SAFETY ANALYSIS OF THE EU PDS-XADS DESIGNS

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Abstract

Within the Fifth Framework Programme of the European Union (EU), the PDS-XADS project is focused on Preliminary Design Studies of an Experimental Accelerator-driven Reactor System (ADS). Three basic designs are being studied in detail – two ADS design options, one with a lead-bismuth eutectic (LBE) cooled core (an 80 MWth unit and a smaller unit) and another (80 MWth) with a gas (helium) cooled core. One part of the PDS-XADS project involves the assessment of the safety of the two 80 MWth designs. The main objectives are as follows: 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; and perform transient analyses with the aim of producing safety analysis reports on the design features required to meet XADS safety objectives.

Introduction

Within the Fifth Framework Programme of the EU, the PDS-XADS project is focused on Preliminary 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 MWth unit and a smaller unit), one with a lead-bismuth eutectic (LBE) cooled core and another (an 80 MWth unit) with a gas (helium) cooled core. Both designs are driven by a neutron spallation source coming from a 600 MeV proton accelerator beam impacting a heavy liquid metal (LBE), windowless target.

One part of the PDS-XADS project involves the assessment of the safety of the two 80 MWth designs. The main objectives are as follows:

- 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 on the design features required to meet XADS safety objectives.

The rationale for the integrated safety approach is quite similar to that practiced for current LWR plants, i.e. defence-in-depth, single failure criterion and 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 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 on the specifications was derived from the safety regulations for LWRs and fast reactors.

For the LBE-cooled XADS designed by Ansaldo/ENEA, a total of 26 transient initiators were identified for detailed analysis and categorised as follows: 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 and categorised as follows: operational transients (3), protected transients (17) and unprotected transients (11). Many of the transient initiators were common to both designs (e.g. spurious beam trip, protected/unprotected loss of flow and loss of heat sink, unprotected subassembly blockage, etc.) while some of the initiators were 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 code systems available to the project partners, which could be adapted to the analysis of the PDS-XADS DBC and DEC transients. These codes include: 1) SIM-ADS code; 2) RELAP5 code modified for LBE by Ansaldo and the RELAP5/PARCS coupled code (with gas-cooled subcritical system kinetics models added by ENEA); 3) TRAC/AAA code of US NRC modified for LBE and gas coolants by the Los Alamos National Laboratory and further modified by PSI; 4) code EAC (European accident code) developed at JRC-Petten; 5) SAS4/SASSYS codes modified to include LBE; and 6) 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 this 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. The results showed 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. These safety characteristics included: excellent heat transfer properties and high boiling point of the coolant, favourable in-vessel and secondary system coolant natural circulation flow characteristics and large thermal inertia within the primary system as a result of large coolant mass (pool design). For the gas-cooled XADS, the results demonstrated the importance of core heat transfer, and the adequacy of the decay heat removal system for protected depressurisation and loss of flow transients. The results also helped 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

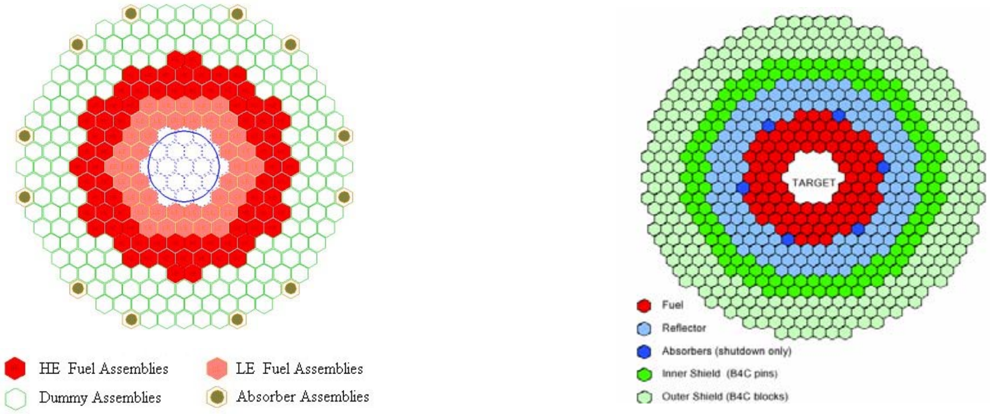
Parameter	LBE	He
Nominal thermal power, MW	80	80
Multiplication factor k_{eff} at BOC	0.973	0.954
Number of FSAs/fuel pins per FSA	120/90	90/37
FSA flat-to-flat distance, mm	138	120
Fuel type/fuel mass, t	MOX/3.24	MOX/4.37
Plutonium content, %	23	35
Core inner/outer diameter, m	0.58/1.7	0.48/1.4
Fuel height, mm	900	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, C	300/400	200/450
Core mass flow rate, kg/s	5 460	61.6
Core pressure drop, kPa	25	100

The core diagrams of the two systems are presented in Figure 1(a) and 1(b), respectively. The subcritical core in both options had an annular configuration. The spallation neutron source unit was inserted in the core central void region. The diagrams of the two systems are shown in Figures 2(a) and 2(b), respectively.

In the LBE option, the primary system did not use traditional mechanical pumps. Instead, the natural circulation of the primary LBE was enhanced with gas lift pumps. Due to the high fuel pin pitch-to-diameter ratio in the core and the absence of mechanical pumps and low coolant velocities, the hydraulic resistance of the LBE primary circuit was 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 LBE properties, use of a passive decay heat removal system and external neutron source, provides a sound basis for a high level of safety with the LBE system. The gas-cooled XADS had a more compact core compared to the LBE-cooled system and in particular had a smaller number of thicker fuel pins, with the result that core average and peak linear ratings were about twice those of the LBE-cooled concept.

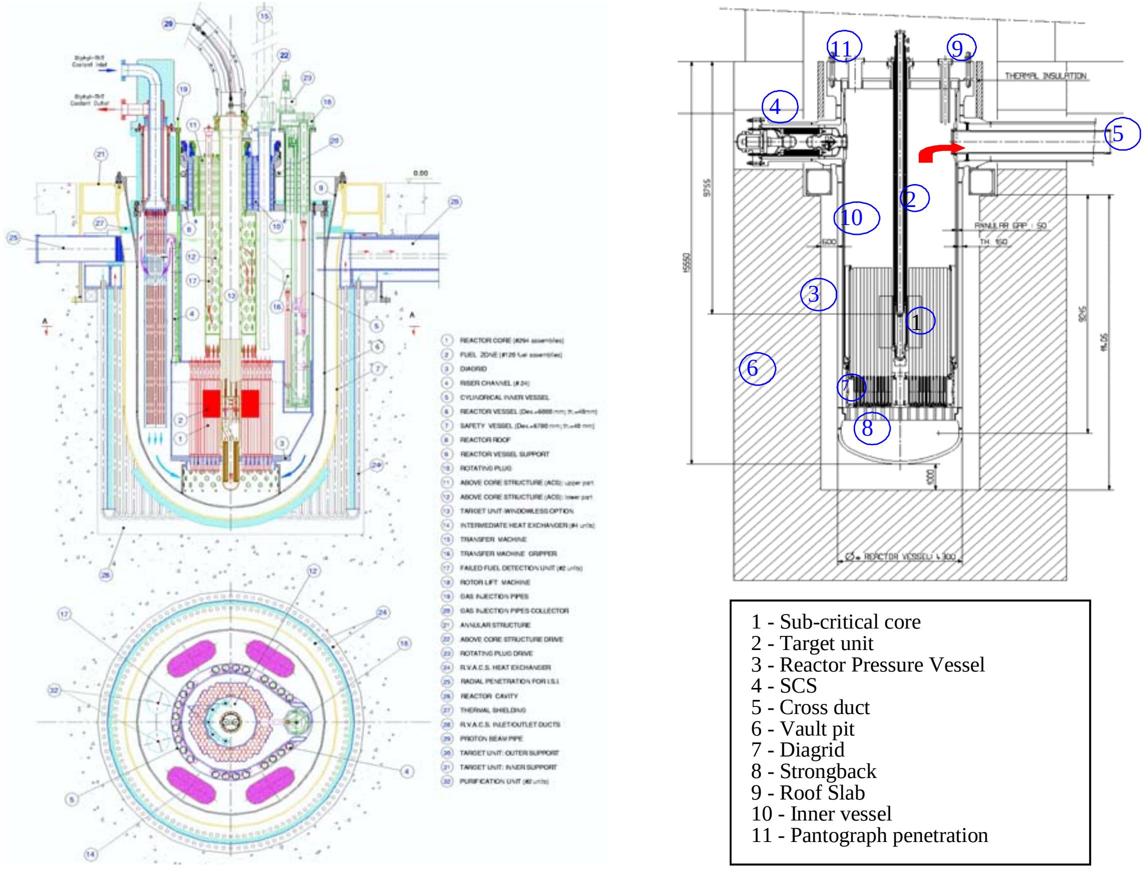
In the gas-cooled option, the coolant (at ~60 bar pressure) flowed out of the core [Figure 2(b)] into the large upper plenum volume, through the inner part of a concentric pipe and to the power conversion system (PCS), which consisted of a heat exchanger and blower unit. The blower drives the coolant along the outer region of the concentric pipe into the reactor vessel downcomer and from there into the lower plenum and the core inlet.

Figure 1. Diagrams of the LBE (a) and He (b) XADS core designs



(a) (b)

Figure 2. Diagrams of the LBE (a) and He (b) XADS system designs



(a) (b)

For the gas-cooled XADS, the decay heat removal system consisted 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 at the same elevation as the connection to the PCS. The heat exchangers had a natural circulation secondary side water coolant flow and were designed to operate on the primary side under natural circulation conditions at full reactor pressure; they also include blowers to circulate the primary coolant flow under low pressure (LOCA) conditions. Another feature of the decay heat removal system was a valve 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 functioning 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. subassembly (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 collect together different analytical tools, including such “system codes” as: TRAC/AAA and RELAP5 (suitably modified for LBE systems); special “fast reactor” codes (e.g. SIM-ADS and SIMMER) that include only 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 Figure 3 for the unprotected loss of flow transient. Here, we see an example of two types of analysis, the first using the system codes (e.g. RELAP5 and TRAC) that include a full represenation of the primary and secondary systems. These show the evolution of the transition to thermally driven natural circulation. The remainder of the codes 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 was between 40% and 50% of the nominal value. Most of the code systems calculate the change in core power using a point kinetics model. And here we see that because of subcriticality there was only a small reduction in the core power. Due to the high core flow under natural circulation conditions, the resultant core temperatures (in almost all of the codes) showed only a modest increase of typically 100 C (i.e. from 400-500 C) for the core exit coolant temperature. The results of this analysis highlight 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 core temperatures. This second feature can be applied to almost all of the transients analysed in Table 2, the only exception being U-5 and the unproteced loss of flow and heat sink (comparative results presented in Figure 4). In this figure, which shows the results from TRAC, RELAP5 and SIM-ADS, we see that even though there was a total loss of heat sink, there was 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 increase was 400 C to 500 C for the RELAP5/TRAC calculations in 1 000 s, which is a more than 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 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. This has 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

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

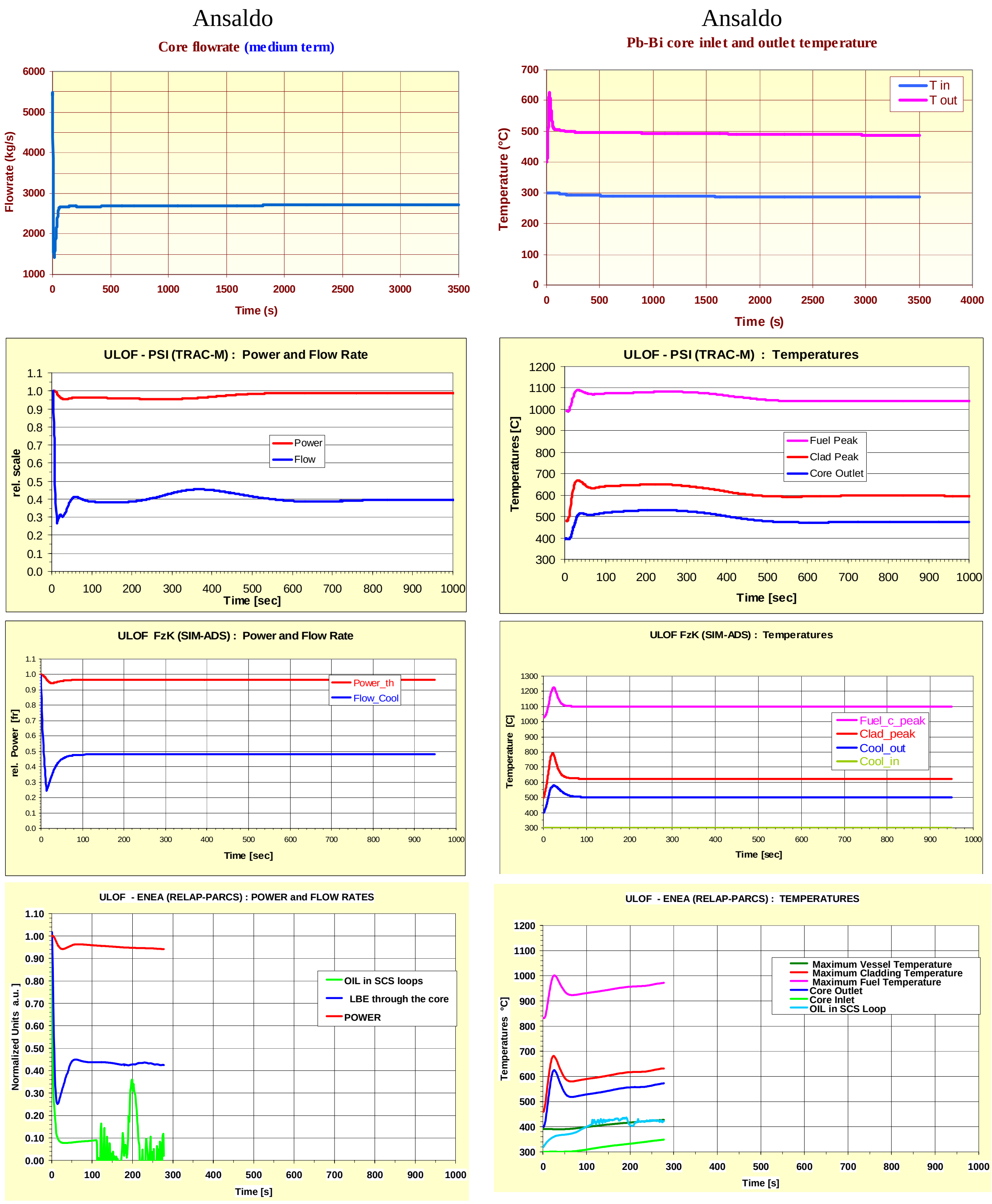
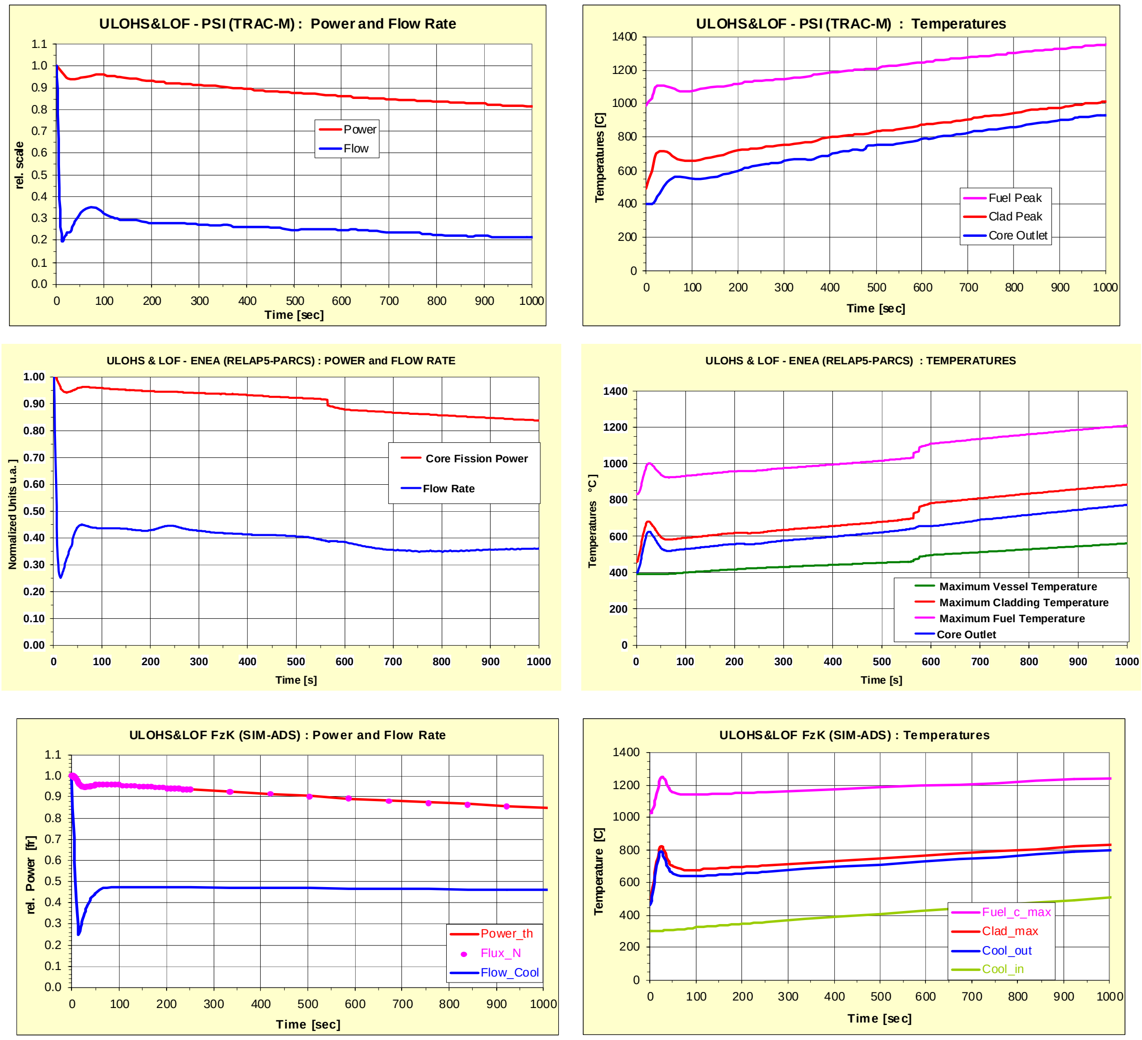


Figure 4. Comparison of code results for loss of flow and loss of heat sink transients



A transient that was considered of importance in the analysis of sodium-cooled fast reactors, was that of local subassembly blockage because of the potential for local fuel melting to go undetected with the result that it may spread into a core-wide problem. As a required condition in the PDS-XADS safety assessment, 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 (permits an analysis of core melt conditions) and STAR-CD (a CFD code). In the two-dimensional (2-D) 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 would be blocked simultaneously and radial heat transfer 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 Figure 5. In case (1) with HGF and RHT, the cladding temperature stayed at ~200 K below the melting point and no clad melting was predicted. If only a single assembly is blocked in an actual three-dimensional (3-D) 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 brought a strong reactivity reduction so that no severe power excursion would occur. Figure 6 shows the fuel particle distribution after the pin failure and the expanding damage in the innermost assembly, indicating that fuel particles could be swept away from the core region and that reactivity would be reduced as a consequence.

In Figures 7(a) and 7(b) below the STAR-CD steady state results with an unprotected inlet blockage in one subassembly are presented. The assumed blockage reduced the coolant flow rate in the concerned subassembly to 2.5% of nominal flow. [Note that this is a more severe restriction than that of the SIMMER analysis, which assumed a flow restriction of 2.5% and led to higher temperatures (as will be seen).] Figure 7(a) below shows the LBE temperatures in the blocked and the neighbouring intact subassembly at full flow. The neighbouring subassembly was locally heated much above the nominal 400 C outlet temperature. Since all six neighbouring SAs were at full flow, they removed nearly all the heat generated in the blocked assembly. In Figure 7(b), the cladding temperatures of the blocked subassembly and the neighbouring one with full flow are shown. It can be seen that the maximum cladding temperature in the blocked subassembly was 1 670 K, i.e. just a few degrees below the steel melting point but approximately 100 C higher than the equivalent SIMMER calculation. (This means rather certainly that many fuel pins have already ruptured and that fission gas release has occurred. But, since the maximum fuel temperature is only 1 900 K, 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 in fact is relatively modest.

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

Figure 5. SIMMER-III clad temperatures for blockage case

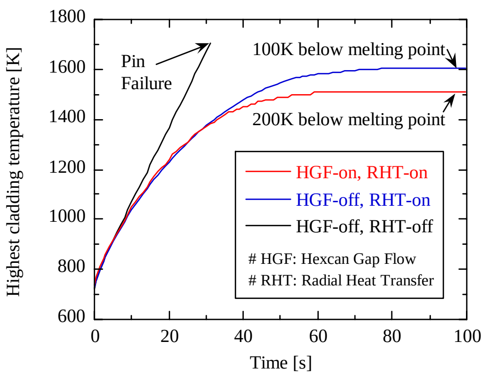


Figure 6. SIMMER-III fuel sweep-out for pin failure case

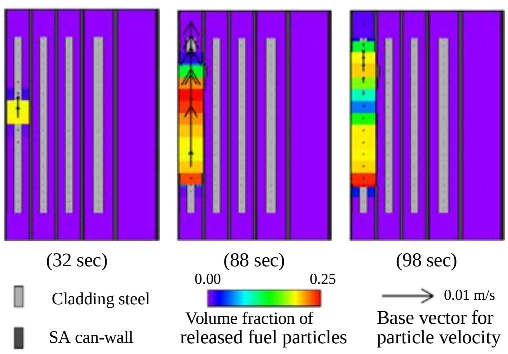
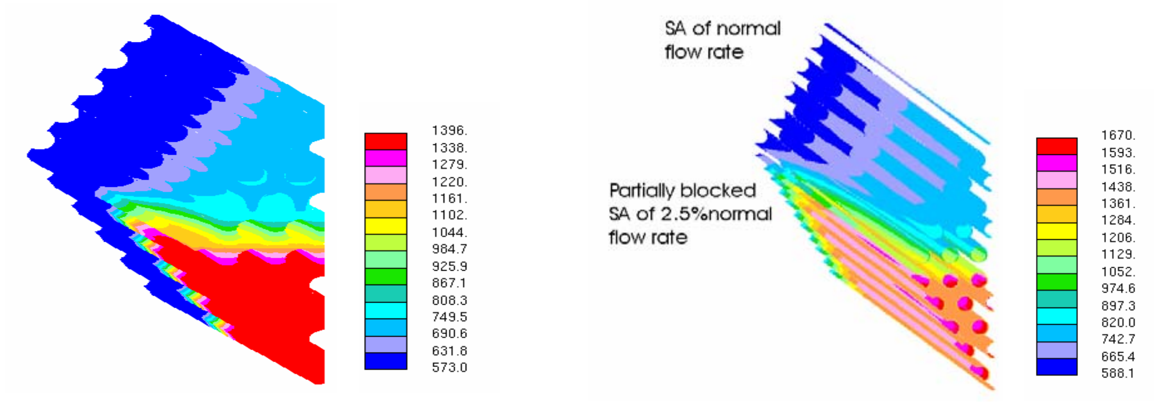


Figure 7. Coolant (a) and clad temperatures [K] (b) in blocked and neighbouring SA at full flow



(a) (b)

Gas-cooled XADS transient analysis

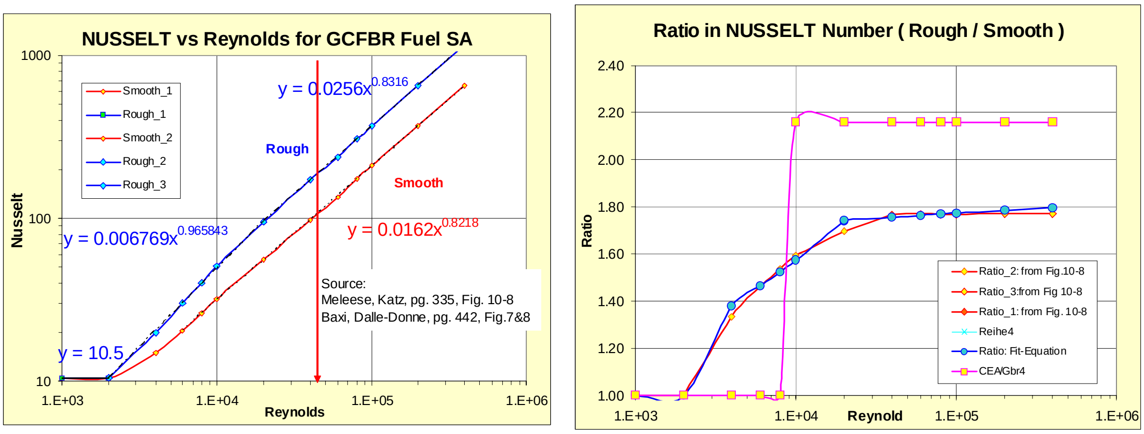
The range of transients to be analysed for the gas-cooled XADS was reviewed and a table similar to that produced for the LBE design (see Table 2 above) was developed. The transients selected for analysis (as for the LBE) included core-driven events (e.g. beam over power, reactivity addition accidents)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

As part of the initial transient analysis of the gas-cooled concept, a number of critical features became apparent including: high clad temperatures were obtained even during normal operation; clad temperatures in excess of 1 200 C were obtained for a range of protected transients; and clad temperatures rose to the melting point in a few tens of seconds unless the accelerator beam was immediately tripped for more “severe” accidents (such as a large break in the pipe connecting the vessel to the power conversion unit).

In order to address the first two of the above-mentioned issues, the reactor core was redesigned to increase the fuel rod to coolant heat transfer and to redirect the coolant flow to the higher rated subassemblies. The first 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 was that both increased the core pressure drop. Therefore, a goal 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 depressurisation.

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

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



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

An example of the results of the revised analysis is shown in Figure 9, which illustrates 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 ~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 of ~1.6 kg/s for two out of the three units. 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 ~600 C after ~2 000 s. However, the magnitude of the peak clad temperatures is primarily defined by the normal operational fuel-stored energy and the cooling during the early period of the transient following the trip of the accelerator beam (for this transient is based on a high core-exit coolant temperature set point). Thus, it is important for this and other system-driven transients 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 Figure 9 (TRAC/AAA) and Figure 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], and with the associated increased transient heat transfer (for high Reynolds numbers), 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.

In addition to the analysis presented, similar conclusions 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. With unprotected transients, the reactivity changes that occur as a result of the increase in fuel temperature, etc., have a minimal effect on core power of subcritical systems, and thus 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) was lost. This is important for both normal operation and accident situations if large gradients may occur. In order to address this concern, computational fluid dynamic (CFD) models are being developed using the STAR-CD code with the detailed mesh shown in Figure 11 as an example. As a first stage in the analysis, thermal-hydraulic calculations for nominal conditions were performed to determine the helium temperature and the temperature in the different structural components (e.g. reactor main vessel, the inner vessel, cross duct, core assemblies and shielding, accelerator vessel, upper shielding plate, etc.). As a second step, the transient calculation of the helium and structural temperatures will be calculated. These calculations will provide the input for a detailed stress analysis of these components under normal and transient conditions.

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

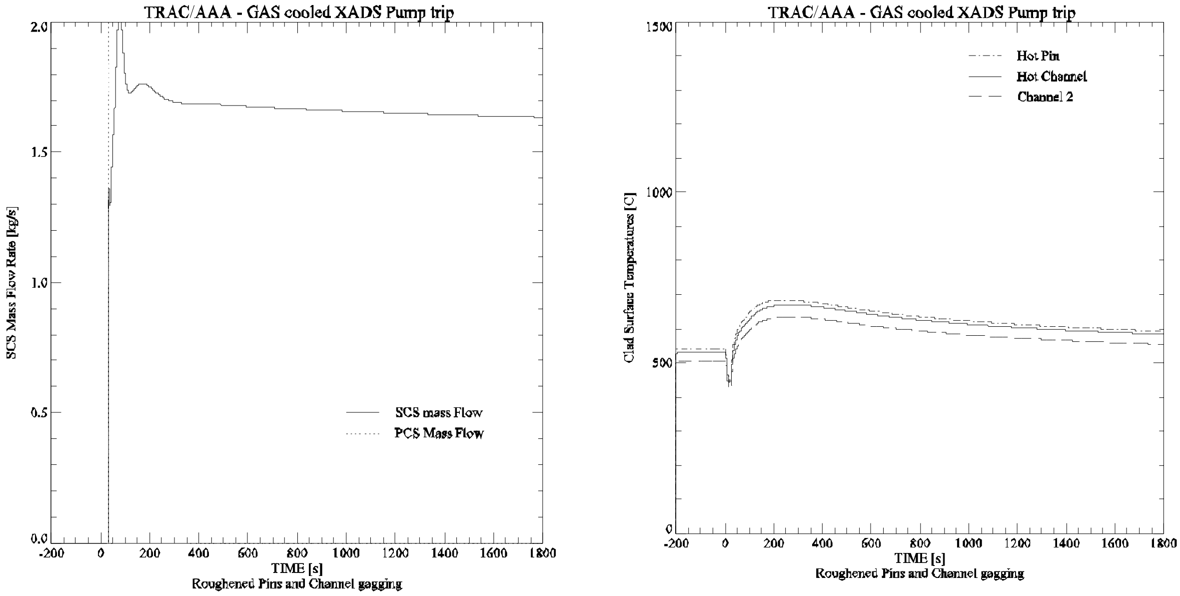


Figure 10. SIM-ADS results for peak fuel and clad temperatures, coolant inlet and outlet temperatures

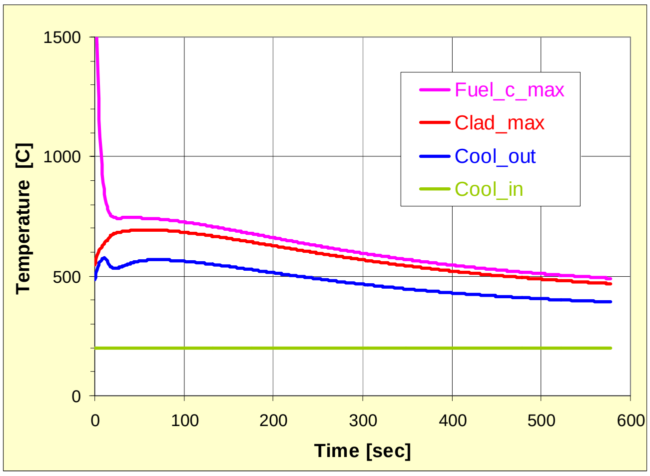
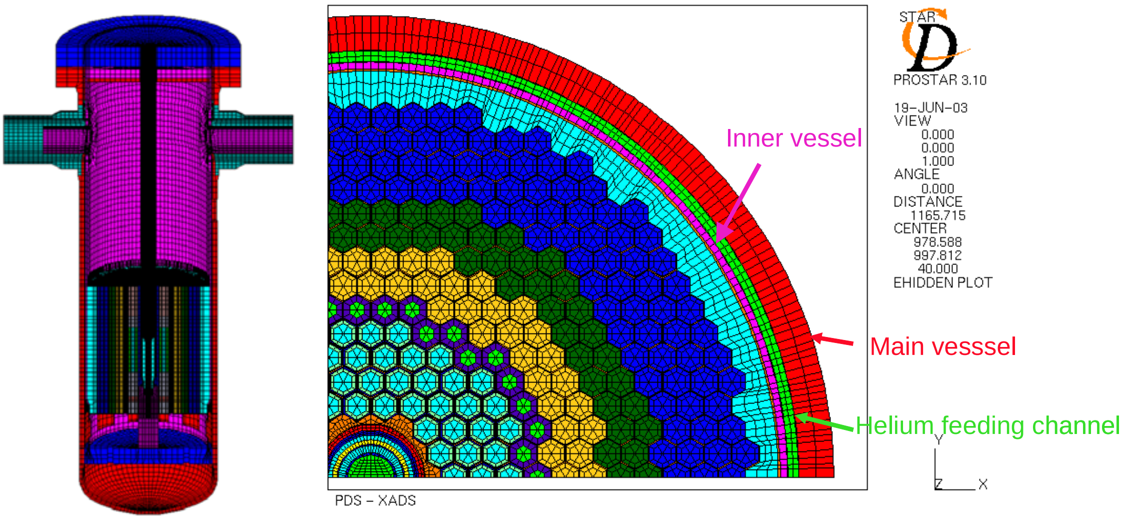


Figure 11. STAR-CD solid mesh and cross-section of the model at core midplane level



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), the reactor system is able to cool the core for all protected transients and almost all unprotected transients because of the high thermal inertia of the coolant, the excellent natural circulation properties and the modest power ratings. Even in the most severe case considered (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 analysis through the PDS-XADS project framework is the ability to provide code-to-code comparisons for a range of transients using a wide range of 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 indicated 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 a depressurised 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, fuel pin roughening and subassembly 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 subcritical 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 these mechanisms function on demand to a very high degree of reliability.

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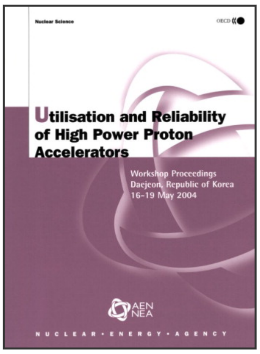

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