

Fuel Performance Modelling under LOCA Conditions by TRANSURANUS Code

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Abstract. The ability to calculate accurately the performance of light water reactor (LWR) fuel rods under long-term irradiation conditions and various operational transients and hypothetical accidents is an important objective of the reactor safety investigations. The IAEA Coordinated Research Project(CRP) FUMAC (Fuel Modelling in Accident Conditions), focuses on the accident conditions and supports the improvement and development of computer modelling codes by compilation and analysis of experimental data for codes validation and for better understanding and enhanced safety of nuclear fuel behavior. The INRNE team participates in this project with simulations and analyses by TRANSURANUS fuel performance code. This report presents the results of simulation of the Halden IFA650.11 experiment with WWER fuel, pre-irradiated up to 56 MWd/kgU and tested under LOCA conditions at Halden.

The goal of this investigation is to study TRANSURANUS code predictions of WWER fuel rods under off-normal conditions (LOCA) and the changes of the fuel rod structure and geometry of fuel and cladding.

Keywords: loss of coolant accident, fuel rod cladding, validation, cladding temperature.

1 Introduction

The present study continues the previous activities [1] on the accidental behaviour such LOCA (Loss of Coolant Accident) and PCMI (Pellet Cladding Mechanical Interaction) issues of nuclear fuel and cladding, including Russian type of fuel. It is presented a part of the research work, done at the frame of the IAEA's Coordinated Research Project FUMAC (Fuel modelling in accident conditions) . Attention is given to experiments that provide support for testing of the TRANSURANUS (WWER version) code for design-basis accidents (DBA) simulations at the first stage of a severe accident, when the cylindrical fuel rod geometry is still preserved.

The application range of the TRANSURANUS code has been extended to LOCA conditions [2,3] and based on the previous experience as users of the TRANSURANUS fuel performance code the simulation of the experiment with LOCA events was done. The present paper demonstrates the team capacity to analyze fuel behavior at LOCA conditions on the base of experiment IFA650.11. LOCA tests at Halden (IFA650) are integral in-pile single rod tests and they address various LOCA issues. The eleventh LOCA test was carried out in the Halden reactor using a high burn-up WWER rod provided by Fortum Nuclear Service. This experiment was simulated and analyzed by means of the latest TRANSURANUS version (v1m1j14), released officially between the users. The calculations were done for base irradiation as well as for the test irradiation (LOCA phase), using restart option of TRANSURANUS code for taking into account rod cutting and gas refilling.

2 OECD Halden Reactor Project – LOCA Testing at the Eleventh Experiment IFA-650.11

2.1 Description of the experiment

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 rod is surrounded 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 [4].

The experimental goal was to produce cladding ballooning and burst and to achieve a peak cladding temperature. The test rig instrumentation consists of two heater thermocouples, two inlet and outlet coolant thermocouples, a flow meter, three self-powered vanadium neutron detectors and two fast response cobalt neutron detectors. 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.

IFA650.11 is test experiment with WWER fuel, manufactured by JSC TVEL and pre-irradiated up to 56 MWd/kgU in the WWER Loviisa NPP (Finland) [5]. The test segment (length of 480 mm) was cut from a standard WWER fuel rod. The rod was filled with a gas mixture of 95% Ar and 5%He at 3 MPa. Argon was chosen to simulate the fission gases. The rod plenum volume (free gas volume) was made relatively large in order to maintain stable pressure conditions until cladding burst. The total free gas volume of

Table 1. Fuel parameters

Description	Value
Burnup	56.0 [MWd/kgU]
Active fuel length	480 [mm]
Enrichment	3.6 [wt% ^{235}U]
Fuel density	10.64 [g/cm^3]
Fuel diameter	7.55 mm
Pellet centre hole	1.484 [mm]
Cycles	4
Cladding material	Zr1%Nb
Clad outer diameter	9.13 [mm]
Cladding thickness	0.679 [mm]
Oxide thickness, irradiated, mean	5 [μm]
Filler gas/Pressure	95% Ar+5% He/ 3Mpa (RT)
Free volume (as designed)	16 [cc]

$\sim 16\text{--}17\text{ cm}^3$ was practically all located in the plenum, outside the heated region. The cladding material was the Zr alloy E110 and the pellet bore diameter 1.50 mm. The main fuel rod parameters as well as the surrounding conditions are presented in the Table 1.

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 70 MPa. 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 4 MPa 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.

2.2 IFA 650.11 LOCA test – TRANSURANUS simulation

The LOCA extension of the fuel performance code TRANSURANUS is designed to calculate with appropriate models both steady state part of the fuel rod life and transient. In the transient LOCA part of the calculation some cladding mechanics have to be treated either with special LOCA models or they have to be switched off. The rod re-fabrication requires the input modifications. When the assumed time of the LOCA event is reached, the calculation is stopped and the steady state models are replaced by the transient mode and special LOCA models. For the change from steady state model to LOCA models and the data manipulation e.g. 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 are adjusted at the moment of the restart according the test data.

LOCA boundary conditions were created using the measured cladding temperature from the Halden database. The cladding temperature was measured at two points in axial direction, 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. Thermo-hydraulic (T/H) behavior is calculated using the mass flow rate and the coolant inlet temperature data as done in the steady state part. More accurate way to simulate the thermo-hydraulic environment during LOCA is to calculate it by an appropriate T/H code and used it as input data for the LOCA part of the TRANSURANUS calculation. In the frame of CRP FUMAC the T/H conditions calculated by SOCRAT code were recently released by the of IAEA. The application of these data as boundary conditions in a new simulation of the case IFA650.11 is in our future plans.

To choose suitable for this case model, the following considerations had to be taken into account. Fuel rod was modelled with 10 equidistance slices and 1 thin slice which attributed plenum temperatures. Linear heat rate and the fast neutron flux are simulated with axial profile according cladding temperature profile The base irradiation power history is slightly simplified (no axial profile) because the tested rod (480 mm long) is a small part of the of whole rod irradiated in the WWER. The model options comprised the standard TRANSURANUS recommendations for simulation of PWR fuel rods. UO_2 material properties were modelled by standard TRANSURANUS models for LWR, including the standard correlation for thermal conductivity, accounting for the local porosity. Standard Zr1%Nb cladding material correlations, models and options for the last TRANSURANUS version were selected.

The values for plenum temperature, system pressure and linear heat generation were taken from the measurements during experiment.

3 Results of Simulation and Comparison

The plenum temperature was modelled by considering a thin 11th slice with prescribed plenum temperature. The modelled plenum and calculated cladding temperature are compared with the thermocouple records during time of LOCA test in Figure 1 and Figure 2. The LOCA test started with the time of blow down phase, which is set to zero according the Halden data.

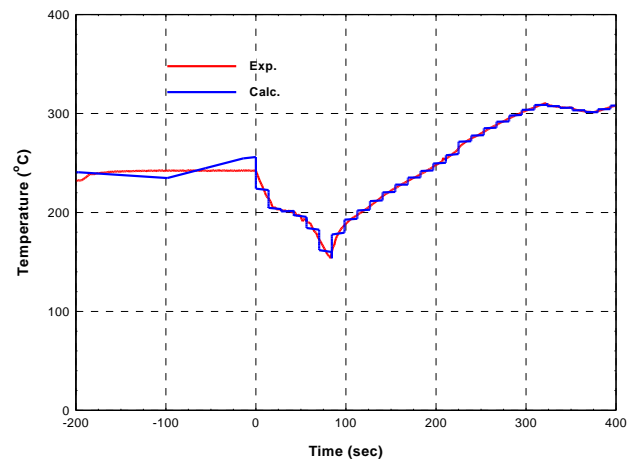


Figure 1. Comparison of plenum temperatures.

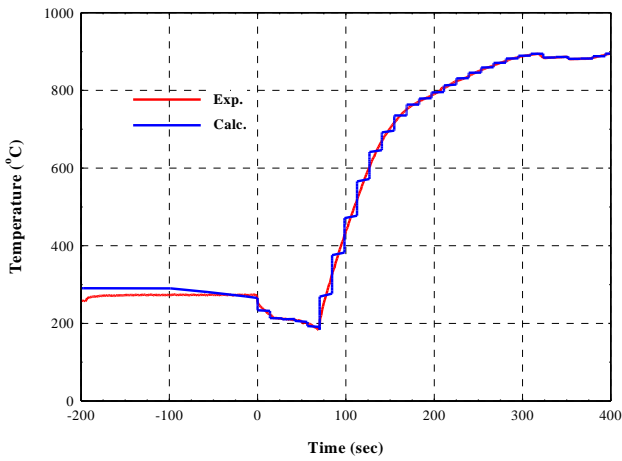


Figure 2. Cladding temperature compared with thermocouple records.

The time of cladding burst could be recognized by the cladding extensometer records as well as the pressure sensor data. The comparison of calculated internal rod pressure and recorded pressure sensor data is presented in Figure 3 below and shows an acceptable accuracy of TRANSURANUS prediction. The calculated inner pin pressure drops

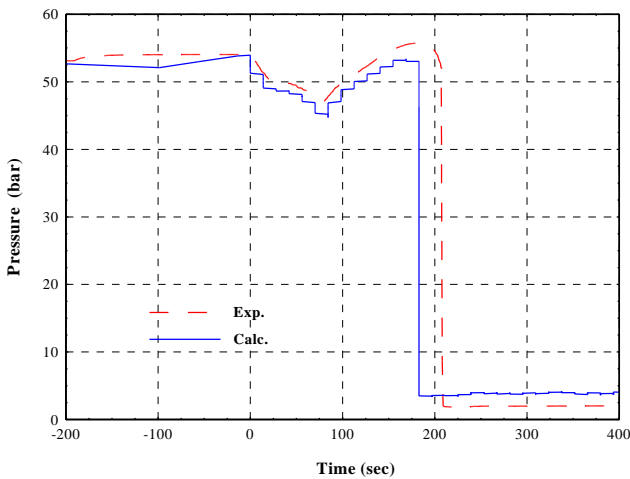


Figure 3. Inner rod pressure during LOCA phase.

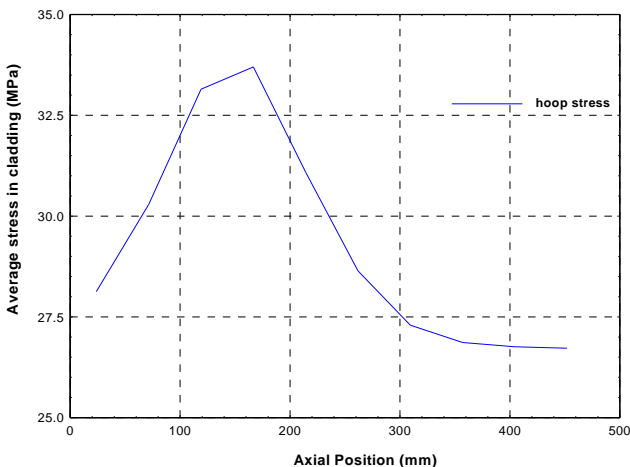


Figure 5. Cladding hoopstress at time of burst.

earlier than the burst was detected by pressure and temperature signals during the heat-up phase. Burst of rod cladding occurs at cladding temperature of 839°C, 207 s after blow-down according experimental data. The calculated time of burst is 183 s after start of LOCA test. The difference between the calculated and measured time of failure have to be analyzed and the model have to be refined.

Calculated cladding diameter profile is compared with rod diameter measured at the end of test in Figure 4. The difference between predicted and measured place of burst most probably is connected with modelled axial profile of the prescribed thermo-hydraulic boundary conditions.

The predicted cladding hoopstress and fuel central temperature are presented in the next two figures (Figure 5 and Figure 6).

The outer cladding oxide layer after base irradiation, before testing is presented on the Fig.7 together with the oxide layer after transient testing. After the steady state irradiation calculation with the TRANSURANUS code the oxide layer is near to the experimental data ($\sim 5 \mu\text{m}$). This is why for the transient part of calculation no additional oxide layer was prescribed.

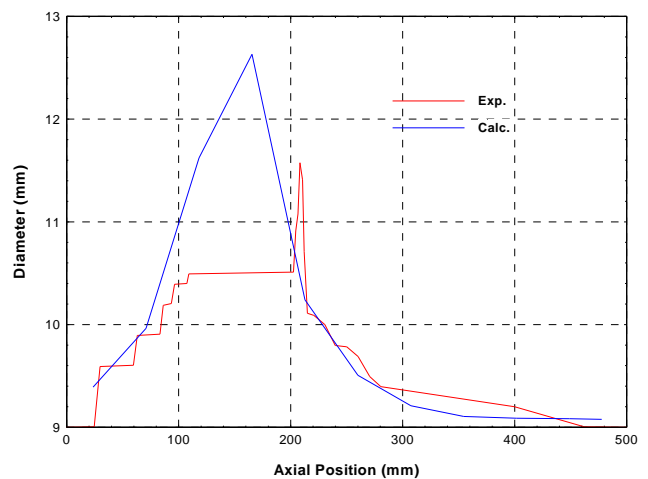


Figure 4. Cladding diameter profile.

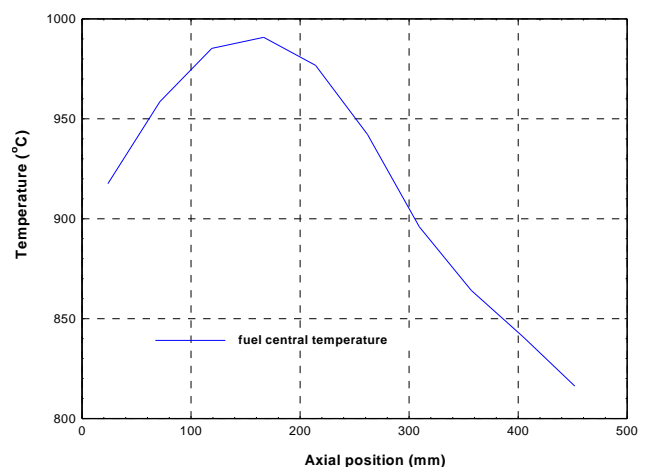


Figure 6. Fuel central temperature at time of burst.

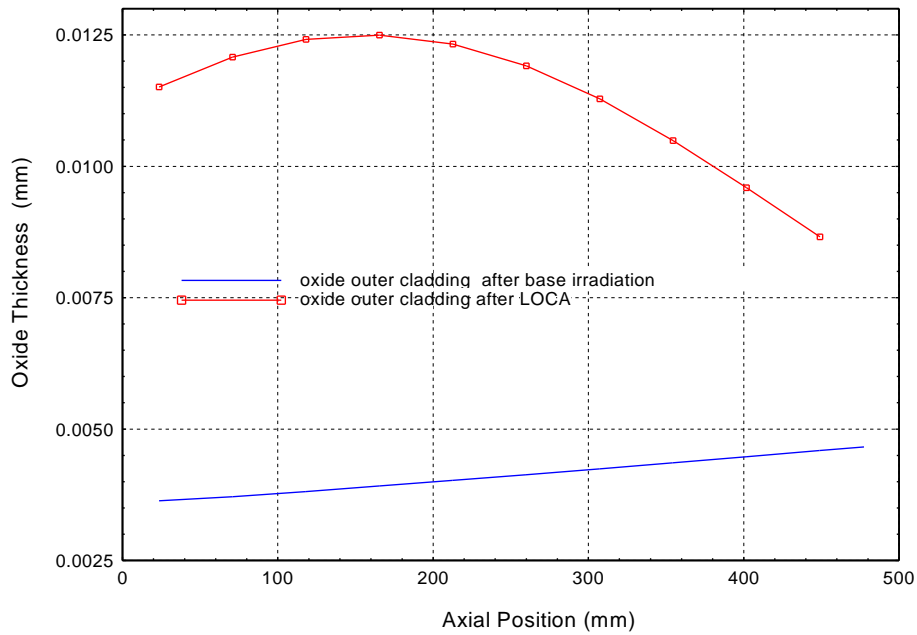


Figure 7. Outer cladding oxide layer before and after LOCA test – axial profile.

4 Conclusion

The participation in the FUMAC Coordinated Research Project is an important opportunity for the INRNE specialists. It allows validation of LOCA extension of the WWER version of TRANSURANUS code.

The presented results are preliminary and the next step is to improve the model for simulation of considered Halden experiment with pre-irradiated WWER fuel under LOCA conditions. A more precise definition of the T/H boundary conditions during LOCA event is expected to lead to better results concerning time and place of burst prediction.

The validated WWER version of TRANSURANUS code is a good base to meet the necessity of a more accurate and reliable tool for analyzing the behavior of the new type of Russian nuclear fuel, now implemented in Kozloduy NPP.

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