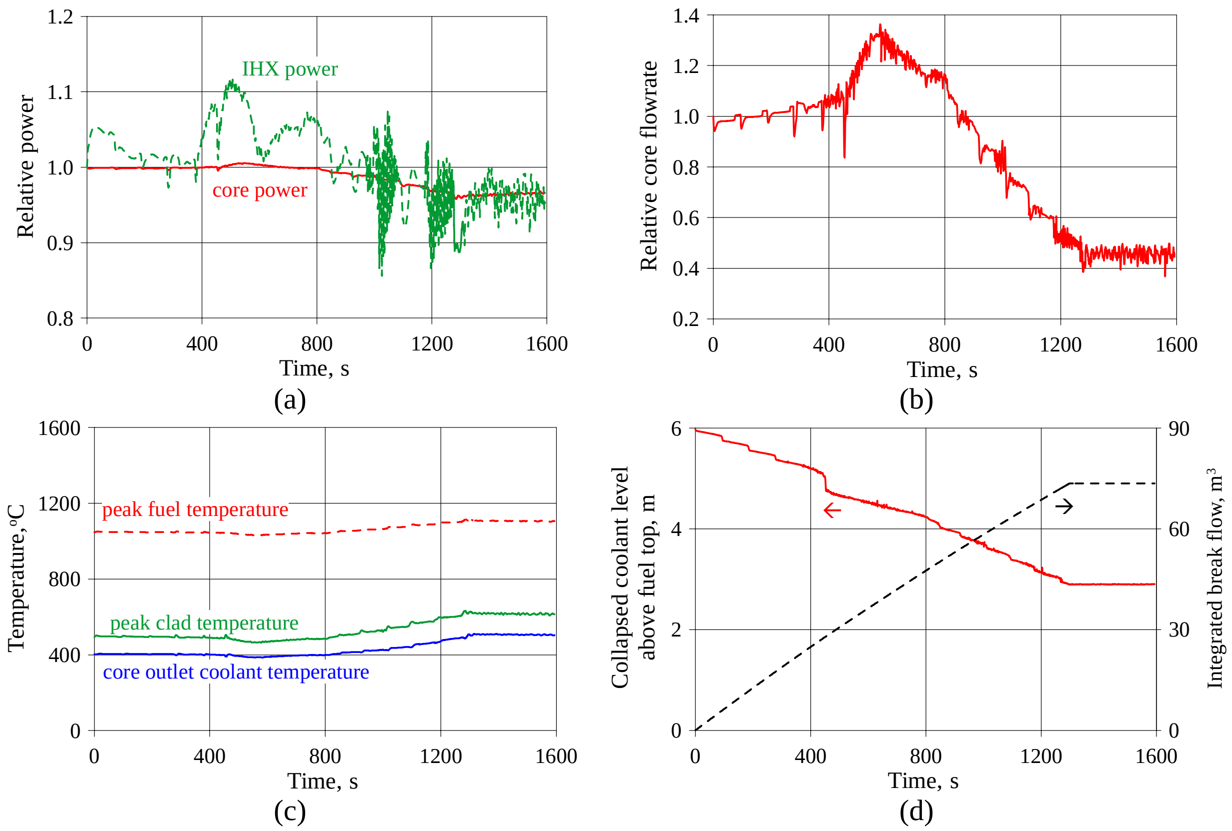


Loss of coolant accident (LOCA) in Pb/Bi-cooled system

The loss of primary coolant was simulated with a leak at the bottom of the primary vessel, the break area was assumed to be 50 cm^2 and the outer pressure was set equal to 1 bar. Results for the unprotected (no beam trip) accident with a loss of 74 m^3 of coolant are presented in Figure 5. The value of 74 m^3 corresponds to the free volume space between the main and safeguard vessels of the reactor system. In this case, due to the increased level swell of the Pb/Bi in the riser, the main circulation path remained unbroken and all the “gas lift” pumps remained in operation. The circulation flow rate was established via the main path at ~45% of the nominal value and so effectively removed the reactor power through the intermediate heat exchangers (IHX) even though the “collapsed” coolant level decreased by almost 3 m. As a consequence of the reduction in coolant flow rate, the fuel and clad temperatures increased in the transient to 1 115 C and 630 C, respectively, and stabilised at these levels. Thus, in case of a main vessel break, the system remained coolable even in the unprotected case.

Figure 5. Calculation results for unprotected LOCA in Pb/Bi-cooled system

(a) Relative core and IHX power, (b) relative primary and secondary coolant flow rate, (c) peak fuel and clad temperatures, core outlet coolant temperature, (d) collapsed coolant level above fuel top and integrated break flow



Loss of coolant accident in gas-cooled system

Since gas-cooled fast reactors, including the current subcritical XADS design, operate at high pressures during normal operation, they are susceptible to large and small break loss of coolant accidents. Breaks in the pressure vessel other than very small ones (e.g. instrument penetrations) are generally excluded from the list of design basis conditions (DBC) and are treated as residual risk. For this reason, for the analysis of DBC events, a range of breaks in the "outer skin" (i.e. cold side) of the pipe connecting the reactor pressure vessel to the power conversion system (PCS) was considered. As an example, the transient results of a large 300 cm^2 break loss of coolant accident are presented here.

As stated above, the gas-cooled XADS decay heat removal system consists of two out of three heat exchangers, each with a nominal heat removal capacity of 2 MW and connected to the pressure vessel at the same elevation as the connection to the PCS. The heat exchangers operate under natural circulation conditions at full reactor pressure but include blowers to circulate the coolant flow under low pressure (LOCA) conditions. The other important feature of the decay heat removal system is the valve located just upstream of the cold side PCS connection to the pressure vessel, which when closed prevents coolant flowing directly out of a break without first flowing through the core. Therefore, it is important that this valve closes early in any LOCA, i.e. before flow reversal occurs in the cold side of the PCS pipe.

In the "large" 300 cm^2 break accident, the reactor depressurises rapidly (i.e. within 30 s) to atmospheric conditions so that, during this time, the flow through the PCS quickly falls to zero, the PCS cold side valve closes and the SCS blowers are initiated. If the accelerator beam is not "shut off" during this period, then the clad and fuel temperatures will rise rapidly within the first 10 s and melting will result. This is similar to the overpower transients discussed above, where the low thermal inertia of the coolant in the gas-cooled XADS together with the higher linear heat generation rates and thicker fuel pellets means that rapid and redundant/independent accelerator beam trip mechanisms are required to prevent core melt. The results presented in Figure 6 (smooth fuel pins and no fuel channel gagging) and Figure 7 (roughened fuel pins and limited gagging) are therefore for protected transients, i.e. assuming accelerator beam trip on high coolant temperature occurs at ~5 s.

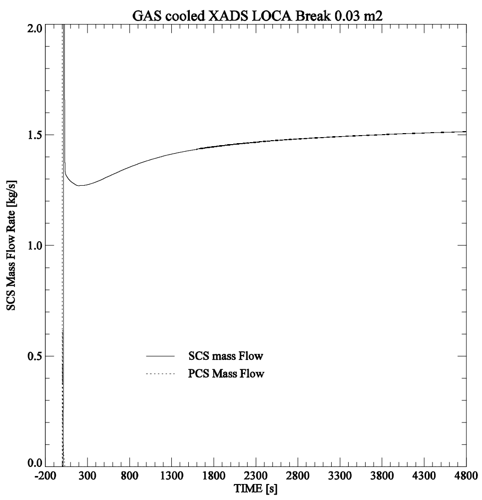
Figure 6 and Figure 7 show that following the rapid depressurisation and termination of the PCS flow, the SCS (two out of three units) flow is quickly established at about the design value of 0.65 kg/s per unit, and that the peak clad temperature increases as the coolant flow through the core decreases. During this period, the fuel and clad temperatures equalise to about the same value. The magnitude of the initial increase in the clad temperature is directly related to normal operation stored energy in the fuel, which is a function of the linear rating, fuel pin size and normal operation heat transfer. This latter dependency is clearly shown in Figure 6 and Figure 7. In the latter case, as a consequence of the increased heat transfer in normal operation due to roughening of the pin surface, the fuel stored energy was lower and the transient increase in the clad temperature was significantly reduced.

Following the initial equalisation of the clad and fuel temperatures, the clad and fuel temperatures increased as the coolant temperature increased to the level needed to match the SCS heat removal rate to the core decay heat. The coolant/clad and fuel temperatures then fell as the decay heat fell.

In summary, for a large break LOCA, due to the low thermal inertia of the coolant, it is not possible to protect the current gas-cooled XADS from clad and fuel melt unless the accelerator beam is tripped off within the first few seconds. For a protected LOCA, the SCS system was shown to work as designed, while the initial increase in the clad temperature was dependent upon the design parameters of the core, e.g. linear rating, fuel pellet diameter, normal operation heat transfer, etc. Through suitable design, the peak clad temperature could be reduced to an acceptable value.

Figure 6. Calculation results for LOCA in gas-cooled system with large (300 cm^2) break in the PCS connecting pipe (smooth fuel pins and without fuel channel gagging)

a) PCS and SCS mass flow rates, b) clad surface temperature



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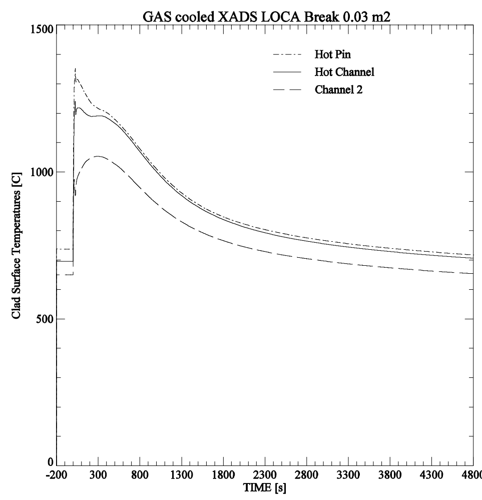
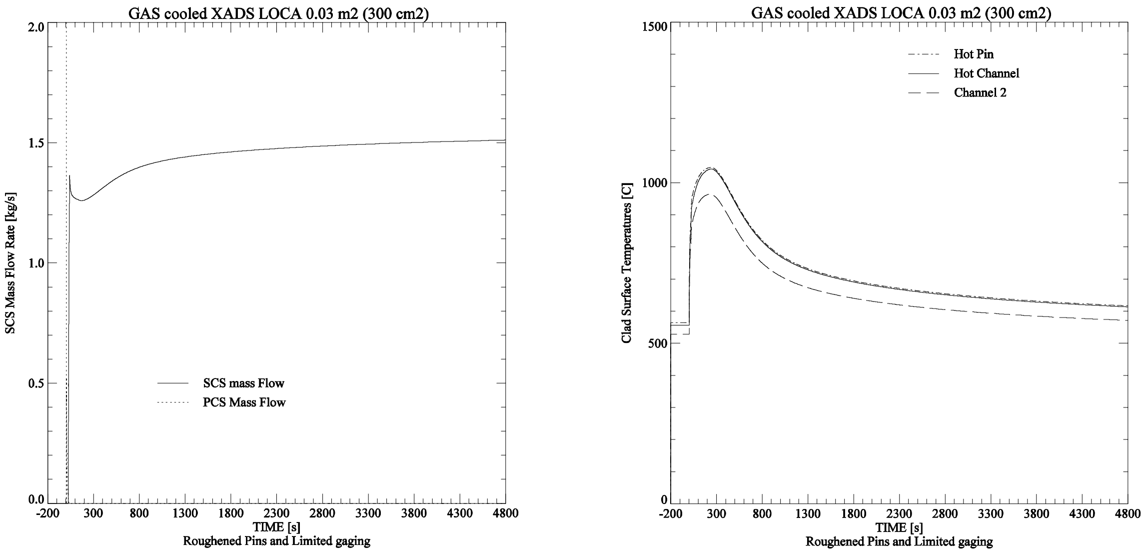


(b)

Figure 7. Calculation results for LOCA in gas-cooled system with large (300 cm^2) break in the PCS connecting pipe (roughened fuel pins and limited gagging)

(a) PCS and SCS mass flow rates, (b) clad surface temperature



(a) (b)

Conclusions

A general conclusion from the two overpower transients presented (i.e. TOP and beam overcurrent) is that although the power increase is dependent on the subcriticality of the system, the response of the reactor to this power increase is more related to the general design of the reactor (e.g. power level, linear rating) and the choice of coolant. This conclusion is even more evident for transients coming from faults in the primary and secondary coolant systems (hydraulically driven transients). For instance, in the case of a main vessel break (LOCA), the Pb/Bi system remains coolable even in an unprotected case. However, for a large break LOCA in the gas-cooled XADS, it is not possible to prevent clad and fuel melt unless the accelerator beam is tripped off within the first few seconds because of the low thermal inertia of the coolant. For a protected LOCA, the SCS system was shown to work as designed, the initial increase in the clad temperature being dependent on design parameters of the core, e.g. linear heat generation rate, fuel pellet diameter, normal operation heat transfer, etc. Through suitable design, the peak clad temperature could be reduced to an acceptable value.

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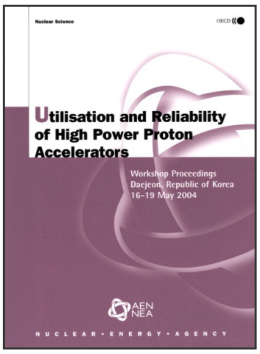
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