SAFETY ANALYSIS OF THE EU-PDS-XADS DESIGNS

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Abstract

Within the Fifth Frame Work Program of the E.U., the PDS-XADS Project is focused on the design studies of an eXperimental Accelerator driven reactor System (ADS). Three basic designs are being studied in detail two ADS design options with a lead bismuth eutectic (LBE) -cooled core (an 80 MW_{th} unit and a smaller unit) and another ($80MW_{th}$) with a gas (helium) -cooled core. One of the work packages of the PDS-XADS project is concerned with the assessment of the safety of the two $80MW_{th}$ designs with the following main objectives, namely to:

- Develop an integrated safety approach common to both the LBE- and the gas-cooled concepts.
- Identify the main safety issues in an XADS with their phenomenology and develop an evaluation methodology for both alternatives.
- Perform transient analyses with the aim of producing safety analysis reports with the identification of the design features required to meet the XADS safety objectives.

Introduction

Within the Fifth Frame Work Program of the E.U., the PDS-XADS Project is focused on the design studies of an eXperimental Accelerator driven reactor System (ADS). Two basic design options are being studied in detail, two ADS design options (an 80 MW_{th} unit and a smaller unit): with a lead bismuth eutectic (LBE) -cooled core and another (an 80 MW_{th} unit) with a gas (helium) -cooled core, both designs being driven by a neutron spallation source coming from a 600 MeV proton accelerator beam impacting a heavy liquid metal (LBE), windowless target.

One of the work packages of the PDS-XADS project is concerned with the assessment of the safety of the two 80 MW_{th} designs with the following main objectives, namely to:

- Develop an integrated safety approach common to both the LBE- and the gas-cooled concepts.
- Identify the main safety issues in an XADS with their phenomenology and develop an evaluation methodology for both alternatives.
- Perform transient analyses with the aim of producing safety analysis reports with the identification of the design features required to meet the XADS safety objectives.

The rationale for the integrated safety approach is quite similar to that practiced for the current LWR plants i.e. defence in depth, single failure criterion, specified safety goals. The PDS-XADS is a subcritical fast reactor, and is cooled either with LBE or gas (helium); thus it has the inherent advantage that reactivity-initiated accidents (RIAs), which were the bane of fast reactors may be prevented by an appropriate choice of the subcriticality level. The safety evaluation approach required the specification of the design-basis conditions (DBC) and the design-extension conditions (DEC) for both the LBE-cooled and the gas-cooled designs. Again, guidance in their specification was derived from the safety regulations for the LWRs and for the fast reactors.

For the LBE-cooled XADS designed by ANSALDO/ENEA a total of 26 transient initiators were identified for detailed analysis, categorized into Operational Transients (3), Protected Transients (11), and Unprotected Transients (12). For the gas-cooled XADS designed by FANP and NNC/CEA a total of 31 transient initiators were identified, categorized into Operational Transients (3), Protected Transients (17), and Unprotected Transients (11). Many of the transient initiators are common to both designs, e.g. spurious beam trip, protected/unprotected loss of flow and loss of heat sink, unprotected sub-assembly blockage etc., while some of the initiators are specific to one particular concept, i.e. loss-of-coolant accidents and water/steam ingress into the reactor core for the gas-cooled design.

In order to perform the analysis a review was made of the codes systems available to the project partners, which could be adapted to the analysis of the PDS-XADS DBC and DEC transients. These include: (i) The SIM-ADS code, (ii) the RELAP5 code modified for LBE by ANSALDO, and RELAP5/PARCS coupled code (with gas-cooled subcritical system kinetics models added by ENEA), (iii) the TRAC/AAA code of USNRC, modified for LBE and gas coolants by the Los Alamos National Laboratory and further modified by PSI, (iv) the code EAC (European Accident Code) developed at the JRC-Petten, (v) the SAS4/SASSYS codes modified to include LBE, (vi) the SIMMER code, which can model fast reactor hypothetical core disruption accidents (HCDA) and the STAR-CD code. The availability of a number of different codes able to analyse the same transients offers the capability of performing code-to-code comparisons, which is very important when analysing new reactor concepts in the absence of extensive experimental validation studies.

In the paper representative results of the transient analyses performed using the different code systems for the different designs, including the code-to-code comparisons are presented and discussed. These results show for the LBE-cooled XADS that this design exhibits a very wide safety margin (for both protected and unprotected transients) as a consequence of very favourable safety characteristics, including; excellent heat transfer properties and high boiling point of the coolant, favorable in-vessel and secondary system coolant natural circulation flow characteristics, and the large thermal inertia within the primary system as a result of the large coolant mass (pool design). For the gas-cooled XADS the results demonstrate the importance of the core heat transfer, the adequacy of the decay heat removal system for protected depressurization and loss of flow transients, and help to define the limited time window for backup proton beam shutdown systems in the event of an unprotected transient.

LBE and He-cooled XADS concepts

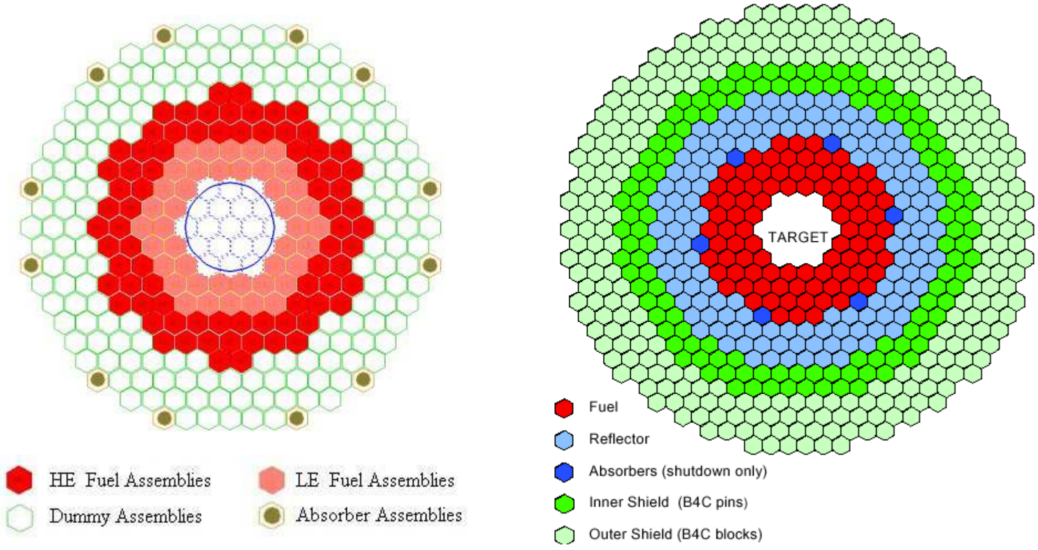
The main parameters of 80 MWth MOX-fuelled LBE- and gas- (He) cooled ADS demonstration facilities developed by Ansaldo [1,2] and by Framatome [3,4] are given in Table 1.

Table 1. Main parameters of LBE and He-cooled XADS systems

Parameter	LBE	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	1500
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 flowrate, kg/s	5460	61.6
Core pressure drop, kPa	25	100

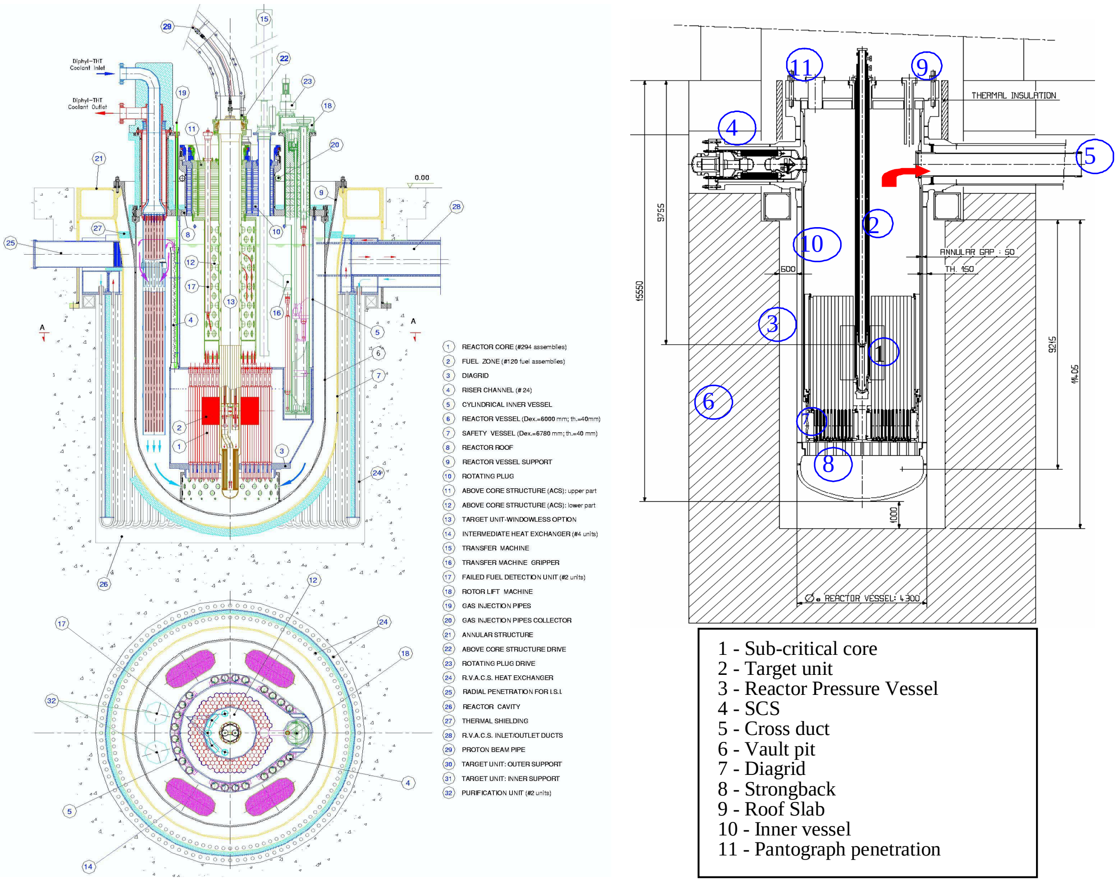
The core diagrams of the two systems are presented in Fig. 1 a) and b), respectively. A subcritical core in both options has an annular configuration. A spallation neutron source unit is inserted in the core central void region. The diagrams of the two systems are shown in Fig. 2 a) and b), respectively.

In the LBE option the primary system does not use traditional mechanical pumps. Instead, the natural circulation of the primary LBE 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 LBE primary circuit is very low (about 0.3 bar), providing a high level of natural circulation in case of pump trip. This along with low core power rating, positive LBE properties, use of the passive decay heat removal system and the external neutron source provide a sound basis for a high level of safety of the LBE system. The gas-cooled XADS has a more compact core compared to the LBE-cooled system and in particular has a smaller number of thicker fuel pins, with the result that the core average and peak linear ratings, are about twice those of the LBE-cooled concept. In the gas-cooled option the coolant, which is at ~ 60 bar pressure, flows out of the core (Fig. 2b) into the large upper plenum volume, through the inner part of a concentric pipe, to the power conversion system (PCS), which consists of a heat exchanger and blower unit. The blower drives the coolant along the outer region of the concentric pipe into the reactor vessel downcomer and from there into the lower plenum and the core inlet.



a) b)

Fig. 1. Diagram of the LBE (a) and He (b) XADS core design



a) b)

Fig. 2. Diagram of the LBE (a) and He (b) XADS system design

For the gas-cooled XADS the decay heat removal system consists of 2 out of 3 heat exchangers (Fig. 2b), each with a nominal heat removal capacity of 2 MW, connected directly to the pressure vessel 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, but include blowers to circulate the primary coolant flow under low pressure (LOCA) conditions. An other 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 when closed prevents coolant for a loss of coolant accident flowing directly out of the break without first flowing through the core.

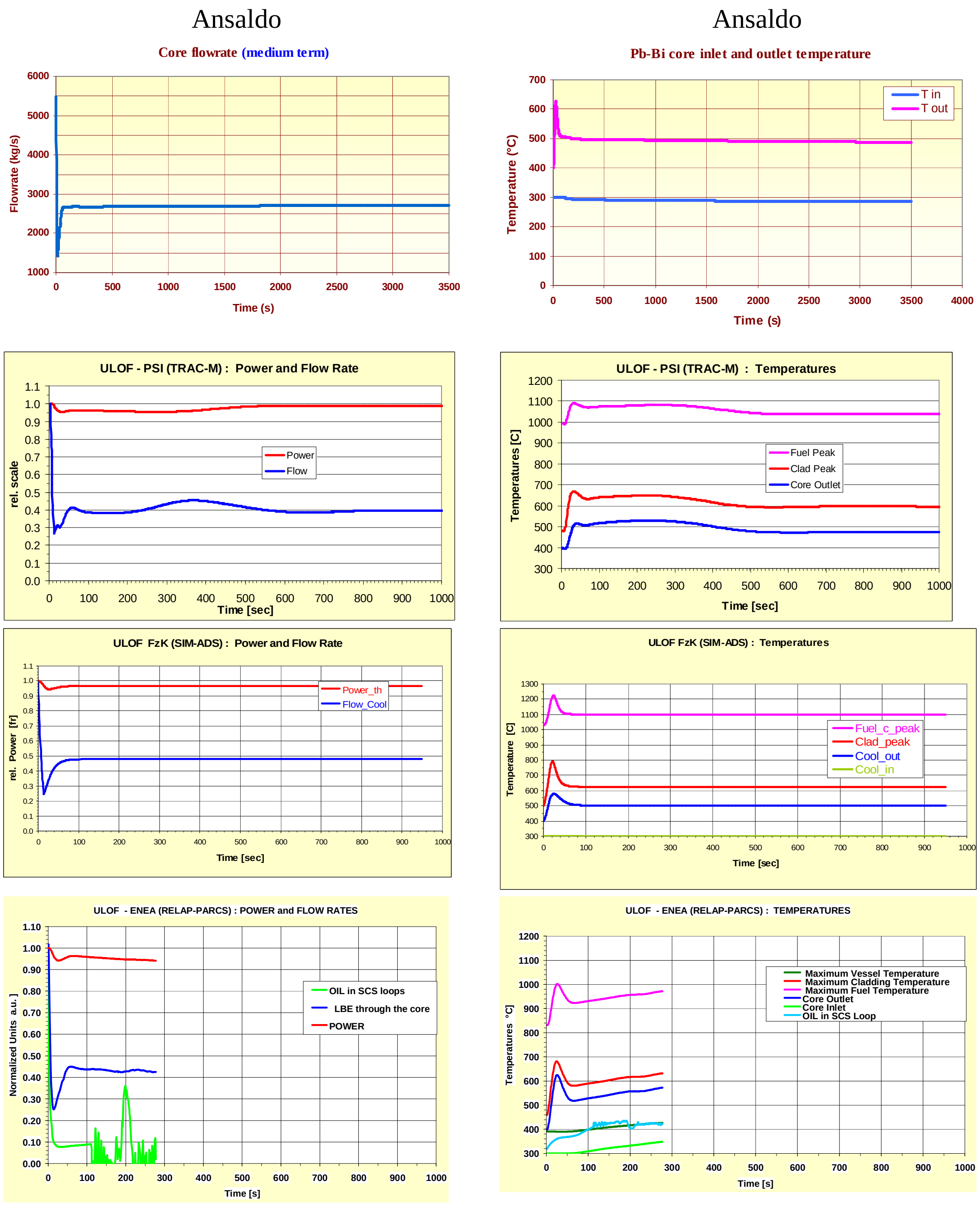
LBE-Cooled XADS Transient Analysis

The range of transients selected to be analysed as part of the project are listed in Table 2. These tansients can be divided into a number of groups, first as shown most of the transients were analysed in a protected (accelerator beam trip) and unprotected (no beam trip) mode. The transient initiators include failures in the primary and secondary system components, e.g. loss of flow, loss of heat sink, loss of inventory (LOCA) etc., failures in the function of the accelerator e.g. beam over power, beam trip etc., reactivity addition tansients and transients with the potential for local core melt e.g. sub-assembly (SA) blockage. Included in Table 2 is the expected analysis allocated to the various teams and code systems. As described above one advantage of a project of this type is the ability to collected together different analytical tools, including for example “system codes” such as TRAC/AAA and RELAP5 (suitably modified for LBE systems), special “fast reactor” codes e.g. SIM-ADS and SIMMER which include only a limited modelling of the primary and secondary systems or are core only codes, and computational fluid dynamics codes such as STAR-CD. The allocation of the analysis tried to take advantage of the different capabilities of the various code systems, while permiting some measure of code-to-code comparison to provide some “benchmarking” of the results.

An example of one of the more extensive comparisons is shown in part in Fig. 3 for the unprotected loss of flow transient. Here we see an example of two types of analysis, first that using the system codes e.g. RELAP5 and TRAC, which include a full represenation of the primary and secondary systems. These show the evolution of the transition to thermally driven natural circulation and the remainder of the codes which use as input either a simplified approach or a core input flow rate taken from one of the system codes. All of the codes that calculate the core flow show that because of the low system pressure loss the natural circulation flow rate is between 40 and 50 % of the nominal value. Most of the code systems calculate the change in the core power using a point kinetics model and here we see that because of the subcriticality there is only a small reduction in the core power. Because of the high core flow under natural circulation conditions the resultant core temperatures (in almost all of the codes) show only a modest increase of typically 100ºC (i.e. from 400 to 500ºC) for the core exit coolant temperature. The results of this analysis highlights two important features 1) that there is a large degree of agreement between the “very” different analytical tools and 2) this reactor (ANSALDO design) is able to accommodate an unprotected loss of flow transient with only a modest increase in the core temperatures. This second feature can be applied to almost all of the transients analysed in Table 2, the only exception being U-5 the unproteced loss of flow and heat sink the comparative results of which are presented in Fig. 4. In this figure, which shows the results from TRAC, RELAP5 and SIM-ADS, we see that even though there is a total loss of heat sink there is still a substantial natural circulation flow rate of between 20 and 35 % for the system code calculations. The natural circulation flow distributes the heat generation in the core over the whole of the primary system resulting in a relatively slow increase in the core temperatures. The maximum cladding temperature increasing by 400 to 500ºC for the RELAP5/TRAC calculations in 1000 s, which is more than a sufficient time window for the accelerator beam to be manually switched off. It should be noted that for operational transients without accelerator beam trip (including the ULOF presented above), which are equivalent to Anticipated Transients Without Scram (ATWS) in a critical reactor it is important that the increase in the primary coolant temperature does not lead to coolant boiling in the secondary system, since this will have the potential to increase the severity of the event by leading to a loss of heat sink.

Table 2. LBE Transients Analysed

Transient Number	Transient	Description	Burnup State		Organisations analyzing Transient						Transient already analysed by ANSALDO
					ENEA	PSI	JRC	FzK	FzK	FzK	
Transients analyzed for LBE -XADS Design (ANSALDO)			BOC	EOC	RELAP5+ PARCS	TRAC-M	STAR-CD, CFD, EAC2	SIMMER	SAS4ADS	SIM-ADS	RELAP5
Operational Transients											
O - 1	Shutdown	plant taken to Ambient (30 C)	X	X						done	from HFP to HZP
O - 2	Shutdown with target flooded	target is flooded and then plant taken down to Ambient (30 C)	X	X			X			done	
O - 3	Startup	plant is taken from CZP to HFP	X	X						done	from HZP to HFP
Protected Transients											
P - 1	PLOF	complete loss of all forced / enhanced circulations in primary and secondary(oil) systems	X	X	BOC done	BOC done				done	X
P - 2	PTOP	300 pcm jump in reactivity at HFP	X	X		BOC done		BOC done		done	
P - 3	PTOP	300 pcm jump at CZP	X	X		BOC done				X	
P - 4	PLOH	complete loss of both secondary trains	X	X	BOC done	BOC done				done	
P - 5	PLOF+PLOH	loss of gas and secondary loops lost	X	X	BOC done	BOC done	BOC done			done	X
P - 6a	LOCA	primary vessel leaks, level in primary drops by 2 m, HX uncovered, (partial) loss of nat. circ. in primary	X	X		BOC done	open				X
P - 6b	LOCA	double vessel leak, level in primary drops, core remain covered, loss of nat. circ. in primary	X	X		BOC done	open				
P - 7	Over-cooling of primary side	core inlet temp. drops by 150 C in 450 sec	X	X		BOC done				X	X
P - 8 DEC	Inlet Blockage of SA w/o radial heat transfer	flow area of peak SA reduced to 2.5%, no radial heat transfer assumed	X	X	open		open			X	
P - 9 DEC	Blockage of SA with radial heat transfer	flow area of peak SA reduced to 2.5%, radial heat transfer assumed	X	X			open				X
P - 10	Spurious beam trips	beam trips for 1,2,3 ...10 sec intervals	X	X	BOC done	BOC done		BOC done	BOC done		X
P - 11	HX Tube rupture	secondary oil leaks into primary side, can happen only when sec. in natural circulation mode	X	X		BOC done					
Unprotected Transients											
U - 1	ULOF	complete loss of all forced / enhanced circulations in primary and secondary(oil) systems	X	X	BOC done	BOC done	BOC done	BOC done		done	various partial ULOFs
U - 2	UTOP	300 pcm jump in reactivity at HFP	X	X		BOC done	open	BOC done, EOC done		done	
U - 3	UTOP	300 pcm jump at CZP	X	X		BOC done	open			done	
U - 4 DEC	ULOH	complete loss of both secondary trains	X	X	BOC done	BOC done	BOC done			done	
U - 5 DEC	ULOF+ULOH	loss of gas and secondary loops lost	X	X	BOC done	BOC done	BOC done			done	
U - 6 DEC	Unprotected LOCA	primary vessel leaks, level in primary drops by 2m, loss of nat. circ. possible	X	X		BOC done	open				
U - 7	Unprotected over-cooling of primary side	core inlet drops by 150 C in 450 sec	X	X		BOC done				done	no feedbacks
U - 8 DEC	Unprotected blockage of SA w/o radial heat transfer	flow area of peak SA reduced to 2.5%, no radial heat transfer assumed	X	X	BOC done		open	BOC done		X	with radial heat transfer
U - 9 DEC	Unprocted inlet blockage of SA with radial heat transfer	flow area of peak SA reduced to 2.5%, no radial heat transfer assumed	X	X			open	BOC done			
U - 10	Unprotected HX Tube rupture	secondary oil leaks into primary side	X	X		BOC done					
U - 11	Beam Overpower to 200 % at HFP		X		BOC done	BOC done		BOC done	BOC done	X	X
U - 12	Beam Power Jump to 100% at HZP		X	X	BOC done	BOC done			BOC done	X	X


Ansaldo

Core flowrate (medium term)

Ansaldo

Pb-Bi core inlet and outlet temperature

ULOF - PSI (TRAC-M) : Power and Flow Rate

ULOF - PSI (TRAC-M) : Temperatures

ULOF FzK (SIM-ADS) : Power and Flow Rate

ULOF FzK (SIM-ADS) : Temperatures

ULOF - ENEA (RELAP-PARCS) : POWER and FLOW RATES

ULOF - ENEA (RELAP-PARCS) : TEMPERATURES

Fig. 3. Comparison of code results for loss of flow transient

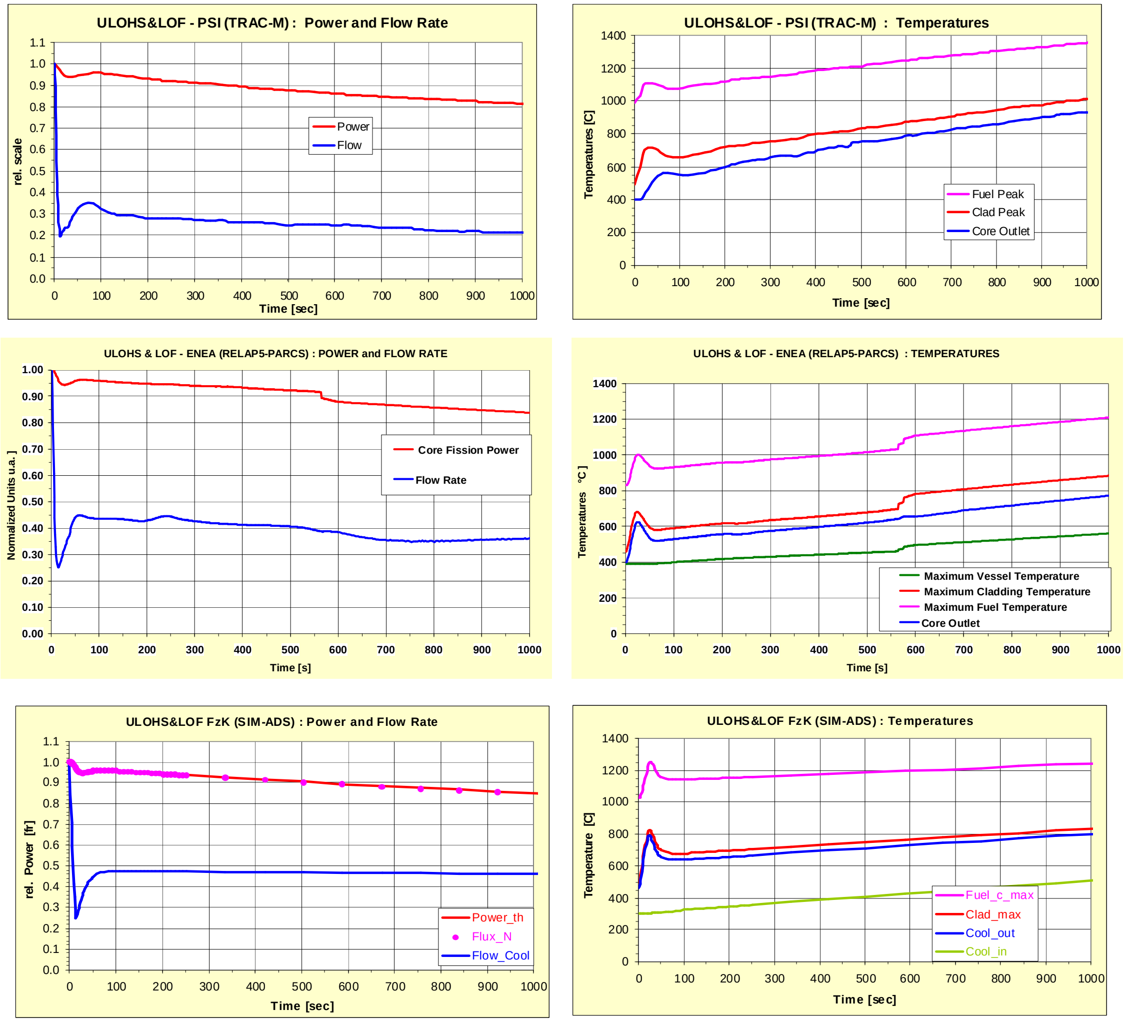


Fig. 4. Comparison of code results for loss of flow and loss of heat sink transients

A transient which was considered of importance in the analysis of sodium-cooled fast reactors was that of local sub assembly blockage because of the potential for local fuel melting to go undetected with the result that this might potentially spread into a core wide problem. As a required condition in the PDS-XADS safety assessment therefore, the impact of local coolant-flow blockages, specifically the reduction of the flow area to 2.5 % in the hottest assembly, was investigated using SIMMER (which permits an analysis of core melt conditions) and STAR-CD (a CFD code). In the two-dimensional SIMMER-III simulation framework, the flow area of the whole innermost subassembly-ring was reduced. This is a pessimistic assumption because all surrounding subassemblies adjacent to the target unit will be blocked simultaneously and radial heat transfer is limited to four flats. In the present study, three calculations were performed to examine the impact of Hexcan gap flow (HGF) and radial heat transfer (RHT). The highest cladding temperatures in the innermost subassembly-ring for the three calculations are presented in Fig. 5. In case (1) with HGF and RHT, the cladding temperature stayed at about 200 K below the melting point, and no clad melting was predicted. If only a single assembly is blocked in an actual three-dimensional simulation, cladding temperatures can be expected to be much lower. In case (2), HGF was artificially suppressed but the cladding temperature still stayed at 100 K below the melting point. Case (3) was performed to investigate conditions, if the core is forced into melting. For this case a pin failure occurred at 31 s, while fuel sweep-out into the upper plenum region at 94 s brings a strong reactivity reduction so that no severe power excursion would occur. Fig. 6 shows the fuel particle distribution after the pin failure and the expanding damage in the innermost assembly, indicating that the fuel particles could be swept away from the core region and that the reactivity would be reduced as a consequence.

In Figs. 7a and 7b below the STAR-CD steady state results of an unprotected inlet blockage in one subassembly are presented. The assumed blockage reduces the coolant flow rate in the concerned subassembly to 2.5% of nominal flow. (Note, this is a more severe restriction than that of the SIMMER analysis which assumed a flow restriction of 2.5%, and as will be seen leads to higher temperatures.) Fig. 7a below shows the LBE temperatures in the blocked and the neighbouring intact subassembly at full flow. The neighbouring subassembly gets locally heated much above the nominal 400ºC outlet temperature. Since all six neighbouring SAs are at full flow, they remove nearly all the heat generated in the blocked assembly. In Fig. 7b the cladding temperatures of the blocked subassembly and of the neighbouring one with full flow are shown. It can be seen that the maximum cladding temperatures in the blocked subassembly is 1670 K, i.e., just a few degrees below the steel melting point, but is approximately 100ºC higher than the equivalent SIMMER calculation. (This means rather certainly that many fuel pins have already ruptured and that the fission gases release has occurred. However, since the maximum fuel temperature is only 1900K few other radioisotopes will have been released from the fuel matrix.) However, given the uncertainty in these analyses and the different boundary condition assumptions (see above), the difference is in fact relatively modest.

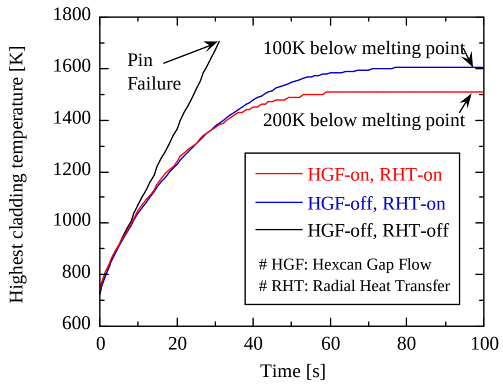


Fig. 5. SIMMER-III clad temperatures for blockage case.

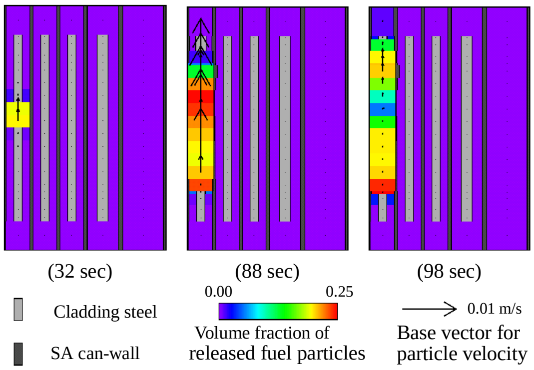
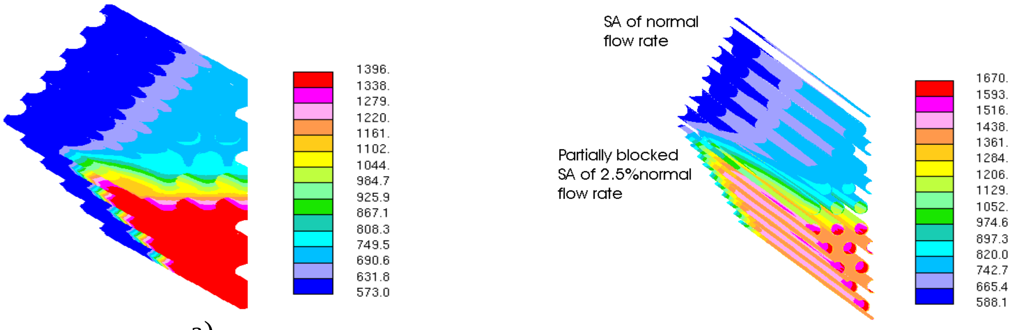


Fig.6. SIMMER-III fuel sweep-out for pin failure case.



a)

b)

Fig. 7. Coolant (a) and clad (b) temperatures (K) in blocked and neighbouring SA at full flow

The distribution of molten fuel within the primary system, which is not modeled by the above codes requires further analysis to determine if it could migrate to the heat exchanges leading to tube failure.

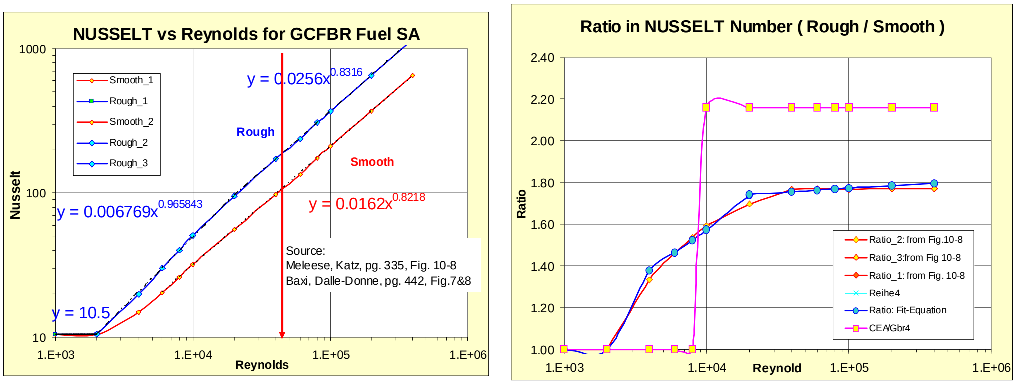
Gas-Cooled XADS Transient Analysis

The range of transients to be analysed for the gas-cooled XADS was reviewed and a table similar to that produced for the LBE design (see Table 2 above) was developed. The transients selected for analysis included (as for the LBE) core driven events e.g. beam over power, reactivity addition accidents, and system driven events e.g. failure of the main blower, loss of heat sink, and loss of coolant etc., all of which were analysed assuming both protected (beam trip) and unprotected conditions. Of special interest are two classes of events, which are more relevant to gas-cooled systems and these are (1) loss of coolant accidents and (2) the ingress of water into the core from particularly, a failure in the decay heat removal heat exchangers.

As part of the initial transient analysis of the gas-cooled concept, a number critical features became apparent including: high clad temperatures were obtained even during normal operation, clad temperatures in excess of 1200°C were obtained for a range of protected transients, and for the more “severe” accidents like a large break in the pipe connecting the vessel to the power conversion unit the clad temperatures rose to the melting point in a few tens of seconds unless the accelerator beam was immediately tripped.

In order to address the first two of the above issues, the rector core was redesigned to increase the fuel rod to coolant heat transfer and to redirect the coolant flow to the higher rated sub-assemblies. The first of these was achieved by introducing roughened fuel rods and the second by applying a gagging scheme to the inlet of the fuel assemblies based on their expected power. One of the consequences of these is that they both increase the core pressure drop. Therefore, one of the goals of the subsequent analysis was to demonstrate the adequacy of the decay heat removal system to function (as designed) under natural convection conditions at full reactor pressure and with the use of the blowers following reactor depressurization.

One of the first tasks of the revised analysis was to determine an adequate data base and consequential heat transfer and pressure loss coefficients for the redesigned core and an example of the “correction factors” introduced into the analysis codes systems is given below in Fig. 8.


NUSSELT vs Reynolds for GCFBR Fuel SA

Source:
Meleese, Katz, pg. 335, Fig. 10-8
Baxi, Dalle-Donne, pg. 442, Fig.7&8

Ratio in NUSSELT Number (Rough / Smooth)

Recommended Correction Factor CF:

1000<Re<2000	CF_NUSSELT = 1
2000<Re<20,000	CF_NUSSELT = 0.4176*Re^0.144043
20,000<Re<E6	CF_NUSSELT = 1.58*Re^0.0102

Fig. 8. Effect of clad roughening on fuel rod heat transfer.

An example of the results of the revised analysis is shown in Fig. 9, which shows the core flow and peak clad temperatures for a TRAC/AAA calculation for a protected main blower trip transient. In this figure we see that in the long term i.e., after about 200 s when the flow through the power conversion system falls to zero, natural circulation flow is established by the decay heat removal system at a flow rate for 2 out of the 3 units of about 1.6 kg/s. This is slightly higher than the nominal design value of 0.65 kg/s per unit. During this period the clad temperatures slowly decrease to a value of about 600ºC after ~ 2000 s. The magnitude of the peak clad temperatures are however primarily defined by the normal operation fuel stored energy and the cooling during the early period of the transient following the trip of the accelerator beam, which for this transient is based on a high core-exit coolant temperature set point. It is therefore important for this and other system driven transient to maintain the flow though the core from the PCS for as long as possible by careful design of the main blower and the PCS isolation valve placed just inside the cold-side of the connection pipe from the vessel to the PCS. In the current analysis, as we see from Fig. 9 (TRAC/AAA) and Fig. 10 (SIM-ADS), the PCS flow rate reduces to zero over a period of 30 s due to closure of this valve. With these constraints i.e., pump run down of up to 30 s, reduced fuel stored energy due to increased normal operation heat transfer (use of roughened fuel pins) and fuel assembly gagging, with the associated increased transient heat transfer (for high Reynolds numbers) heat transfer, we see that it is possible to reduce the peak clad temperatures to ~ 700 C for a main blower trip transient, which is considered the operational transient with a relatively high probability of occurrence.

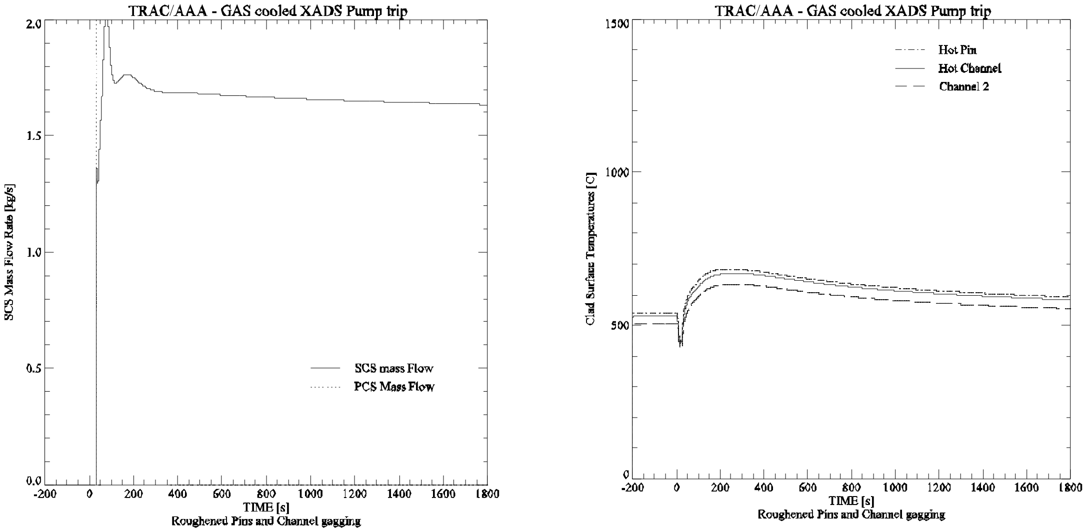


Fig. 9 TRAC/AAA analysis of pump trip transient for the gas-cooled XADS.

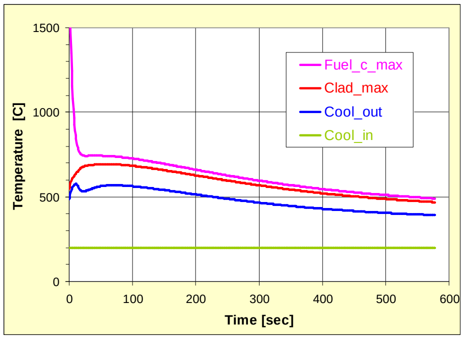


Fig. 10. SIM-ADS results for peak fuel and clad temperatures, coolant inlet and outlet temperatures

In addition to the analysis presented, similar conclusion can be drawn for most of the protected system driven transients. However, none of the above design changes have any significant impact on the response of the reactor to unprotected transients. Since for unprotected transients the reactivity changes that occur as a result of the increase in the fuel temperature etc. have a minimal effect on the core power of sub-critical systems, the core will continue to heat up to unacceptable temperatures.

The results of the transient calculations presented above were obtained using system codes in which the coolant temperature and flows are averaged over large volumes or nodes with the result that any information relating to the thermal and flow gradients e.g. those exiting the core for example is lost. This is important for both normal operation and accident situations if large gradients might occur and in order to address this concern computational fluid dynamic (CFD) models are being developed using the STAR-CD code with as an example the detailed mesh shown in Fig. 11. As a first stage in the analysis, thermal-hydraulic calculations for nominal conditions have been performed to determine the helium temperature, and the temperature in the different structural components e.g. the reactor main vessel, the inner vessel, cross duct, core assemblies and shielding, accelerator vessel, upper shielding plate etc. In a second step, the transient calculation of the helium and structural temperatures will be calculated. These calculations will also provide the input for a detailed stress analysis of these components under normal and transient conditions.

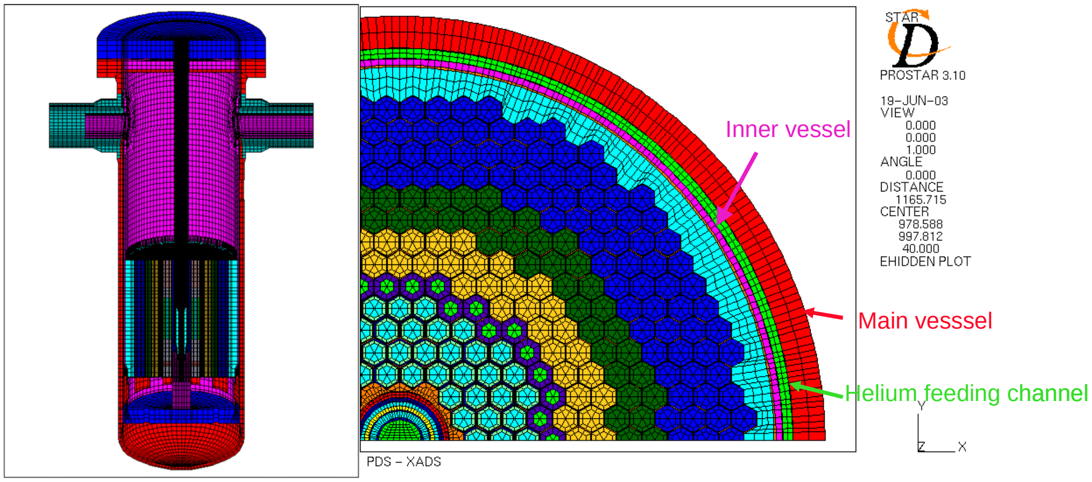


Fig. 11 STAR-CD Solid mesh   Cross section of the model at core mid-plane level

Conclusions

A general conclusion from the analysis performed and the transients presented (i.e., loss of flow loss of heat sink etc.) is that for the LBE-cooled reactor concept (as designed by ANSALDO), because of the high thermal inertia of the coolant, the excellent natural circulation properties, and modest power ratings, the reactor system is able to cool the core for all protected transients and almost all unprotected transients. Even in the most severe case considered, i.e., unprotected loss of flow and complete loss of heat sink, there is a grace period between 30 and 60 minutes to switch off the beam before the cladding temperatures reach excessive levels. An additional benefit of the analysis through the framework of the PDS-XADS project is the ability to provide code-to-code comparisons for a range of different transients using a wide range of different codes. In the context of the analysis of the

LBE-cooled design a high degree of agreement was obtained both for system driven and local transients.

For the gas-cooled concept, the analysis performed shows that for the long term cooling of the core to be assured the decay heat removal system needs to operate as designed at all of the different reactor states to be considered, namely at nominal system pressure, under natural circulation conditions, and with the reactor in the depressurized state. In addition, for most of the protected transients, it can be shown that with adequate consideration given to the system design, e.g., linear heat generation rate, fuel pellet diameter, sufficient operational heat transfer e.g., fuel pin roughening and sub-assembly gagging, a slow main blower coast down characteristics, etc., the energy stored in the fuel can be removed without encountering an excessive increase in the peak clad temperatures. However, none of the design changes made during the course of the analysis change the basic response of the gas-cooled system to unprotected transients. Since the reactivity changes that occur as a result of the increase in the fuel temperature etc. have a minimal effect on the core power of sub-critical systems, the core temperatures will quickly increase to unacceptable levels. This therefore places an increased emphasis on the reliability of the beam shutdown mechanisms in order to assure that this mechanism functions on demand to a very high degree of reliability.

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