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Halden LOCA Test Simulation by TRANSURANUS Code with Different Thermo-Hydraulic Boundary Conditions

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Abstract. This paper summarizes the work performed by the Institute for Nuclear Research and Nuclear Energy (INRNE, BAS) – Sofia, Bulgaria in the IAEA's Coordinated Research Project "Fuel Modelling in Accident Conditions (FUMAC)". The IFA 650 LOCA experiments in Halden are integral in-pile tests on fuel behaviour under simulated LOCA conditions. Object of the proposed analysis is the case IFA650.11 from the Halden LOCA experiments. It is a test of the fuel rod with WWER fuel, manufactured by JSC TVEL and pre-irradiated up to 56 MWd/kgU in the Loviisa NPP (Finland). The cladding material was Zr alloy E110. The modified version of the TRANSURANUS code with incorporated specific LOCA models as well as two different models of thermo-hydraulic boundary conditions was applied. Fuel behaviour code predictions were analysed and compared.

Keywords: fuel performance, LOCA, oxide layer thickness.

1 Introduction

TRANSURANUS code is one of the most powerful computer codes for assessing fuel performance developed to high level of reliability at the Modeling Group of the European Commission DG Joint Research Centre-JRC, Directorate G – Nuclear Safety & Security, Unit G.I.5 Advanced Nuclear Knowledge in Karlsruhe, Germany [1]. Reactor Physics Laboratory in INRNE-BAS gained experience with this code and the new version developed [2] in order to simulate design basic accident (DBA) conditions. Halden LOCA experiment IFA650.11 with WWER fuel was simulated. The new TRANSURANUS version with developed and implemented models for transient fission gas behavior, double sided cladding oxidation after burst of the rod, H-uptake and accounting for effects on mechanical cladding properties was implemented for simulation of the IFA650.11 experiment. The calculations were performed for base irradiation as well as for the LOCA test performance, using restart option of TRANSURANUS code for account rod cutting and refilling. The calculations were done with two different models of thermo-hydraulic boundary conditions and code predictions were analyzed and compared.

2 Experiment

The IFA650 LOCA experiments in Halden are integral in-pile tests on fuel behavior under simulated LOCA conditions. The IFA 650 test rig is designed for a single fuel rod. The test section is located inside a test channel in the Halden research reactor and is connected to the external Heavy Water High Pressure loop. The rig is cooling by natural circulation [3].

The rod is surrounded by an annular flow channel, which is separated from the outer annular channel by an electrically heated shroud. One fuel rod is located in a standard high-pressure flask, which was connected to a heavy water loop and a blow down system. Heating was provided from the fuel pellets and from the heater surrounding the fuel rod. The heater was used to simulate the heat from the adjacent rods. The cladding temperature was controlled by the rod and heater power. The experimental goal was to produce cladding ballooning and burst and to achieve a peak cladding temperature.

The rod power can be controlled by varying the additional heating and by changing the reactor power. The test rig instrumentation consists of two heater thermocouples, two inlet and outlet coolant thermocouples, a flow meter, three self-powered vanadium neutron detectors (ND) and two fast response cobalt neutron detectors (NDs). The two embedded heater thermocouples are located above and below the axial mid height of the fuel rod. The volume flow rate is measured in the external loop.

The test conditions were planned to meet the following primary objectives: to maximize the ballooning size to promote fuel relocation and to evaluate its possible effect on the cladding temperature and oxidation. The Halden LOCA test project covers both fuel rods with fresh fuel and pre-irradiated rods up to high burnup during steady-state normal operation.

The subject of this analysis is Russian type of nuclear fuel, manufactured by Russian company TVEL, pre-irradiated up to 56MWd/kgU at Loviisa NPP and re-fabricated in Halden for the LOCA test IFA650.11. The whole fuel rod from Loviisa was re-fabricated – 480 mm part was truncated and gas refilled.

Prior to the test during normal operation (25 days), the rig was connected to the loop and forced circulation flow, the system pressure was set to 7MPa. Shortly before the test about 3 min, the rig was disconnected from the loop and flow separator enabled natural convection flow in it. When blow down started the channel pressure decreased to 4MPa and the rig was practically emptied of water in 70 s. The heat-up phase started – ballooning and burst (207 s after blow down). The test was ended by reactor scram.

3 IFA650 LOCA Test Simulation

The LOCA test IFA 650.11 with pre-irradiated WWER fuel was of special interest for our work. The IFA650.11 case was simulated by two versions of TRANSURANUS code (v1m1j14 and v1m1j17). In the frame of CRP FUMAC the last version (j17) was developed [4] by including new options for the LOCA-modelling: the corrosion model is changed and it considers oxidation both on the outside and on the inside of cladding after rod burst incl. spalling, hydrogen uptake is considered; some of the material properties of the fuel are refined.

The rod re-fabrication requires the input modifications. When the time of the LOCA event is started, the calculation is stopped and the steady state models are replaced by the transient mode and special LOCA models. To simulate the re-fabrication, the TRANSURANUS restart option and restart data modification modules are used. Using the re-start mode of the code the plenum volume (height), inner gas amount, gas composition and rod pressure (95% Ar+5% He/ 3Mpa (RT)) are adjusted at the moment of the restart according the test data.

Halden test IFA650.11 was simulated using two models of the boundary conditions (BC) during LOCA phase of the test:

A) The axial distribution of rod outer cladding temperature was created using the measured cladding temperature from the Halden TFDB database. The cladding temperature was measured at two points in axial direction of the rod, but there aren't any data about axial profile and the position of peak cladding temperature. Cladding temperature was modelled by using the measured data at two points and assuming a parabolic temperature profile with the peak clad temperature at elevation 150 mm. The thermo-hydraulic behaviour in test period was calculated using the mass flow rate and the coolant inlet temperature data as done in the steady state part. The data for plenum temperature (thermocouple TCC3, placed on the outside surface at axial midplane of the plenum) were prescribed at the last (11th) small node of fuel.

B) More accurate way to simulate the thermo-hydraulic (T/H) environment during LOCA test is to calculate it by means of multi-physics/dimensional tools and used it as input data for the LOCA part of the TRANSURANUS calculation. The recently release T/H data for Halden LOCA tests calculated by SOCRAT code system are applied and new simulation of IFA650.11 was performed by new version of TRANSURANUS code (J17). In this new simulation the linear heat rate, coolant pressure, cladding outside temperature and upper plenum temperature are prescribed in input file of TRANSURANUS code according results of SOCRAT code calculations.

The simulation with new version (j17) takes into account the new oxidation model as well. Cladding failure criterions used in the both models are: ICIFaiL=1 - overstress is assumed if the average true tangential stress was larger than the failure stress calculated by the material properties. (J14)and ICIFail=4 - failure is assumed if the tangential stress or the tangential strain limit is achieved. (J17)

The base irradiation (4cycles in Loviisa WWER 440,Bu=56MWd/kgU) was modeled in of these two TRANSURANUS simulations (applied versions v1m1j14 and v1m1j17) without any differences. The base irradiation power history is slightly simplified (no axial profile) because the tested rod (480 mm long) is a small part of the whole rod irradiated in the WWER NPP. The rod re-fabrication was accounted – new filling gas, new inner rod pressure and large plenum volume of 17cc. were the same in both models.

4 Results

Some results are presented below as a demonstration of the TRANSURANUS predictions by two code versions and two different models of thermo-hydraulic boundary conditions.

Comparisons of cladding outer temperature (axial) according two models of boundary conditions are presented in Figure 1. Calculated fuel central temperature is presented as well in Figure 2.

The axial profile of the cladding oxide layer predictions according the two different thermo-hydraulic conditions and temperature profiles are presented in Figure 3. As well as the cladding oxide layer predictions are compared in Figure 4 applied in the both code versions.

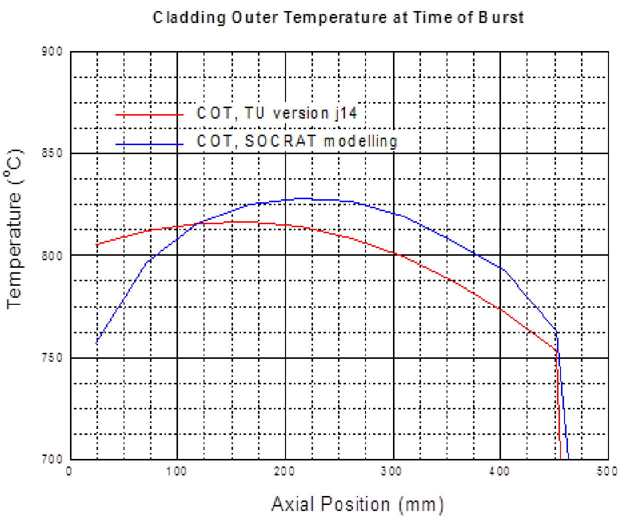

Figure 1. Outer cladding temperature (axial).

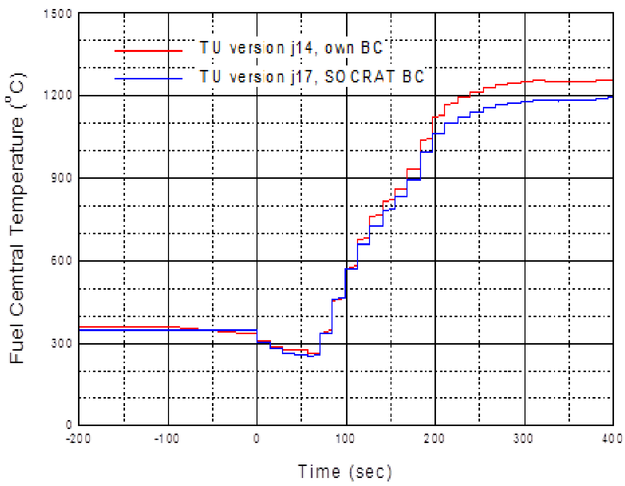

Figure 2. Fuel central temperature during LOCA phase.

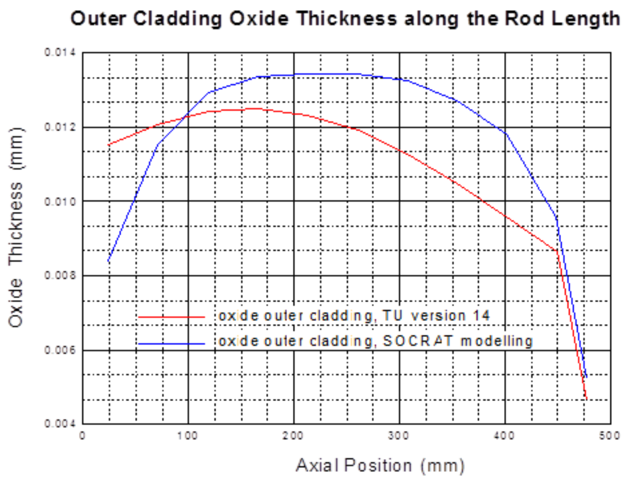

Figure 3. Outer cladding oxide layer v/s rod length.

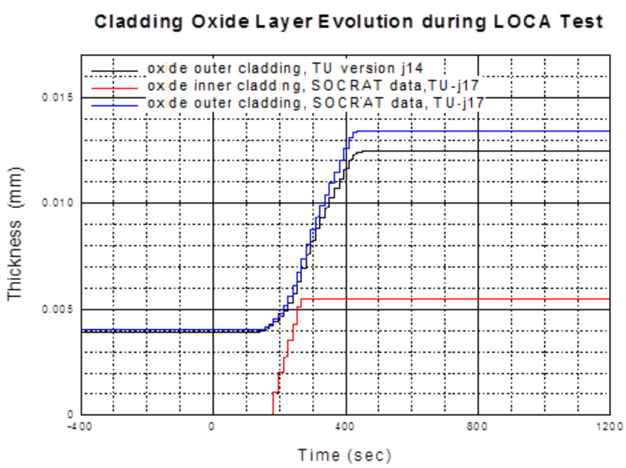

Figure 4. Cladding oxide layer predictions v/s according the models of oxidation applied in both code versions.

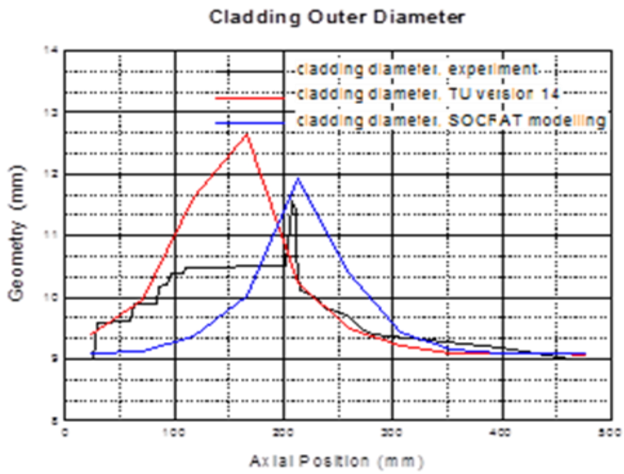

Figure 5. Axial cladding diameter at time of burst.

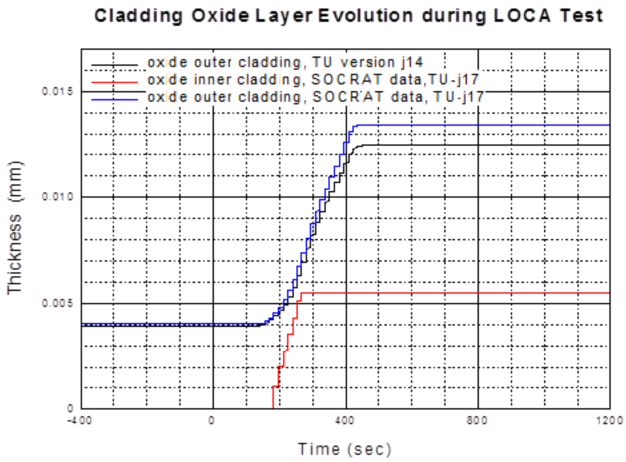

Figure 6. Inner pin pressure during LOCA phase of the experiment compared with experimental data.

The difference of the results of cladding oxidation is caused to the double side oxidation model, developed and incorporated in the last version of TRANSURANUS code.

The results for the place of rod burst and cladding outer diameter change according these two models are compared with the experimental data. The observed difference in the predicted place of burst was expected in accordance with different axial distribution of the prescribed cladding temperature in two applied models.

The predictions according two models of boundary conditions during LOCA test are similar and were compared with the data from Halden TFDB database. The TRANSURANUS calculations performed with two TRANSURANUS versions show the main difference at place of burst and oxide layer thickness according the different axial distribution of outer cladding temperature prescribed by two different models of boundary conditions and new model of double side cladding oxidation (see Figure 5 and Figure 6).

An indicator of rod failure is a sharp drop in inner pin pressure. Calculated inner pin pressure is compared with the pressure transducer records in Figure 6. Coolant pressure after start of the blow down (LOCA phase) and calculated inner pin pressure for the same time period are presented below. Measured rod and coolant pressures are presented on the figure as well.

Despite the observed difference in the predicted location of the rupture, the predicted time of burst according two different models of boundary conditions is the same, 183 sec after blow-down. The results are shown in Figure 6.

TRANSURANUS simulations of the HALDEN test IFA650.11 performed with two versions show the main difference at place of burst and oxide layer thickness according the new axial distribution of the outer cladding temperature and new model of oxidation.

5 Conclusion

The HALDEN LOCA test IFA650.11 was simulated by two versions of the TRAMSURANUS code and two different models of the rod boundary conditions inside the reactor.

More accurate way to prescribe the thermo-hydraulic environment during LOCA test by means of multi-physics code system SOCRAT result in the better coincidence between predicted and measured place of burst and pointed out the importance of the input data preparation. New version of the TRANSURANUS code developed in the frame of FUMAC project with new model of cladding oxidation was applied and tested as well.

Fuel performance calculations and analysis applying two code versions and two models of thermo-hydraulic conditions are important step in INRNE team experience concerning fuel behavior modelling and understanding

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