IAEA FUMAC BENCHMARK ON THE HALDEN, STUDISVIK AND QUENCH-L1 LOCA TESTS

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ABSTRACT

The International Atomic Energy Agency (IAEA) sponsored the Coordinated Research Project (CRP) on Fuel Modeling under Accident Conditions (FUMAC) to coordinate and support research on nuclear fuel modelling under accident conditions in member countries. The focus of the FUMAC CRP (2015-2018) has been on loss-of-coolant accidents (LOCA). Various institutions performed fuel performance simulations of selected experiments using different fuel performance codes (e.g., FRAPCON-FRAPTRAN, TRANSURANUS, ALCYONE, DIONISIO, SOCRAT, FTPAC, BISON, RAPTA) and system codes (e.g SOCRATE, ATHLET). One of the results of the FUMAC CRP is a comprehensive code-to-code benchmark of selected results, and a comparison of simulations with experimental data as well. This paper represents an overview of the current state-of-the-art of nuclear fuel simulation capabilities for LOCAs and paves the way to further analyses and future developments. More precisely, we discuss the results of the simulation of a subset of the experiments considered in the FUMAC CRP, i.e., (i) the Halden LOCA tests (IFA-650.9/10/11, but only IFA-650.10 is in detail presented in this paper), (ii) the Studsvik LOCA test NRC-192, and (iii) rod 4 of the KIT QUENCH-L1 bundle test. These experiments, briefly presented in the paper, cover a wide range of conditions relevant for LOCA scenarios from different sources. The presented benchmark results are considered in more detail at the end of the LOCA transient (e.g., time of failure, cladding outer diameter, cladding oxidation thickness…). The experimental data are always included in the comparisons, when available. The results are also critically discussed, with the aim of identifying modelling developments required for the improvement of LOCA analyses. Finally, the outcome is complemented with an uncertainty and sensitivity analysis in a separate paper in this conference.

1. Introduction

The International Atomic Energy Agency (IAEA) initiated the Coordinated Research Project on Fuel Modeling in Accident Conditions (FUMAC) [1] to coordinate and support research on nuclear fuel modelling for accident scenarios in member countries. The focus of FUMAC has been on loss-of-coolant accidents (LOCA). The partner institutions used a variety of fuel performance codes to perform the simulations of these LOCA transients, i.e., FRAPCON-FRAPTRAN, TRANSURANUS, ALCYONE, DIONISIO, SOCRAT, FTPAC, BISON, RAPTA, and system codes like SOCRATE, ATHLET and MELCOR. The outcome of FUMAC is the comprehensive code-to-code benchmark of selected results from the institutions involved, including the comparison with experimental data (when available). This benchmark result represents an overview of the current state-of-the-art of nuclear fuel simulation capabilities for LOCAs and paves the way to further analyses and future developments.

In this paper, we discuss the results of the simulation of a subset of the experiments considered in the FUMAC CRP, i.e., (i) the Halden LOCA test IFA-650.10, [3] (simulated by sixteen institutions), (ii) the Studsvik LOCA tests [4] (NRC-192, seven institutions), and (iii) the KIT QUENCH-L1 bundle test [5] (four institutions). For the sake of brevity, only selected results are reported. For a complete description of the benchmark results, reference is made to the IAEA FUMAC TECDOC (under preparation) [2].

The paper is organized as follows. A description of the simulated experiments is provided in Section 2. Benchmark calculations from participating modelling groups in FUMAC are presented and discussed in Section 3.

2. Experiments

In this Section we briefly describe the experiments used in the FUMAC benchmark.

2.1 Halden LOCA test (IFA-650.10)

The Halden LOCA tests address the performance of high burnup fuel segments irradiated in commercial nuclear power stations in a LOCA-like scenario. From this test series, three experiments have been selected for the FUMAC project:

- IFA-650.9 (PWR fuel). The test resulted in considerable ballooning, fuel fragmentation and relocation after the LOCA transient.
- IFA-650.10 (PWR fuel) with moderate ballooning, fuel fragmentation and dispersal
- IFA-650.11 (VVER fuel) which experienced little ballooning and fuel fragmentation

A low level of fission power in the fuel rod (between 10 and 30 W/cm) provides the energy to drive the LOCA heat-up. The energy inflow from surrounding rods is simulated by an electrical heater surrounding the test fuel rod. The instrumentation consists of three cladding surface thermocouples, a cladding extensometer, a fuel pressure sensor, three vanadium neutron flux detectors, two heater surface thermocouples, and thermocouples at the inlet and outlet of the rig. The temperature of the heater is measured by two embedded thermocouples.

After a few minutes at maximum temperature, the experiment is terminated by switching off the electrical heating and scramming the reactor which causes the fission heat generation in the fuel rod to cease.

For the sake of brevity, in this paper we present only the results of IFA-650.10.

2.2 Studsvik LOCA test (NRC-192)

The selected rod is part of a series of six out-of-reactor LOCA simulation tests performed from 2011 to 2012 by Studsvik Nuclear AB, Sweden, under contract with the U.S. Nuclear Regulatory Commission (U.S. NRC). The tests were done on fuel rodlets that had been sampled from full-length mother rods with average rod burnups ranging from 55 to 72 $MWd(kgU)^{-1}$. All the mother rods were of Westinghouse PWR design and had UO_2 fuel pellets and first generation ZIRLO™ (Zr-1.03Nb-0.98Sn by wt%) cladding [4].

A typical test starts at room temperature by heating the rodlet such that a nearly constant heating rate of 5 Ks^{-1} is attained for the cladding tube. The cladding temperature is monitored by a single thermocouple above the axial midplane of the rodlet. The peak cladding temperature ranged from about 1220 to 1430 K for the six tests, and the rodlets were held at the peak temperature from 0 to 85 seconds to achieve various degrees of oxidation. The rodlet 192 was first cooled with an average rate of 3 Ks^{-1} to 1073 K, after which it was quenched by rapidly filling the tube with room temperature water [4]. The test rodlets were filled with helium to pressures between 8.2 and 11.0 MPa at 573 K. These pressures, which are consistent with high-end end-of-life internal pressures in PWR fuel rods, where chosen to induce cladding ballooning and rupture with hoop rupture strains in the range of 30–50 %. Rupture typically occurred at cladding temperatures around 950–1000 K, i.e. significantly below the peak cladding temperatures reached in the tests.

During the tests, the rod internal pressure was monitored by pressure transducers connected to the top and bottom ends of the rodlet.

2.3 QUENCH L-1

Test QUENCH-LOCA-1 (QUENCH-L1) with electrically heated bundle was performed according to a temperature/time-scenario typical for a LBLOCA in a German PWR with maximal heat-up rate of 7 K/s. Temperatures are recorded on-line at 17 axial elevations in different radial positions in the bundle. The maximal temperature of 1373 K was reached at the end of the heat-up phase at elevation 850 mm. This resulted in a progressive ballooning and consequent burst of all rods during the transient. Due to prototypical internal heating and enhanced heat transfer at the contact between pellet and cladding, a circumferential temperature gradient occurred and one-side cladding thinning during ballooning was registered.

The cladding burst occurred at temperatures between 801 and 896 °C with an average value of 853 ± 30 °C. All the inner rod pressures were measured on-line and relief to the system pressure occurred during less than 40 s. The average linear burst opening parameters are: width 4.2 ± 2.6 mm, length: 15 ± 6 mm.

Strong rod bending up to 23 mm was observed for several rods due to the limited axial expansion of the heaters. Without taking into account strong bended rods, the average cladding strain at the burst opening elevation was about 30 ± 6% including burst opening width (or about 20 ± 5% only for cladding perimeter without opening).

After the burst, the steam penetrates the gap between cladding and pellet and oxidizes the inner surface of the cladding. The hydrogen released diffuses partially into the cladding (secondary hydrogenation) and builds asymmetrical bands above and below burst opening. The oxide layer thickness measured on the *inner* cladding surface was up to 25 µm at burst elevations and less than 2 µm at the hydrogenated bands.

3 Benchmark results

3.1 Halden LOCA tests (IFA-650.10)

Sixteen organizations from different countries have provided results for the IFA-650.10 test, i.e., CNPRI (China), FRAPCON 3.4 and FRAPTRAN 1.5; INRNE (Bulgaria), TRANSURANUS v1m1j17; CEA (France), ALCYONE v1.4; CIEMAT (Spain), FRAPCON 3.5 and FRAPTRAN 1.5; CNEA (Argentina), DIONISIO 2.0; IBRAE (Russia), SOCRAT/V3; JRC-Karlsruhe (European Union), TRANSURANUS; KAERI (Korea), FRAPCON 3.4 and FRAPTRAN 2.0; CIAE (China), FTPAC 1.0; IPEN (Brazil), FRAPCON 3.4 and FRAPTRAN 1.5 (with axial fuel relocation and FEA models); Quantum Technologies AB (Sweden), FRAPCON 3.5 and FRAPTRAN-QT-1.5b; INL (United States), BISON 1.4; SSTC NRS (Ukraine), TRANSURANUS v1m1j17; Tractebel (Belgium), FRAPCON 4.0 and FRAPTRAN-TE-1.5 (with axial fuel relocation and FEA models); VTT (Finland), FRAPCON 4.0 and

FRAPTRAN 2.0; VNIINM, Bochvar Institute (Russia), RAPTA 5.2.

For the benchmark of results during the LOCA transient, Fig. 1 reports the comparison of the calculated plenum temperatures. A clustering in two groups emerges. The difference probably arises in specific modelling options selected by the participants for the calculation of the plenum temperature (the clustering does not depend on the code used for the simulation). Indeed, certain participants imposed the calculated or measured coolant or outside cladding temperatures in an external plenum as a boundary condition.

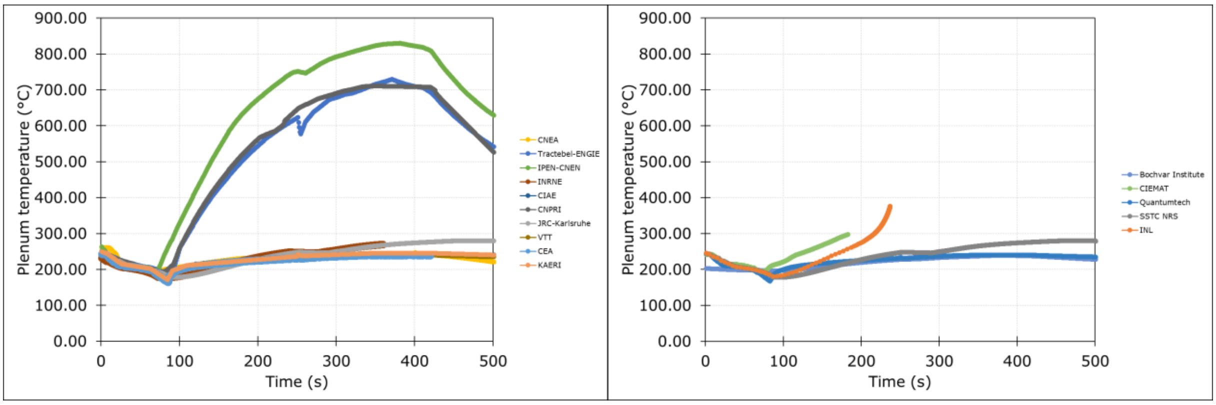

Fig. 1. Comparison of the plenum temperature during the LOCA transient of the IFA-650.10 test.

Fig. 2 reports the comparison of the calculated internal pressures. Instead of the ballooning phase (pressure decrease before burst), several participants predict an increase in the pressure prior to the burst. As suggested by CIEMAT this could be ascribed to the specific algorithm used by FRAPTRAN to evaluate the inner pressure in the plenum. The qualitative agreement among the participants is good. The scatter in the predicted failure times among the different participant is significant (Fig. 2).

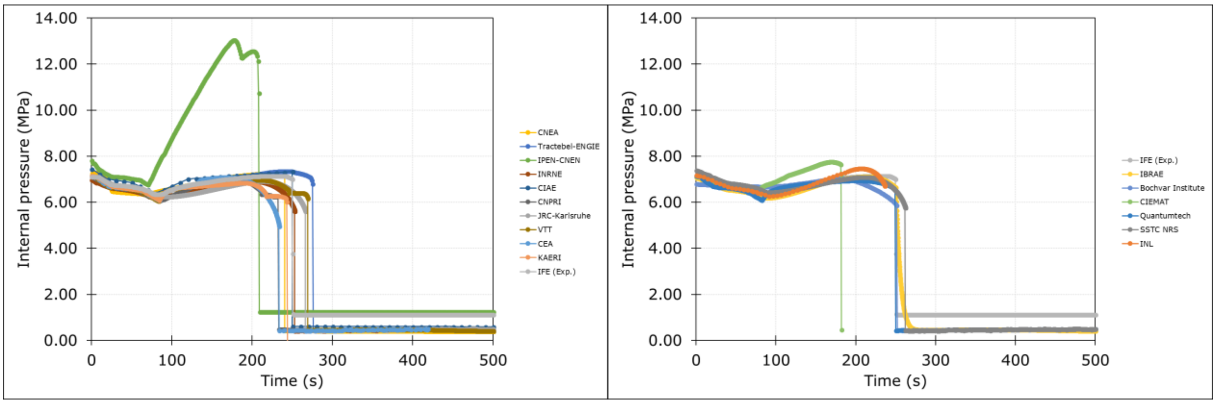

Fig. 2. Comparison of the internal pressure during the LOCA transient of the IFA-650.10 test.

Fig. 3 reports the cladding outer temperature (at the location of the burst), showing the agreement in the thermo-hydraulics boundary conditions among the participants to the benchmark. Some dispersion is present albeit the thermo-hydraulics for the benchmark were prescribed. On the other hand, Fig. 4 reports the comparison of cladding axial elongations, showing that there is room for improvement for the mechanical models.

The position of the burst and in general the axial profile of the cladding diameter (Fig. 5) present a significant scatter as well. The scattering of the calculated maximum cladding deformation is certainly related to the differences of burst criteria in the different codes (maximum strain or stress criteria). As the experimental data available to build this criterion are very much scattered, different approaches may lead to different deterministic criteria.

The cladding oxidation thickness calculated by the participants is also scattered (Fig. 6), even though the cladding temperature used as input to the codes is very similar for all participants. Cladding oxidation is probably very sensitive to this parameter.

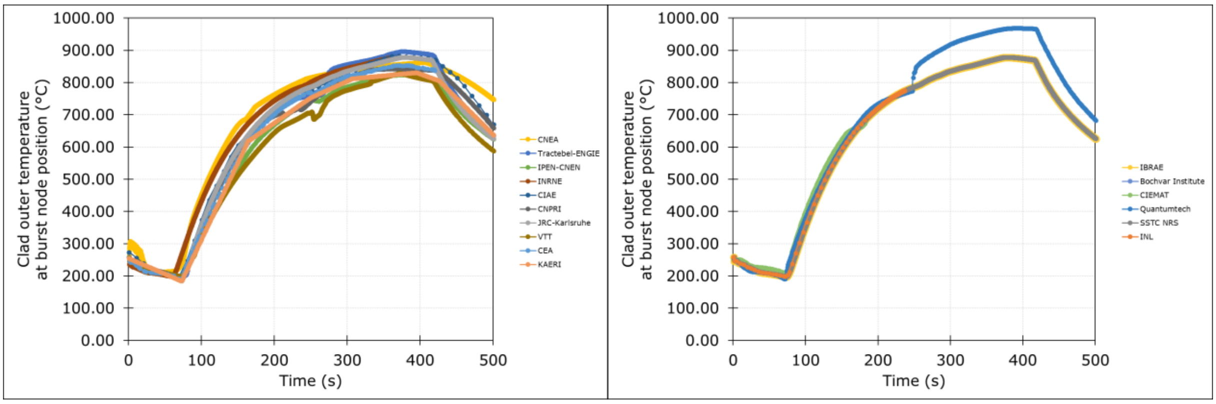

Fig. 3. Comparison of the cladding outer temperature at burst node position during the LOCA transient of the IFA-650.10 test.

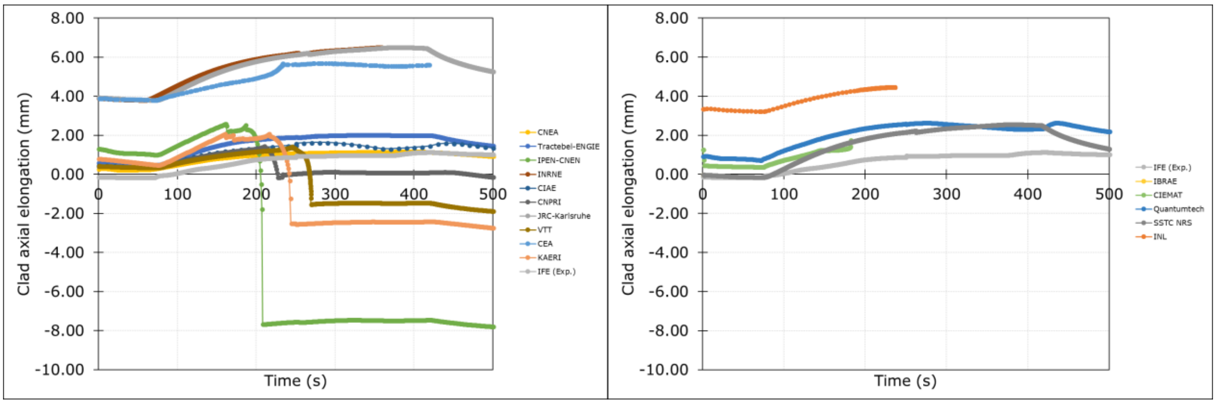

Fig. 4. Comparison of the cladding axial elongation during the LOCA transient of the IFA-650.10 test.

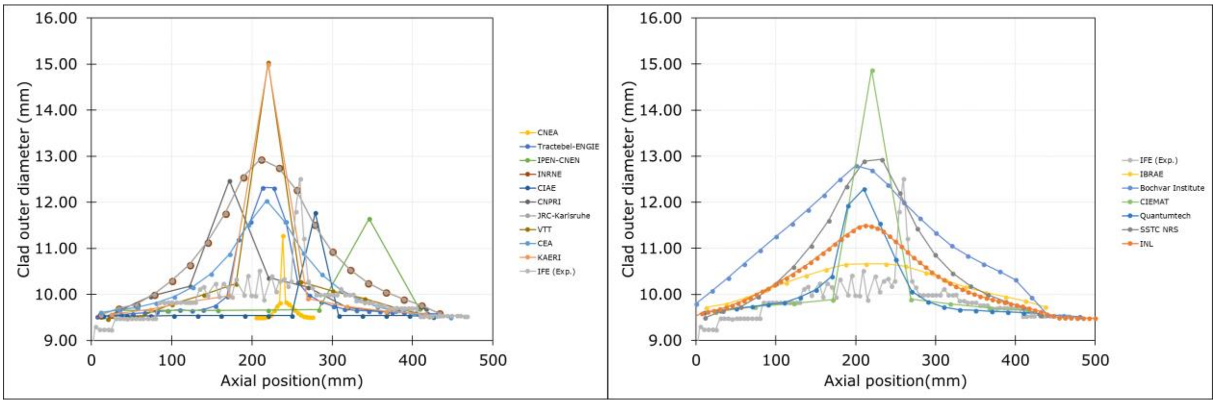

Fig. 5. Comparison of the cladding outer diameter after the IFA-650.10 test.

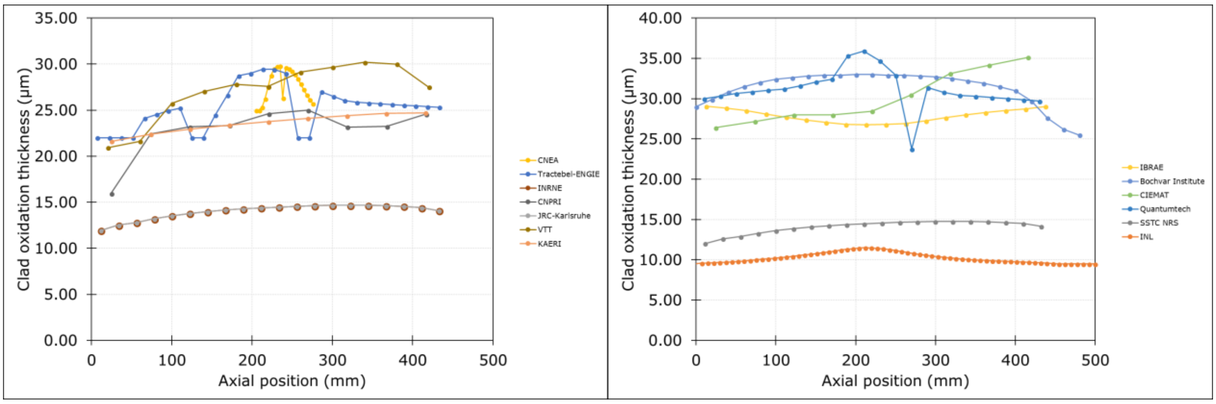

Fig. 6. Comparison of the cladding oxidation thickness after the IFA-650.10 test.

3.2 Studsvik LOCA test (NRC-192)

Seven organizations from seven different countries have provided results for the Studsvik 192 test: CNEA (Argentina), DIONISIO 2.0 code; CEA (France), ALCYONE V1.4 code; VTT (Finland), FRAPCON 4.0 & FRAPTRAN 2.0 codes; CIEMAT (Spain), FRAPCON 3.5 & FRAPTRAN 1.5 codes; SST-CNRS (Ukraine), TRANSURANUS v1m1j17 code; MTA-EK (Hungary), FRAPTRAN 1.4 code; Quantum tech (Sweden), FRAPCON 3.5 & FRAPTRAN-QT-1.5 codes.

Most of the participants used the base irradiation conditions (power history) provided by the US NRC to simulate the initial state of the rodlet before the transient. Only MTA-EK did not calculate the behavior of the father rod but considered the end-of-life measured data as initial state of the rod segment before the LOCA test.

On the following figures, the time reference is set at the beginning of heat up.

Inner rod pressure evolution (Figs. 7) shows that all the participants overestimate the burst time between 10 and 30 seconds. The pressure evolution during the test shows a ballooning phase (pressure decrease before burst).

The modelling of plenum temperature was left to the participants, as the experiment is complex and not all temperatures are measured. Most participants considered a quasi-constant temperature in the plenum, except CEA (Fig. 8). But even if this participant considers a higher level of temperature in the plenum, it does not result in an over-estimation of the pressure in the rod.

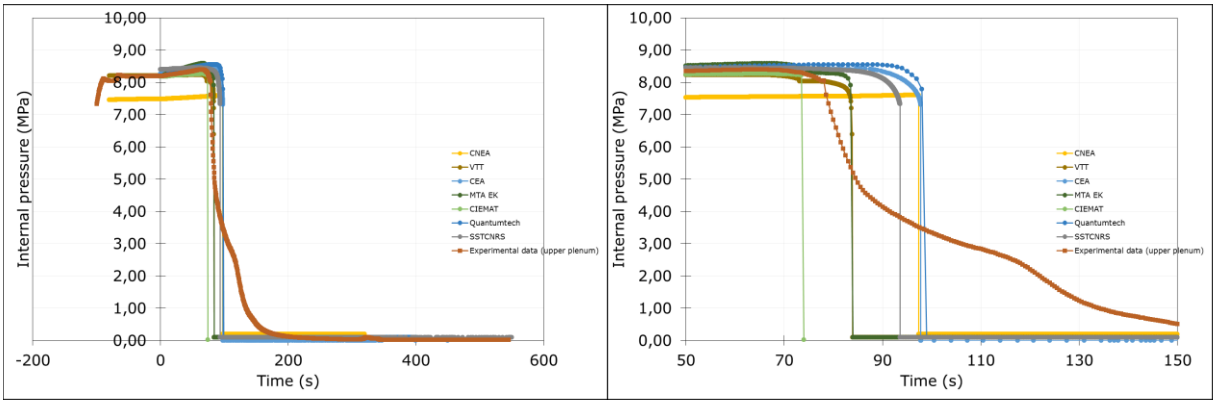

Fig. 7. Rod inner pressure calculated during test (on the right, focus around the burst time) (Studsvik 192 LOCA test).

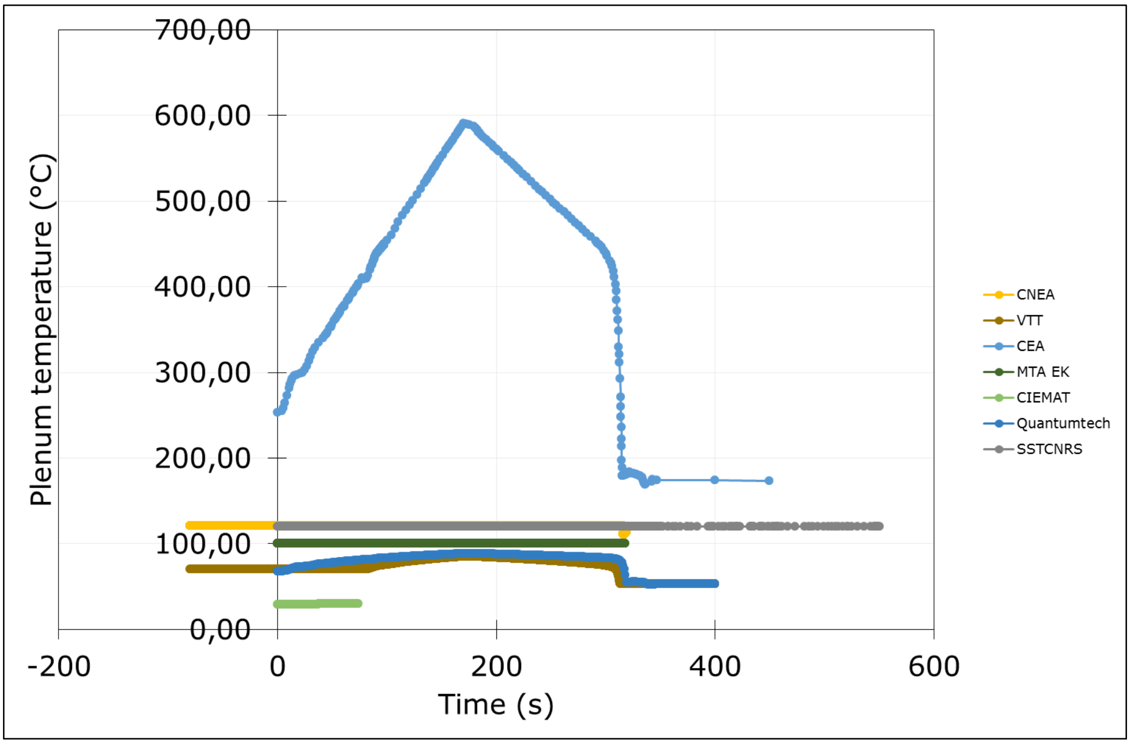

Fig. 8: Plenum temperature calculated during test (Studsvik 192 LOCA test).

All participants slightly over-estimate the time of failure of the rod segment (Fig. 7). Practically all participants locate the burst node at mid height of the rod segment (Fig. 9), whereas the experimental burst node is a bit higher. Two possibilities could explain the experimental result: either an axial temperature gradient along the rod segment, which makes the temperature a little bit higher at experimental burst node, or a localized overpressure in the rod due to local fragmentation (and so fission gas release) before the burst. The scatter of the calculated maximum cladding deformation is certainly related to the differences of burst criteria in the different codes (maximum strain or stress criteria). As the experimental data available to build this criterion are very much scattered, different approaches may lead to different deterministic criteria.

The cladding oxidation thickness calculated by the participants is also scattered (Fig. 10), even though the cladding temperature used as input to the code is very similar for all participants. And it is even scattered for participants who use the same code. e.g., FRAPTRAN. Maybe differences in the parametrization of the models exist for the different participants.

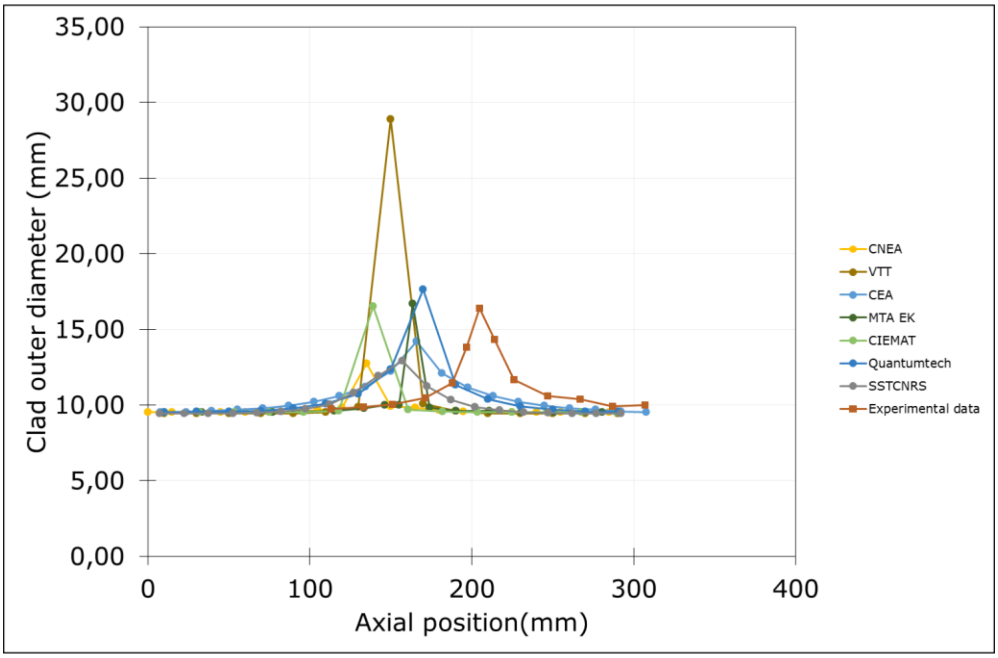

Fig. 9. Cladding outer diameter calculated at end of test (Studsvik 192 LOCA test).

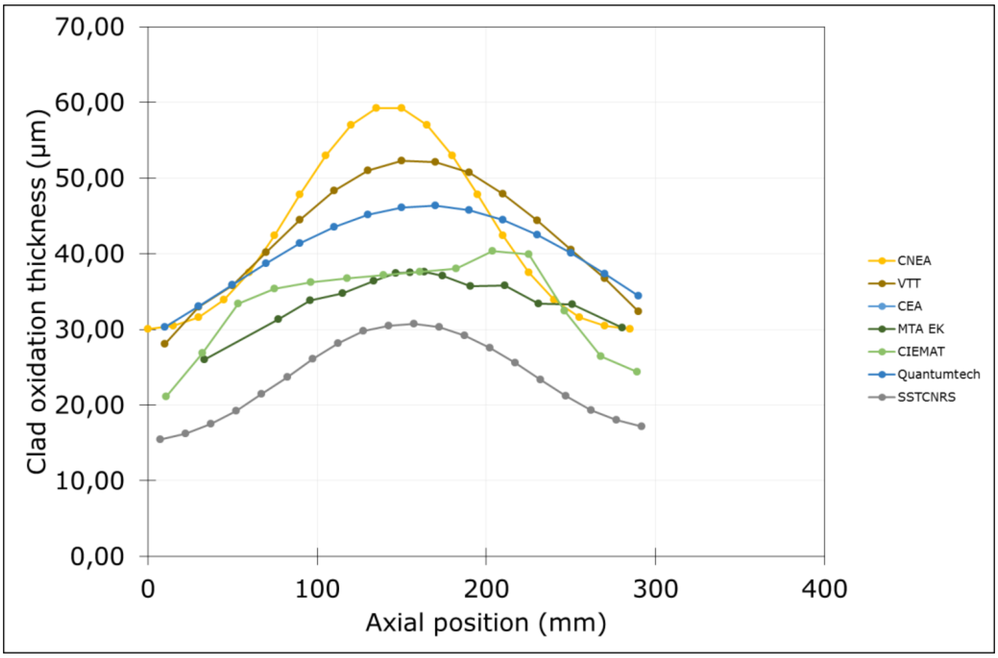

Fig. 10. Cladding oxidation thickness calculated at end of test (Studsvik 192 LOCA test).

3.3 QUENCH L1

A total of 4 organizations have provided results for this case: CNEA (Argentina), DIONISIO 2.0 code; INL (USA), BISON 1.4 code; JRC (European Commission), TRANSURANUS v1m2j17 code; GRS (Germany), ATHLET-CD code.

The results of the different codes have been compared with some of the experimental data provided by KIT. More precisely, it has been decided to compare the calculated internal gas pressure (MPa) during the experiment as a function of time (s) in Fig. 11 and Fig. 12, as well as the outer cladding temperature (^{o}C) at the axial level of cladding burst (around 950 mm axial elevation) (Fig. 13).

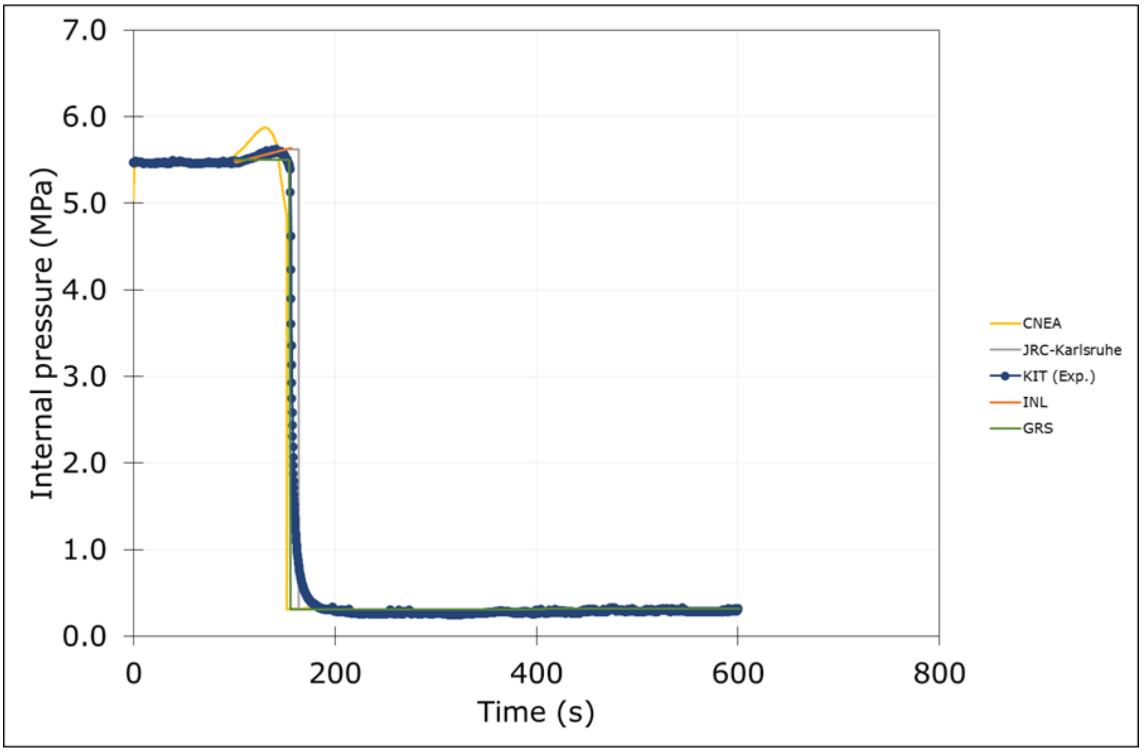

Fig. 11: Comparison of the rod internal pressure (MPa) versus time (s) in rod 4 of the QUENC-LOCA L1 experiment at KIT, with predicted values obtained by means of DIONISOS, TRANSURANUS, BISON and ATHLET-CD.

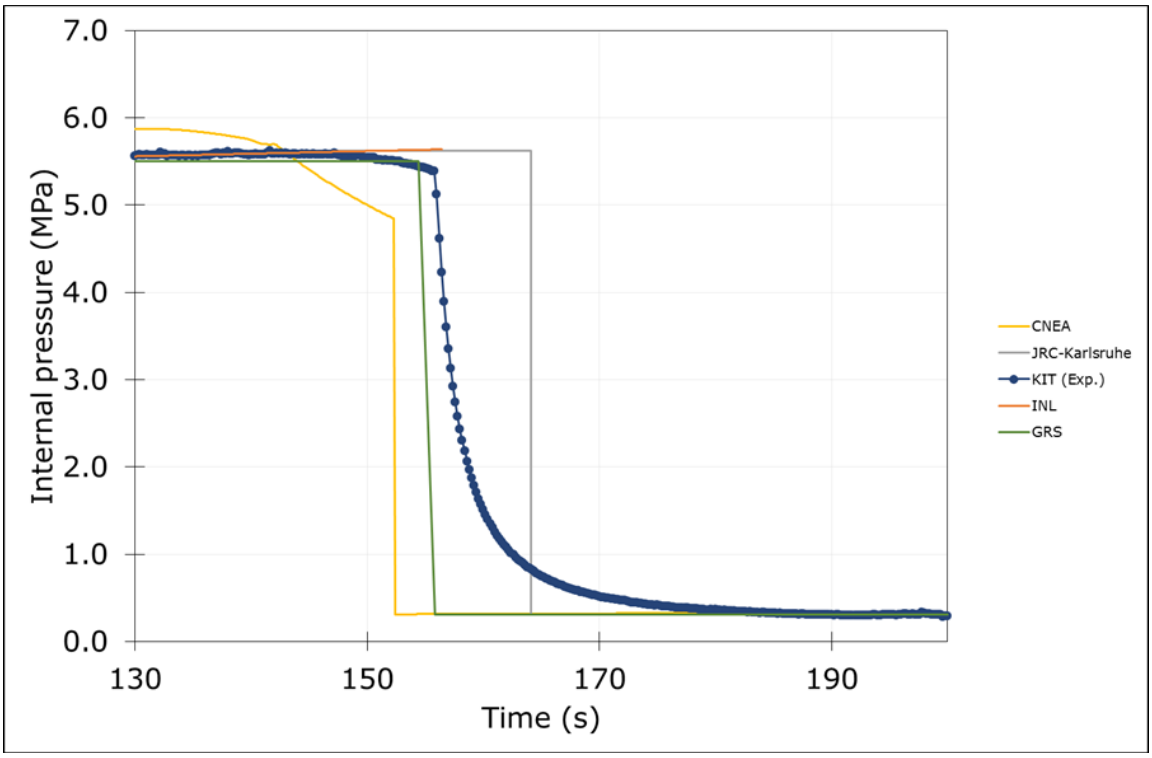

Fig. 12. Comparison of the rod internal pressure (MPa) versus time (s) around the burst time in rod 4 of the QUENC-LOCA L1 experiment at KIT, with predicted values obtained by means of DIONISOS, TRANSURANUS, BISON and ATHLET-CD.

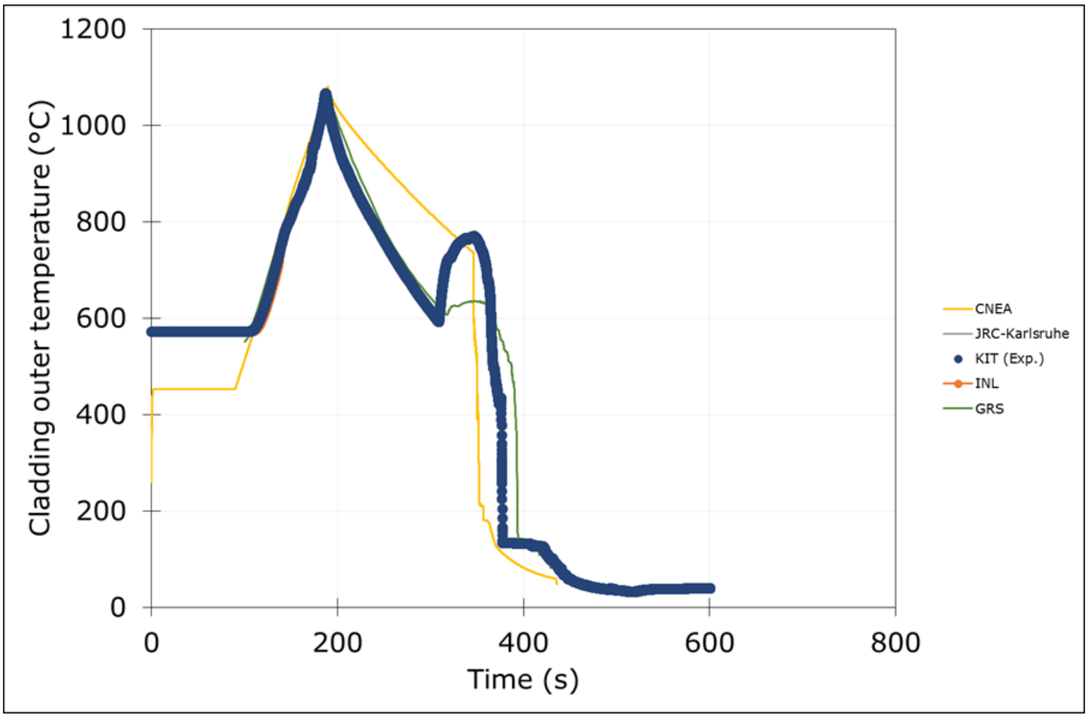

Fig. 13. Comparison of the cladding outer temperature (^{o}C) at the axial elevation of the burst versus time (s) in rod 4 of the QUENC-LOCA L1 experiment at KIT, with predicted values obtained by means of DIONISOS, TRANSURANUS, BISON and ATHLET-CD.

Simulated values as a function of the axial elevation (mm) for the cladding outer diameter (mm) (Fig. 14), and the cladding oxidation thickness (microns) (Fig. 15) are compared for the end of the LOCA test.

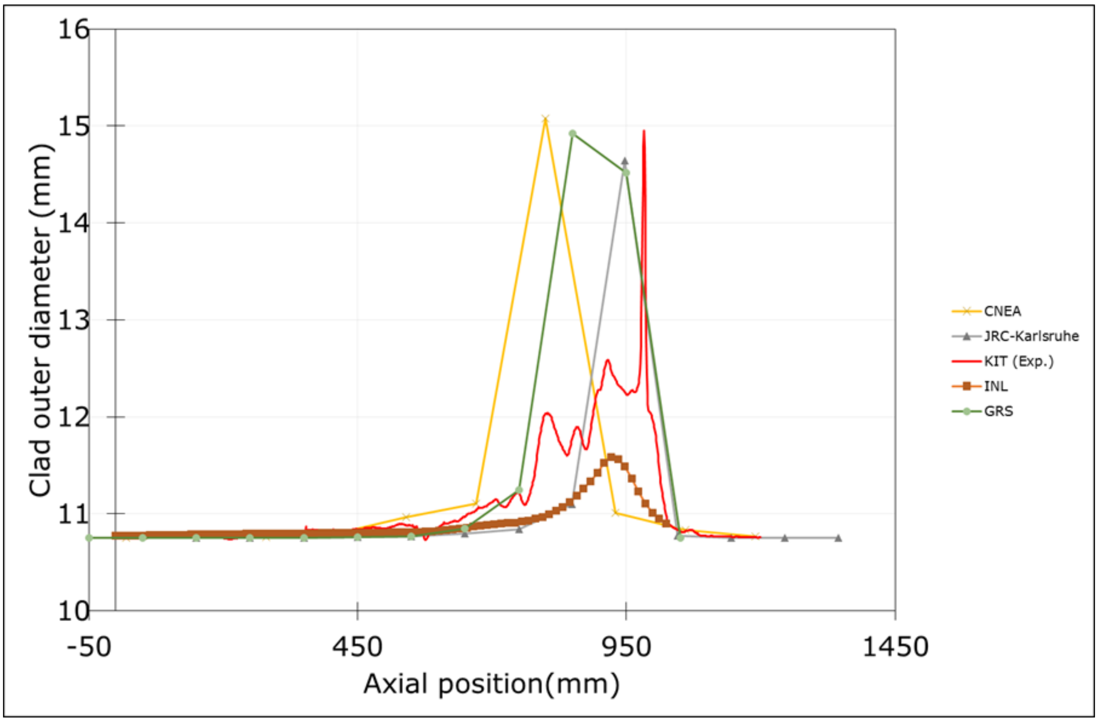

Fig. 14. Cladding outer diameter calculated at end of test for rod 4 (QUENCH LOCA L1 test).

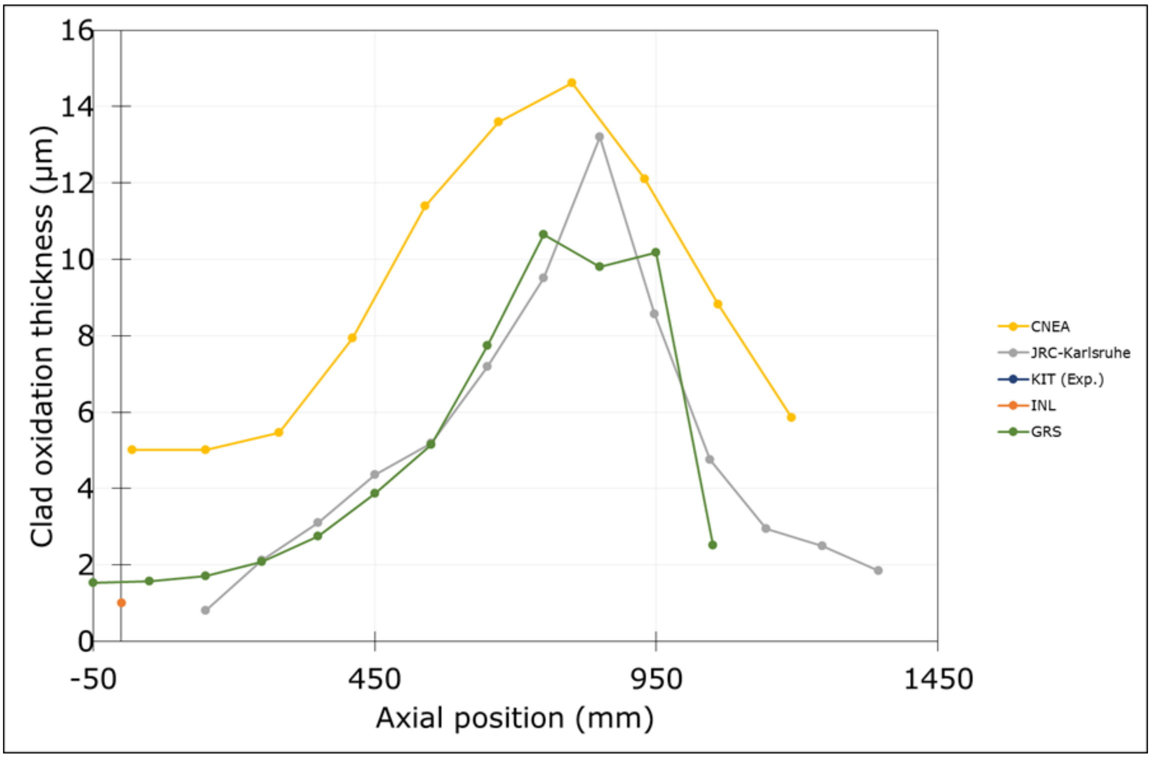

Fig. 15: Cladding oxide thickness calculated at end of test for rod 4 (QUENCH LOCA L1 test).

4. Conclusions

In this paper, a brief account was given of the IAEA FUMAC benchmark of fuel performance codes based on single-rod as well as bundle tests under LOCA conditions, and separate-effects cladding tests. Simulations by FUMAC participating organizations were compared to each other and to experimental data. For the sake of brevity, just selected results at the end of the tests were reported in this paper. The complete set of results and discussion of the FUMAC CRP will be published by the IAEA separately.

On the one hand, the results during the LOCA transients in terms of plenum temperature and inner pressure were generally satisfactory, with no bias being observed in the codes. On the other hand, results at the end of the LOCA transients (in particular, axial variations of cladding diameter, including burst position, and axial variations of oxidation thickness) are quite scattered. Both from the deformation and oxidation point of view, the presented results are encouraging but show room from improvement. They also corroborate and complement the conclusions about the separate effect clad ballooning tests considered in the frame of FUMAC and reported separately at this conference.

One of the main differences between the codes observed during the integral rod tests under LOCA conditions were related to differences in plenum temperature models applied and to the boundary conditions. More precisely, some of the codes have applied identical boundary conditions (derived either directly from the thermocouple measurements available or from predictions made by the system code SOCRAT), while others applied a specific model included in the fuel performance code for LOCA conditions. This detailed analysis has enabled to improve some of the experimental data sets for later incorporation in the IFPE database.

Finally, the FUMAC benchmark of fuel performance codes partly presented in this paper supports the code validation of fuel performance codes in simulating LOCA transients, and further leads to recommendations for future work on fuel modelling developments for LOCA analysis. At this level, it is possible to say that further investigation and modelling activities are advisable to better represent cladding behavior during LOCA. For example, it was pointed out that a review of the different cladding failure criteria would be valuable, as well as the implementation of models for better accounting for the (secondary) hydrogen uptake and to consider the new materials including those for so-called accident tolerant fuels.

Acknowledgements

This work was performed within the IAEA Coordinated Research Project on Fuel Modeling in Accident Conditions (CRP T12028).

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