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A GFR benchmark comparison of transient analysis codes based on the ETDR concept

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Abstract – *As a precursor to a detailed deterministic transient analysis of the Gas-cooled Fast Reactor (GFR) and the Experimental Technology Demonstration Reactor (ETDR) options, which are currently being studied within the Generation IV GFR and EU GCFR projects, a GFR transient benchmark study was initiated. The goal of the study was to "benchmark" the transient analysis codes being used by the GFR partners: RELAP5, TRAC/AAA, CATHARE, SIM-ADS, MANTA and SPECTRA. The benchmark was coordinated by the EU GCFR project but was open to all Generation IV partners. As a starting point, the benchmark was based on a main blower failure event in ETDR with reactor scram in order to investigate the ability of the different code systems to calculate the transition in the core heat removal from the main circuit forced flow to natural circulation cooling using the plant Decay Heat Removal (DHR) system. Benchmark results were received from nine organizations: AREVA France, CEA France, NRG and TUD Netherlands, AMEC-NNC UK, INL USA, CIRTEN Italy, JRC-IE EURATOM and PSI Switzerland. For comparison purposes the benchmark was divided into several stages: the initial steady-state solution, the main blower flow run-down, the opening of the DHR loop and the transition to natural circulation and finally the "quasi" steady heat removal from the core by the DHR system. The results submitted by the participants showed that all the codes gave consistent results for all four stages of the benchmark. In the steady-state the calculations revealed some differences in the clad and fuel temperatures, the core and main loop pressure drops and in the total Helium mass inventory. Also some disagreements were observed in the Helium and water flow rates in the DHR loop during the final natural circulation stage. Good agreement was observed for the total main blower flow rate and Helium temperature rise in the core, as well as for the Helium inlet temperature into the core. In order to understand the reason for the differences in the initial "blind" calculations a second round of calculations was performed using a more precise set of boundary conditions. The paper will present the results of both sets of calculations, and highlight the differences in the different code system simulations and show how these influence the results of the benchmark calculations.*

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I. INTRODUCTION

The benchmark specification i.e. loss of flow transient with reactor scram (for the Experimental Technology Demonstration Reactor (ETDR)[1,2] was defined at the first GCFR WP 1.5 benchmark meeting (PSI, Oct 2005) and the calculations were subsequently performed by all benchmark partners, which are AREVA France, CEA France, NRG The Netherlands, AMEC-NNC The United Kingdom, INL USA (phase 1), CIRTEN Italy, JRC-IE EURATOM and PSI Switzerland. Results of the first phase calculations were forwarded to PSI during March-April 2006. Following the submissions, PSI compiled all the results and the comparison of the results was presented at the second GCFR WP 1.5 benchmark meeting (PSI, May 2006).

During the meeting, the conclusion was made that the agreement between all the participants was good, but better agreement of the results was to be preferred. Significant discussion took place as to the reason for the discrepancies and a number of differences between the codes and the modelling of the ETDR facility were identified, which included:

- different heat transfer correlations used for the main heat exchanger i.e. cross-tube correlation or straight tube correlation (e.g. Dittus-Boelter) with adjustment factor;
- different core (rod bundle) heat transfer correlations;
- different heat transfer correlations in the DHR heat exchangers;
- modelling of the vessel wall heat structures;
- vessel pressure drop and flow resistance in the DHR helium and water loops;
- coolant (helium) inventory in the primary and decay heat removal (DHR) loop.

There was a proposal from the benchmark participants to review the benchmark specifications and make a second attempt to model the same transient but with more ‘strict boundary conditions’ in order to try and identify, which of the above gave the largest contribution to the differences in the first "blind" phase submissions. Specification for the second phase benchmark calculation was issued at the beginning of August 2006 and further clarification on the coolant volumes in different parts of the ETDR cooling system was made available to the second phase benchmark participants.

Results of the second phase benchmark calculations were forwarded to PSI during September-October 2006. Following these submissions, PSI again compiled the calculational results and the comparison of the results was made available to all participants of the second phase benchmark calculations.

Comparison of the calculation results of both phases of the GCFR benchmark calculations, along with the corresponding discussions and explanations, is presented below in this paper.

II. BENCHMARK SPECIFICATION

This section of the paper provides a brief summary of the GCFR benchmark specification.

For the ETDR model development, the initial system specification was provided to all the benchmark participants. The information included:

1. The core configuration, including the number and dimensions of the fuel pins and the fuel assemblies, the radial and axial, and hot assembly peaking factors, the core power, mass flow rate and coolant pressure, etc. In the benchmark calculation only the fuel active length was modelled (i.e. the 0.86 m fissile length). Since the radial peaking factor of 1.15 applied to the hot assembly, it was suggested that the models should include a representation of this in addition to the “average core” assembly. The core pressure drop is primarily determined by the presence of the spacer grids and the inlet orifice and the final value of the core pressure drop based on 3 (three) grids of 0.41 bar was specified for a total mass flow rate of 32.0 kg/s and core inlet temperature of 260 ºC;
2. Fuel and clad material properties;
3. The main vessel dimensions and material thickness. An average value of 75 mm was used in the benchmark analysis for the vessel thickness. Based on this the total mass of the vessel was estimated to be ~ 70 tonnes;
4. Length and diameter (flow area) of the cross duct between the main vessel and heat exchanger and blower for both the hot and cold gas flow paths. The pipe thicknesses were not specified and were not included in the benchmark exercise;
5. The main tube and shell heat exchanger with the secondary fluid (water at 65 bar pressure) flowing inside the tubes. The number and dimensions (including material) of the tubes was provided. For the secondary side the pressure, inlet temperature and total mass flow rate were given;
6. The main blower unit. The behaviour of the main blower was to be represented using the provided homologous curves, both for the blower head and for the blower torque. The reference speed and volumetric flow and nominal density were also provided, but not the reference head or torque. In the ETDR plant design 3 + 1 blowers in parallel of about 400 kWe are proposed as a possible option, but in the calculation model a single unit was modelled with a motor power of 1 MW. It was decided for the benchmark that the calculational blower unit be initialised by assuming that the operating point is for $\alpha = \nu = h = \beta = 1$, i.e. at the reference speed, volumetric flow rate, head and torque. For the transient calculation a preliminary value of 130 kg·m^2 was defined for the moment of inertia. However it was decided for the first transient calculation to define a flow run down curve that was also presented to the participants;

7. Information was also provided on the decay heat removal (DHR) system. In the plant there will be three (3) loops, but for the benchmark exercise a single loop was modelled. The DHR system consists of a helium loop, a helium to water vertical heat-exchanger, a water loop and a water to water horizontal heat exchanger. The final heat sink is a large pool of water at a temperature of 90 °C. The helium loop is composed of cross-duct piping. Information was provided on the loop flow areas and lengths, the number and dimension of tubes for both the helium and water heat exchangers. Because of the uncertainty in the heat transfer to the final heat sink, i.e. the water pool, and the difficulty of calculating this with general-purpose codes it was decided to set the external temperature of the tubes to the water temperature of 90 ºC, which is equivalent to the use of a very high heat transfer coefficient. In the final ETDR design blowers maybe included in the DHR system, however for the benchmark exercise both loops of the DHR were assumed to operate in natural circulation. For the benchmark exercise the DHR loop was assumed to be closed with all secondary circuits at 90 ºC, which is the temperature of the (water pool) final heat sink;

8. It should be noted that cross duct piping was used for the helium flow in the primary circuit and DHR loop, and the possible heat conduction between the two paths was not modelled as part of the benchmark.

In summary:

- The total core flow rate was set to 32 kg/s, with no core bypass;
- The core inlet and exit temperatures are 260 °C and 560 °C, respectively;
- Implying a core temperature increase of 300 °C;
- All fuel assemblies have the same power density except for a “hot” assembly with a radial peaking factor of 1.15;
- An assembly gagging scheme should be used to obtain a uniform coolant exit temperature;
- Only one of the three DHR loops is assumed to function;
- The decay heat is to be removed by natural convection, i.e. the DHR blowers are not to be included;
- The core pressure drop should be 0.41 bar;
- DHR loop is isolated under normal operation and is at a temperature of 90 °C, equal to that of the final heat sink.

III. BENCHMARK RESULTS COMPARISON

Before performing the benchmark transient (a loss of flow transient with reactor scram) calculations, a steady-state calculation of the ETDR corresponding to the system specification was performed. Selected examples of the steady-state conditions of the ETDR, as well as transient calculational results from the participants are presented below.

III.A. Phase 1 calculation results

Steady-state conditions of the ETDR, obtained from the first phase benchmark calculations corresponded closely to the system specification. The axial fuel and clad temperature profiles in the ‘hot’ channel are presented in Figs. 1 and 2, respectively.

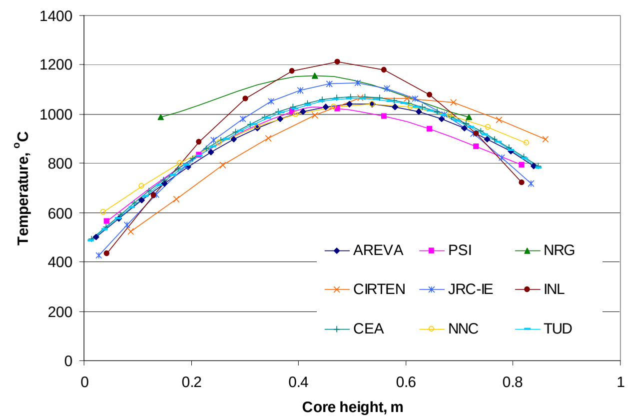

Fig. 1. Fuel temperature profile in ‘hot’ channel.

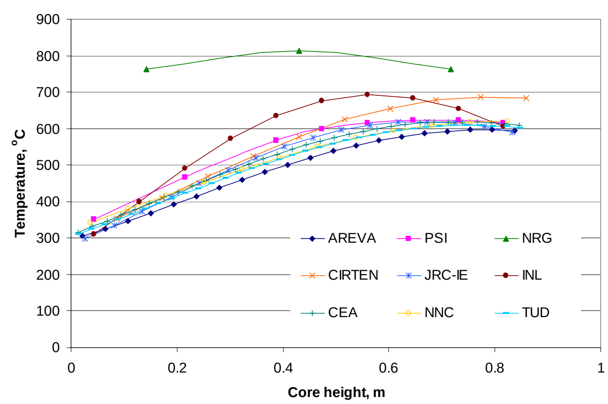

Fig. 2. Clad temperature profile in ‘hot’ channel.

The results in Figs. 1 and 2 show a good measure of agreement, except for the high NRG clad temperatures. The INL clad temperatures lie above the majority of the other partners because of the low “conservative” heat transfer correlation. All partners used a gagging scheme except for INL, NRG and CIRTEN, which for NRG and CIRTEN influenced the coolant outlet temperature in the “hot” assembly and for CIRTEN the axial profile of the clad and fuel temperatures.

Major differences in the steady-state results were observed in the:

- coolant inventory, with differences of more than a factor of 2,

- main coolant loop pressure drop, most participants modelled a core pressure drop of 0.41 bar, however the specifications were not clear as to whether the 0.41 bar was to be with or without gagging.

Transient scenario and the calculation results

The scenario of the benchmark transient (a loss of flow transient with reactor scram) is as follows:

• The main blower is tripped ("switched-off") at time t = 10 s. The blower speed decreases according to flow run down curve provided for the benchmark purpose;

• The reactor is scrammed when the pump speed reaches 90 % of the nominal (steady-state) value. Prior to the scram the reactor is assumed to remain at full power, i.e. reactor kinetics is not considered as part of this benchmark exercise. Following the reactor scram the power follows the decay heat curve with a linear interpolation over the first one second. (The decay heat curve was defined as: $P(t)/P_n = 0.1458 * t^{-0.28}$; where: t - is the time in seconds after scram, P(t) - is the power and P_n - is the nominal power);

• When the blower speed reaches 5 % of its nominal value the main blower circuit is isolated and the decay heat removal circuit is opened. The main heat removal circuit is isolated by closing an isolation valve located in the "cold" helium flow path i.e. between the blower and the vessel downcomer. The valve flow area is decreased linearly between 100 % and 0.0 % over the time period of 10 s. Similarly the isolation valve in the DHR circuit is opened fully over 10 s. Again the valve flow area is increased linearly between 0.0 % and 100 % over 10 s. The DHR isolation valve is located in the "cold" part of the DHR loop, i.e. between the heat exchanger and the vessel downcomer;

• Prior to the isolation of the main cooling circuit, the main heat exchanger secondary side is assumed to operate with fixed (i.e. steady-state) values of the inlet coolant temperature of 130 ºC, and water mass flow rate of 175 kg/s at the nominal secondary pressure of 65 bar, following the isolation of the main circuit the secondary flow is ramped to zero;

• During the course of a transient the coolant average temperature will change (both increasing and decreasing) resulting in a pressure change in the system. It is anticipated that the ETDR will include a form of pressure control however in advance of the specification of the pressure controller the transient is performed assuming a constant mass of helium.

Calculation results comparison

Taking the above description into account, the calculations of loss of flow transient with reactor scram were performed. Following the simulations, selected calculation results of this transient are presented below in Figs. 3 to 8.

As can be seen, the transient can be divided into 3 stages:

i) Blower run-down stage – 10 to ~ 190 s;

ii) Establishment of natural circulation stage – ~100 s (from 190 s to 290 s);

iii) Natural circulation stage – starting from 300 s and onwards.

Important features of this transient as related to its different stages are:

Stage 1: Transient core and main HX heat transfer;

Stage 2: DHR He and H_2O loop heat transfer and flow resistance;

Stage 3: Quasi equilibrium, water loop flow rate and temperature, helium loop flow rate – flow resistance at low Reynolds numbers.

As can be seen from Figs. 3 to 8, the transient calculations were performed for 1000 seconds. At time t = 10.0 seconds the main blower is tripped (see Fig. 3). After ~ 2 s the blower speed reaches 90 % of the nominal value and the reactor is scrammed. Since the reactor power decreases much faster than the blower speed at the beginning of the transient, there is no heat-up of the core. In fact the heat removed by the main heat exchanger dominates the behaviour during the flow run down stage and the whole system is cooled and the fuel temperatures never exceed the initial steady-state value (see Fig. 8). After ~174 s from the start of the transient, the blower speed reaches 5 % of its nominal value and the main blower circuit is isolated, in the defined period of 10 s. At the same time the DHR circuit is opened. The core flow, first decreases as the main loop is isolated but then increases as the DHR loop opens, natural circulation is established and the gas at 90 ^{o}C in the DHR loop flows into the core. There is a small delay in the start of the flow in the DHR loop in most of the calculations of up to 30-40 s, however only in the CIRTEN calculation there is an extended delay of ~ 150 s.

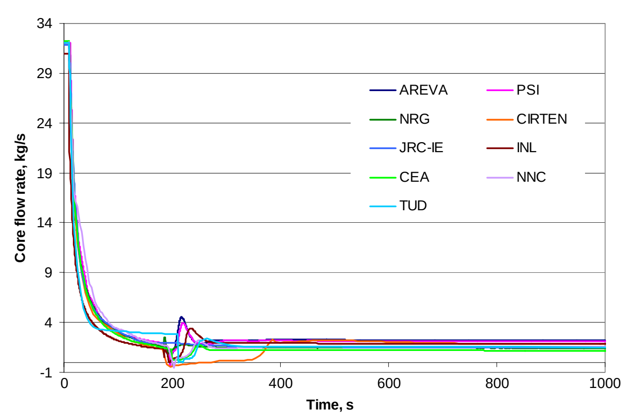

Fig. 3. Total core flow rate versus time.

A quasi-equilibrium natural circulation DHR and core flow is established at a transient time of about 300 s (400 s for the CIRTEN calculation) (Figs. 3 and 4). The DHR natural circulation provides a core Helium mass flow that is sufficient to cool the core, with all the calculations showing approximately constant clad temperatures. The clad temperatures slowly decrease as the decay heat decreases. However the helium flow rate in the DHR loop varies by about a factor of 2 between 1.2 and 2.2 kg/s (Fig. 4) and with a variation in the DHR water loop flow between ~ 20 to 50 kg/s.

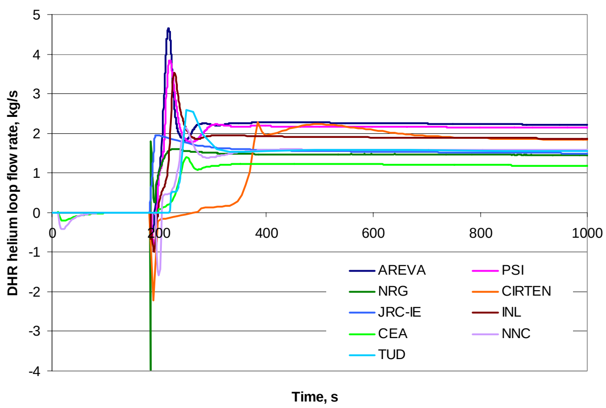

Fig. 4. DHR helium loop flow rate versus time.

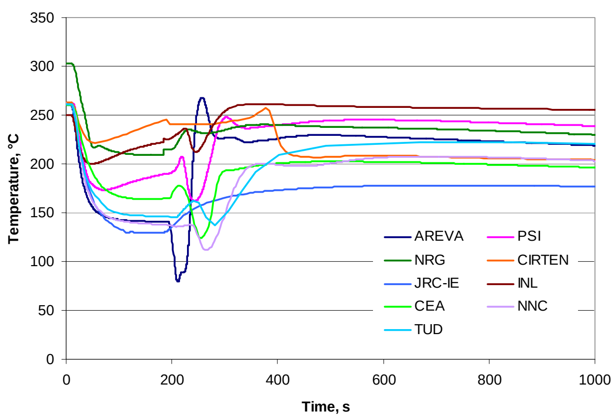

Fig. 5. Coolant temperature at the core inlet versus time.

At the start of the transient the system pressure decreases because of the reactor trip and the system cools down, then it stabilizes for a while and increases again when the main coolant loop is isolated and DHR system is opened and the cold (90 ^{o}C) helium flows into the vessel and is heated. When natural circulation through the DHR loop is established, the system pressure settles to a new value.

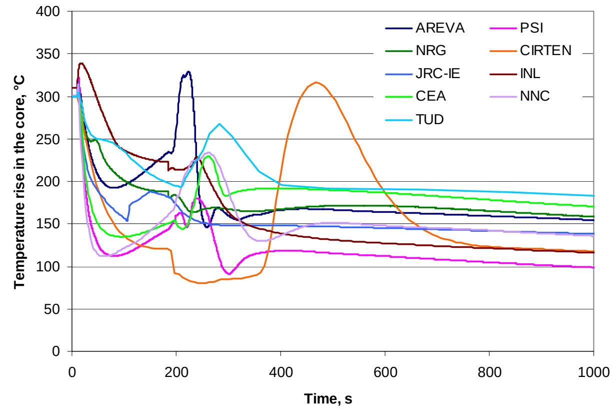

Fig. 6. Coolant temperature rise in the core versus time.

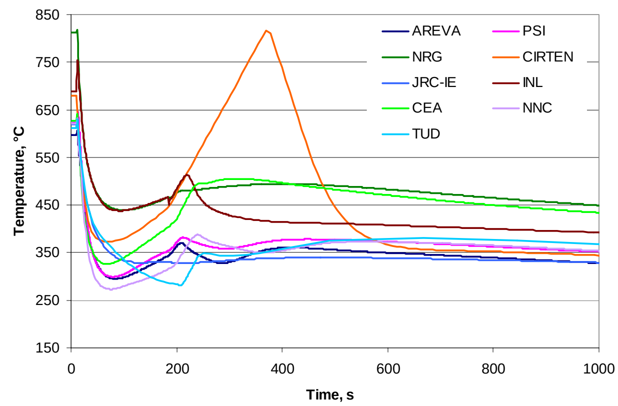

Fig. 7. Max. clad temperature in hot channel versus time.

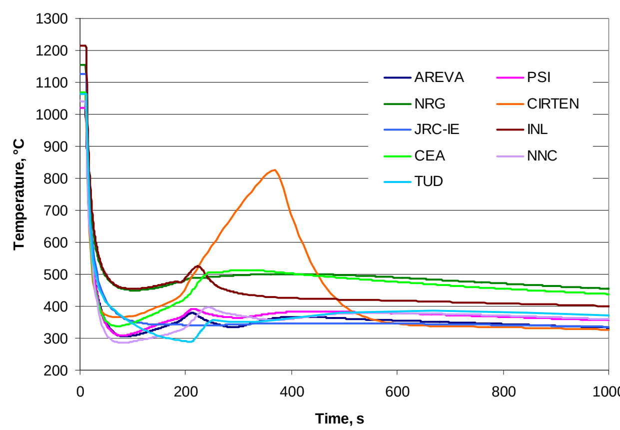

Fig. 8. Max. fuel temperature in hot channel versus time.

The coolant (He) temperature at the core inlet (Fig. 5) at first falls as the heat removed by the main heat exchanger exceeds the decay heat and the whole system cools down. Then after ~ 50 s there are two groups of calculations (1) in which the core inlet temperature remains constant and is either close to or just above the main heat exchanger secondary temperature and (2) those

(PSI, INL, CIRTEN) in which the temperatures slightly increase, with the value depending on the modelling of the vessel and other structures. After the opening of the DHR loop most calculations show a decrease in the core inlet temperatures as the cold helium in the DHR loop flows into the core. The difference in the coolant temperatures between the different partners after the end of the flow run down stage are carried through to the quasi-equilibrium natural circulation stage.

The increase in the coolant temperature through the core (Fig. 6) decreases as the core flow decreases and the difference between the different partners after ~ 50 s of more than 100 ^{o}C reflects the differences in the core flow (Fig. 3) and different core heat transfer correlations. There is an approximate consistency in that for example NNC has the highest core flow during the run down stage and the lower core coolant temperature rise, while TUD and INL show the lowest core flow and the highest core coolant temperature increase.

After the flow run down stage and the closing of the main loop and opening of the DHR loop most calculations show an increase and then decrease in the core coolant temperature as the flow through the core first stalls and then increases as the natural circulation flow in the DHR loop is established. The exception is the CIRTEN calculation which shows a reduction in the core coolant temperature increase as the core flow stagnates. In this case the reduction in the core flow is sufficient to limit the heat transfer from the fuel pin to the coolant resulting in a large increase in the clad and fuel temperatures (Figs. 7 and 8).

The transient results were compared between all the participants of the benchmark. Comparison of the transient results obtained by the 9 organizations indicated that the agreement was reasonable, but further improvement of the ETDR model was necessary. This was done in the second phase of the benchmark having more 'strict boundary conditions' for the same transient specification (see section III.C). In order to guide the second phase of the benchmark PSI performed a limited set of sensitivity calculations to help identify the key phenomena influencing the calculational results during the flow run down stage of the transient i.e. during the first ~ 200 s of the transient. The results of these sensitivity calculations are described below.

III.B. Phase 1 sensitivity studies - sensitivity to heat transfer and heat structure modelling

During the second ETDR benchmark meeting a discussion took place related to the differences between the partners regarding the core inlet coolant temperature behaviour during the initial pump run-down stage of the transient. The following two observations were made: i) the differences might be due to the different heat transfer correlations used by the participants for the main heat exchanger, ii) the differences might be due to the additional wall heat structure modelling, i.e. other than the core, and the main and DHR heat exchanger heat structures, used by some participants.

In order to test these ideas the following sensitivity studies were performed at PSI.

Sensitivity to the main heat exchanger heat transfer correlation

The model of ETDR used in the sensitivity studies is the same as that used for phase 1 of the benchmark. As the source files of the TRAC/AAA code are available at PSI, this provides an opportunity to perform sensitivity studies that require changes in the code. This was done for this case, when the Incropera cross-flow correlation ($Nu = 0.55 * Re^{0.56} * Pr^{0.33}$) used during the benchmark (PSI) was changed to Dittus-Boelter correlation multiplied by a factor of A, i.e. $Nu = A * 0.023 * Re^{0.8} * Pr^{0.33}$ where A = 1.79 (PSI2). The results obtained during this study are presented in Figs. 9 and 10 for the coolant temperature at the core inlet and coolant temperature rise in the core. In these figures the contributions from the benchmark partners are allocated to one of 3 categories, i.e. no vessel wall heat structures modelled, limited vessel wall heat structures modelled, vessel wall heat structures modelled.

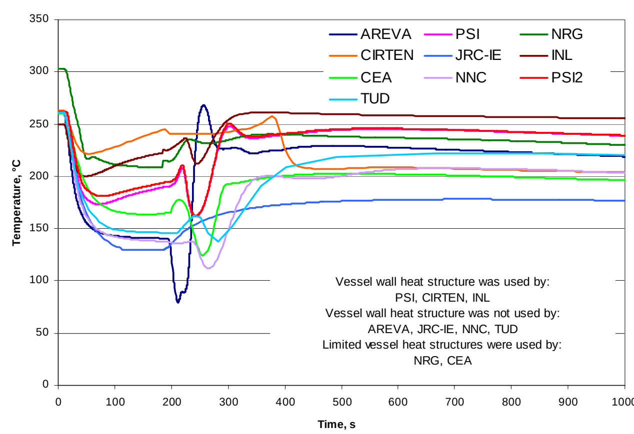

Fig. 9. Coolant temperature at the core inlet versus time during the loss-of-flow transient (PSI – Phase 1 benchmark result; PSI2 – additional calculation with the changed heat transfer correlation).

As can be seen from the results presented in Figs. 9 and 10, changing the main heat exchanger heat transfer correlation does not produce any significant effect neither on the coolant temperature at the core inlet, nor on the coolant temperature rise in the core. This is to be expected since in all calculations the overall heat transfer under steady-state conditions is adjusted to match the required core inlet temperature and the transient response is largely determined by the Reynolds number dependence and this is similar for the two correlations.

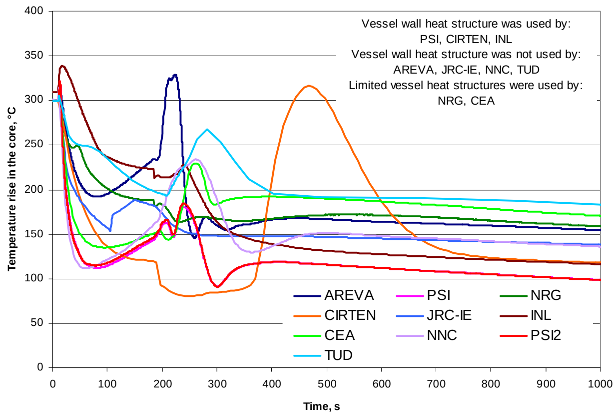

Fig. 10. Coolant temperature rise in the core versus time during the loss-of-flow transient (PSI – Phase 1 benchmark result; PSI2 – additional calculation with the changed heat transfer correlation).

Sensitivity to the vessel heat structure modelling

More significant changes are observed in the second sensitivity study – when the calculation was performed without the vessel wall heat structure. This was the only additional heat structure modelled by PSI apart from the core, and the main and DHR heat exchanger heat structures. The results obtained are presented in Figs. 11 and 12 for the coolant temperature at the core inlet and coolant temperature rise in the core, respectively.

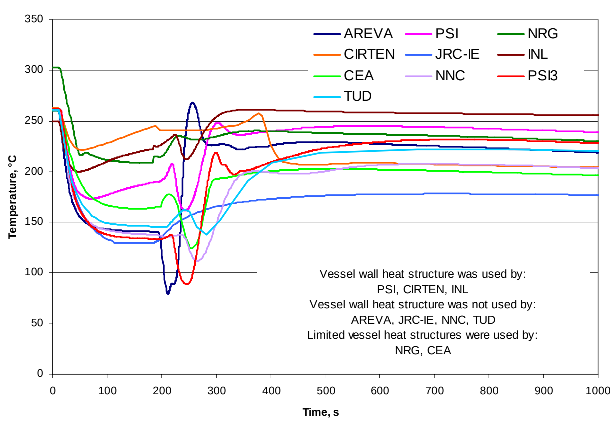

Fig. 11. Coolant temperature at the core inlet versus time during the loss-of-flow transient (PSI – Phase 1 benchmark result; PSI3 – additional calculation without the vessel wall heat structure).

As can be seen from the results, the elimination of the vessel wall heat structure in the ETDR input significantly influences the coolant temperature at the core inlet, making it similar to the results presented by the participants, which were obtained without the representation of any additional wall heat structures. As can be seen the elimination of the vessel wall heat structure has only a small impact on the coolant temperature rise in the core, which will depend more strongly on the core (fuel rod) heat transfer.

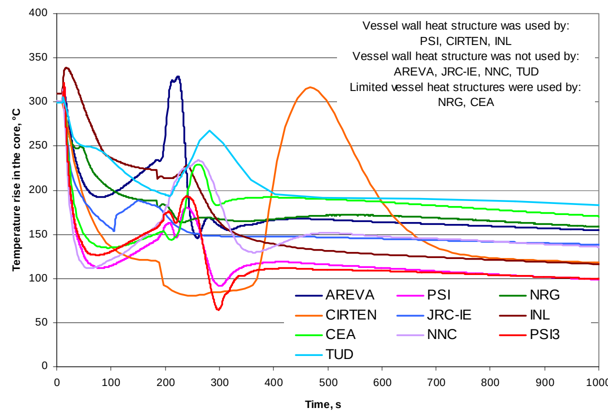

Fig. 12. Coolant temperature rise in the core versus time during the loss-of-flow transient (PSI – Phase 1 benchmark result; PSI3 – additional calculation without the vessel wall heat structure).

In summary, it was shown that the modelling of ETDR heat structures has a major impact on the core inlet temperatures during the pump rundown stage of benchmark calculation. This is because: i) the heat transfer through the main heat exchanger reduces the coolant temperature to close to the secondary side temperature and ii) the heat released from the vessel heat structures (if modelled) then heats up the coolant as it flows to the core inlet. The amount of increase in the core inlet temperature depends upon the details of the representation of the heat structures.

III.C. Phase 2 calculation results

Following the first phase calculations (section III.A) and the sensitivity analysis (section III.B) a proposal was made by benchmark participants to review the benchmark specifications and to perform a second phase to model the same transient but with more "strict", i.e. rigid boundary conditions. The goal being to try and eliminate the uncertainties in the transient specification and boundary conditions observed in the first phase "blind" submissions and so identify the important differences in the physical modelling between the different code systems.

After a long discussion, it was agreed to perform a second phase of the benchmark based on the original transient specification, but using the following revised 'boundary conditions':

• Remove ALL heat structures (except those needed for the core, i.e. fuel rods, and the main and DHR heat exchangers);

• Specify 0.41 bar pressure drop for the ungagged core (lower plenum to upper plenum);

• Every participant should gag the average power channels in order to obtain a uniform core exit temperature in all fuel channels;

• No additional vessel and DHR loop flow resistance other than that defined below should be used;

• For the DHR helium loop - specify k=0.5 (k – additive loss coefficient, where the pressure loss $\Delta p=(k/A^2)(m^2/2\rho)$, A – coolant flow area, m – coolant mass flow rate, ρ – coolant density) at the inlet & k=1 at the exit of heat exchangers, k=0.5 at the inlet to the DHR pipe from the vessel & k=1 at the exit of the DHR pipe to the vessel downcomer and k=0.15 at the bends;

• For the DHR water loop - specify k=0.5 at the inlet & k=1 at the exit of heat exchangers, k=0.15 at the bends;

• Participants should fix their core inlet temperature to 260 °C, and investigate their phase 1 clad temperatures;

• CEA specified the Helium volume in the vessel, main loop including the main heat exchanger (total) and DHR (one loop);

• PSI specified the DHR water volume - the estimated value is ~2.8 m^3 for one loop;

• PSI specified the total main loop pressure drop - proposed value is ~1.0 bar for the total main loop pressure drop (as a mean value from the first phase);

• Participants should fix main blower flow run down curves in the second round of calculations;

• Participants should to the extent possible, review and analyze cross-flow heat exchanger and rod bundle heat transfer for turbulent and laminar flows at high and low pressures (as used in their codes) and examine the sensitivity to heat transfer modelling of the main heat exchanger, as well as sensitivity to the core heat transfer modelling.

The steady-state results obtained from the second phase calculations were summarized and a conclusion was made that the steady-state results again nicely correspond to the system specification. Most of the results were now in better agreement between themselves when compared to the first phase.

The axial fuel and clad temperature profiles in the ‘hot’ channel are presented in Figs. 13 and 14, respectively. These show a significant improvement in the agreement between the different participants compared to phase 1.

Using the transient description presented in section III.A, the revised boundary conditions for the second phase of the benchmark and the correction of known errors by some partners, the calculations of the loss of flow transient with reactor scram were repeated, and the selected results of the second phase benchmark calculations are presented below in Figs. 15 to 20.

As can be seen from Figs. 15 to 20, the transient calculation was again run for 1000 seconds. At time t = 10.0 seconds the main blower is tripped (Fig. 15). After ~ 2 s the blower speed reaches 90 % of the nominal value and the reactor is scrammed.

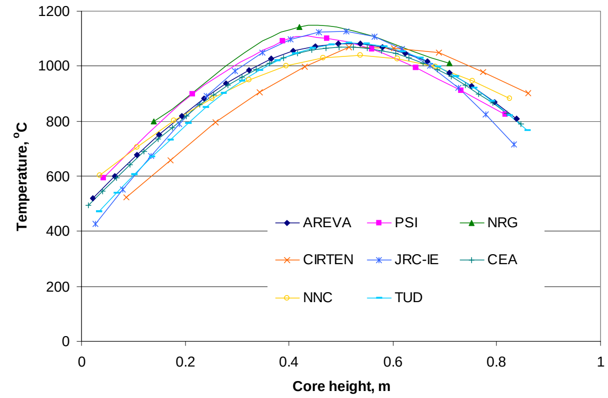

Fig. 13. Fuel temperature profile in ‘hot’ channel.

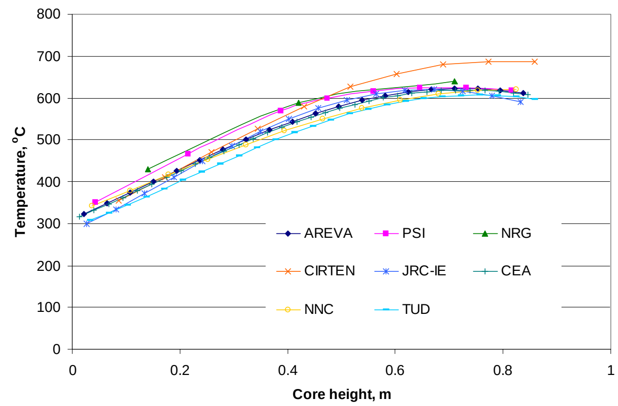

Fig. 14. Clad temperature profile in ‘hot’ channel.

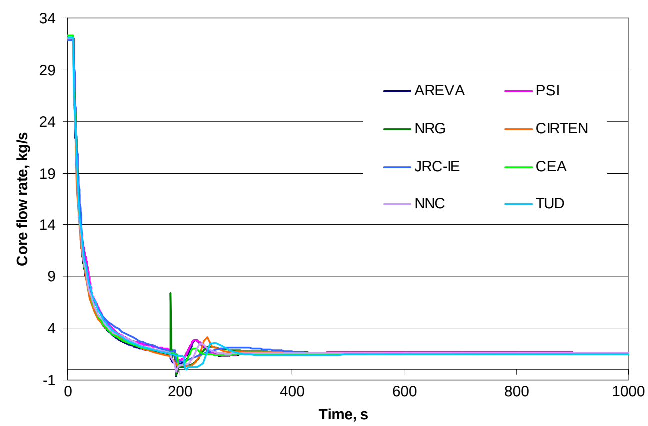

Fig. 15. Total core flow rate versus time.

Since the reactor power goes down much faster than the blower speed at the beginning of the transient there is no heat-up of the core elements, so that the fuel temperature never exceeds the steady-state value (Fig. 20). After ~174 s from the start of the transient, the blower speed reaches 5% of its nominal value and the main blower circuit is isolated in a period of 10 s and the DHR circuit is opened (see Fig. 16).

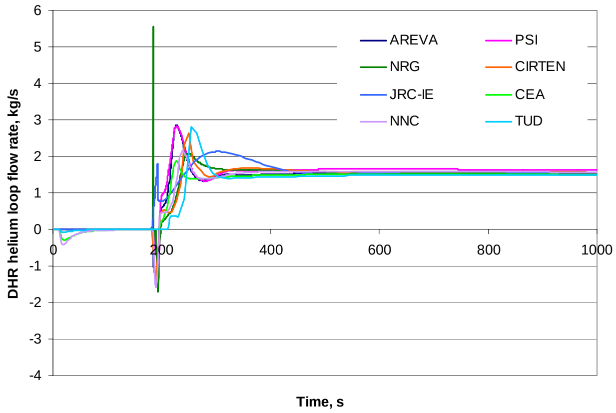

Fig. 16. DHR helium loop flow rate versus time.

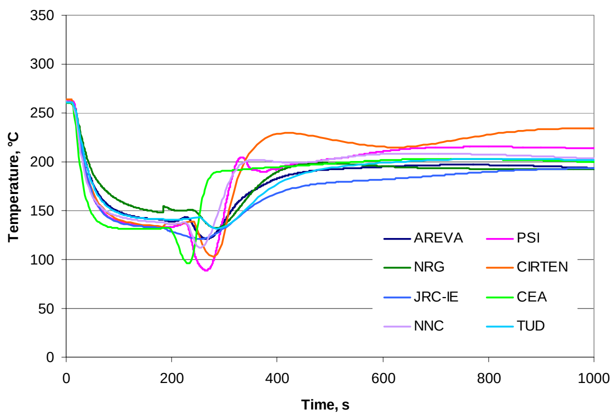

Fig. 17. Coolant temperature at the core inlet versus time.

The phase 2 transient results show a significant improvement in the consistency between the different participants. In particular the elimination of known errors, the removal of the "additional" heat structures and the unification of the flow losses in the DHR loops leads to an improvement in the core flow rate during both the flow run down stage and during the start-up and the quasi-equilibrium natural circulation stages (Fig. 15). Also there is a major improvement in the agreement in the DHR water loop flow rate with the flow rates now varying between 30 and 40 kg/s compared to ~ 20 to 50 kg/s in phase 1. The tightening of the boundary conditions leads, as expected, to closer agreement between the different partners in the core inlet coolant temperature (Fig. 17), although there is still a small difference of ~ 20-30 ^{o}C, which may come from the small differences in the core flow during the flow run down stage. There is a more significant difference in the core coolant temperature rise (Fig. 18), with all partners except CIRTEN and NRG showing very similar results, i.e. within ~ 20 ^{o}C, while the core coolant temperature rise is ~ 50 ^{o}C higher for CIRTEN and NRG. It is assumed that the reason for this difference is due to differences in the core flow rates and in particular for NRG which has a high main loop pressure drop of 1.57 bar. After the initial flow run down and cooling of the core structures, the clad temperatures (Fig. 19) just "follow" the coolant temperatures with only a few degrees difference, between the coolant and cladding temperatures.

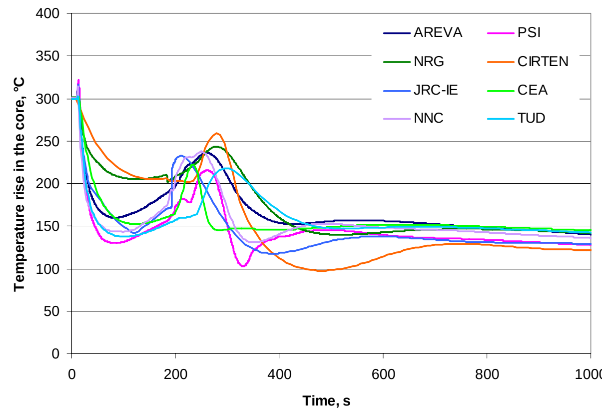

Fig. 18. Coolant temperature rise in the core versus time.

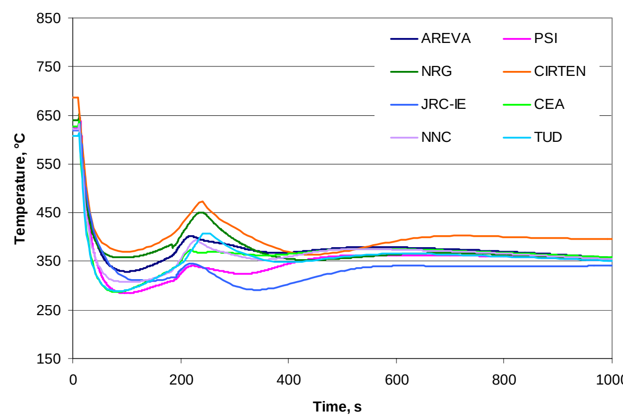

Fig. 19. Max. clad temperature in hot channel versus time.

After the closure of the main loop and the opening of the DHR loop, there is very close agreement in the DHR helium flow rates and consequently between the core inlet temperatures. The "slightly" less than perfect agreement comes from differences in the modelling the gas side heat transfer of the DHR heat exchanger, for which during the natural circulation stage has a Re number of typically 6000. This produces differences in the temperature difference between the gas side and water side of this heat exchanger and therefore in the heat exchanger gas-side exit temperature.

At the start of the transient the system pressure decreases as the system cools, then it stabilizes and increases again when the main cooling loop is isolated and DHR system is opened and the cold helium is heated. The difference in the "final" pressure, i.e. after 800 s is reduced to ~ 5 bar compared to more than 15 bar in phase 1. This difference is due to differences in the initial inventory and the "final" average coolant temperature.

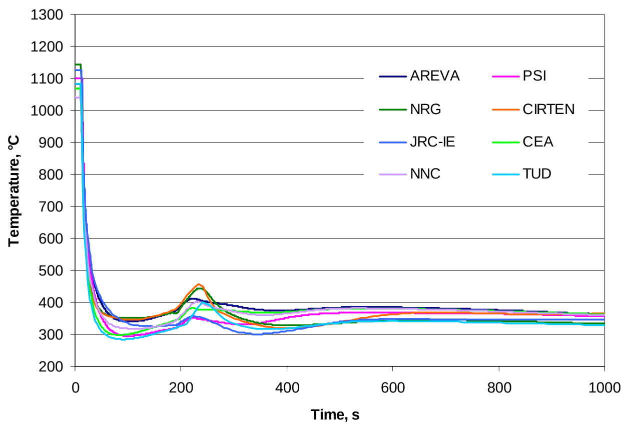

Fig. 20. Max. fuel temperature in hot channel versus time.

In summary: following the second phase calculations the results presented above show an improved agreement between the results compared to the first phase submissions. The additional restrictions imposed on the boundary conditions together with the correction of errors helped to obtain more consistent results and so identify limitations and differences in the physical modelling of the various codes.

IV. CONCLUSIONS

A GFR transient benchmark study was performed based on a main blower failure in ETDR with reactor scram, to investigate the ability of the different code systems to calculate the transition in the core heat removal from the main circuit forced flow to natural circulation cooling using the DHR system.

The results submitted by the participants, on one hand, showed that all the codes gave consistent results for all stages of the benchmark but, on the other hand, revealed some differences in the behaviour of some reactor parameters during the transient.

The differences in the calculational results mainly resulted from:

- modelling of the vessel wall heat structures (that have a major impact on the core inlet temperature during the pump rundown stage) and other additional heat structures representing the piping;

- different vessel pressure drop and flow resistance in the DHR helium and water loops; also the use or not of a fuel channel gagging scheme to obtain a uniform core exit temperature in the fuel channels;

- different coolant (helium) inventory in the primary and DHR loops;

- different heat transfer correlations used for the main and DHR heat exchangers, as well as different core (rod bundle) heat transfer correlations;

- modelling errors and inconsistencies with the benchmark specification.

The identification of the different modelling approaches of the benchmark participants demonstrated the value of such benchmarks when applying existing codes to new reactor systems. The two phases of the benchmark showed the importance of a clear and precise definition of the plant and transient boundary conditions, since uncertainty in these can mask any differences in the physical modelling.

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NOMENCLATURE

DHR – Decay Heat Removal
ETDR – Experimental Technology Demonstration Reactor
GCFR – Gas-Cooled Fast Reactor
WP – Work Package

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