TRANSURANUS Analysis of the Fuel Behaviour under LOCA Conditions

N. Mihaylov[1], **S. Kalburov**[2], **S. Boneva**[1], **M. Manolova**[1]

[1] *Institute for Nuclear Research and Nuclear Energy, Bulg. Acad. Sci., 72 Tsarigradsko shose Blvd., 1784 Sofia, Bulgaria*

[2] *Kozloduy NPP Plc., 3321 Kozloduy, Bulgaria*

Abstract. The move to high burnup fuels, new fuel designs and introduction of new cladding materials have generated a need to re-examine and verify the validity of the safety criteria for LOCA accidents. Fuel designers and nuclear research community, as well as the safety authorities rely on fuel performance codes for predicting the behaviour and life-time of fuel rods. The simulation tools are developed and validated on the basis of experimental results. The present report demonstrates the team capacity to analyse LOCA conditions on the base of the Halden experiment IFA 650.2 by means of the TRANSURANUS code and results are compared with experimental data.

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

1 Introduction

Reliability of nuclear fuel plays a key role in ensuring safety, competitiveness and public acceptance of nuclear power. The Fukushima accident has especially demonstrated the necessity for detailed analysis of all aspects of fuel design and performance related to both normal and accident conditions, including severe design-basis accidents (DBA) with durable loss of active fuel cooling. The behaviour of in-core materials, especially of fuel cladding, in extreme high temperature and corrosive environments is among the primary factors that define accident evolution. Most of on-going developments of fuel performance codes lie in the field of design-based accident conditions as applicable for loss-of-coolant and reactivity-initiated accidents (LOCA and RIA). The simulation tools are developed and validated on the basis of the OECD/NEA and IAEA.

LOCA tests in the Halden reactor IFA 650 are an excellent basis for assessing codes themselves as well as to compare codes that are being developed by independent teams. The application range of the TRANSURANUS code has been extended [1,2] to LOCA conditions and based on our experience as users of TRANSURANUS fuel performance code the first step to simulate Halden IFA650.2 experiment was done. The present report demonstrates the team capacity to analyse LOCA conditions on the base of the experiment IFA 650.2 by means of the TRANSURANUS code and results are compared with experimental data.

2 Experiment

The IFA 650 LOCA experiments in Halden are integral inpile tests on fuel behaviour 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. The rod is surrounded by an annular flow channel, which is separated from the outer annular channel by an electrically heated shroud. In IFA-650.2 one fresh fuel rod, tight-gap and pressurized PWR fuel rod with Zr-4 cladding was located in a standard high-pressure flask, which was connected to a heavy water loop and a blow down system [3]. Heating was provided from the fuel 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 and during the experiment the temperature level 1050°C was reached and held for 4.5 minutes. The experimental goal was to produce cladding ballooning and burst and to achieve a peak cladding temperature.

The length of active fuel rod was 500 mm and the outer diameter of the pellets 8.29 mm. The fuel pellets were 8 mm long and dished at both ends. The density of the fuel was 95% of theoretical density and the enrichment was 2% ^{235}U. The diametric gap between the fuel and cladding was 0.070 mm. The outer diameter of the cladding was 9.50 mm and its thickness 0.57 mm. The cladding material was low tin Zr-4 and the rod was filled with helium at 4.0 MPa at room temperature. A high fill pressure was chosen to ensure that the cladding would balloon and burst in the test. The rod plenum volume (free gas volume) was made relatively large to be able to maintain stable pressure conditions also during ballooning. The total free gas volume was 17.4 cm^3, of which 15.8 cm^3 was located outside the heated region.

The rig instrumentation consists of four cladding surface thermocouples, a cladding extensometer, a fuel pressure sensor, two fast response cobalt neutron detectors and three vanadium neutron flux detectors at three elevations, two heater surface thermocouples and thermocouples at the inlet and outlet of the rig. Three cladding thermocouples are located in the upper part of the rod, 10 cm below the fuel top and one in the lower part, 10 cm above the fuel bottom. The temperature of the heater is measured by two embedded thermocouples, which are located at two levels on both sides of the middle line of the fuel segment.

The axial power distribution was measured by three self-powered vanadium neutron detectors (ND). Rapid power changes were monitored using two fast responding cobalt NDs (see the Figure 1). The main fuel rod parameters as well as the surrounding conditions are presented in Table 1 and Figure 1 below.

Table 1. Fuel parameters

Description	**Value**
Burnup	fresh
Active fuel length	500 mm
Fuel weight	0.282 kg UO_2
Enrichment	2% ^{235}U
Fuel density	95% theoretical
Fuel diameter	8.29 mm
Rod gap	0.070 mm
Pellet length	8.29 mm
Dishing	0.070 mm
Cladding material	Zr-4 low tin
Clad outer diameter	9.50 mm
Cladding thickness	0.57 mm
Filler gas / Pressure	He / 40 bar (75 bar in hot phase)

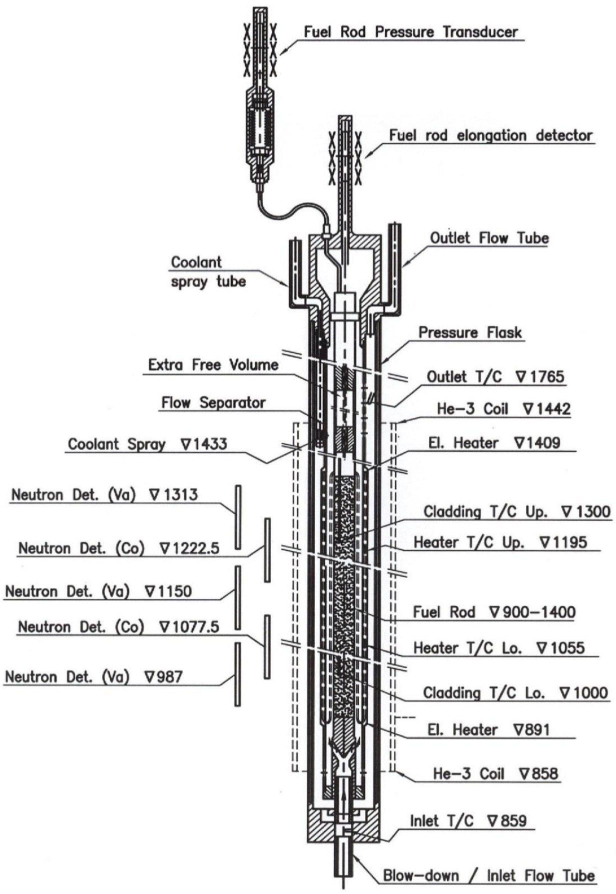

Figure 1. Test rig schematic of IFA 650-2.

3 IFA 650.2 LOCA Test – Simulation and Results

The LOCA extension of the fuel performance code TRANSURANUS is designed to calculate the steady state part of the fuel's rod life with appropriate models. 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. 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. For instance the thermo-hydraulic behaviour is no longer calculated using the mass flow rate and the coolant inlet temperature data as done in the steady state part. During the LOCA the temperature of the fuel rod is calculated either from the outer cladding temperature or from a fuel temperature and an appropriate heat transfer coefficient between cladding and coolant. These thermo-hydraulic data is calculated with special thermo-hydraulic codes like ATHLET or RELAP and used as input data for the LOCA part of the TRANSURANUS calculation. To choose suitable for this case model, the following considerations had to be taken into account. According the experimental data the fuel rod was modelled with 30 equidistance slices. 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 of the fuel (ModFuel(6)=21), accounting for the local porosity. Standard Zircaloy 4 cladding material correlations, models and options for the TRANSURANUS version v1m1j14 were selected.

The first simulation with TRANSURANUS code of an integral LOCA test was carried out by colleagues from TÜV in Hannover [4], and was in the frame of the benchmark organized by the OECD-NEA. The maximum cladding temperature and the temperature increase rate were 1050°C and 5–7 K/s, respectively. The IFA-650.2 post calculation the normal operation and natural convection parts were modelled using standard TRANSURANUS options for these cases. The post experimental calculations of the blow down and dry out phase are based on thermo-hydraulic boundary conditions calculated with the ATHLET code and data obtained from the experiment itself. As thermo-hydraulic boundary condition the calculated outer cladding temperature was used as TRANSURANUS input. The values for plenum temperature, system pressure and linear heat generation were taken from the measurements. The average coolant outlet temperature was chosen as plenum temperature. Figures 2 and 3 are represented below.

The time of cladding burst could be recognized by the cladding extensometer records as well as the drop of inner pin pressure. The comparison of calculated cladding elongation and extensometer data is presented on Figure 4 and shows an acceptable accuracy of TRASURANUS prediction.

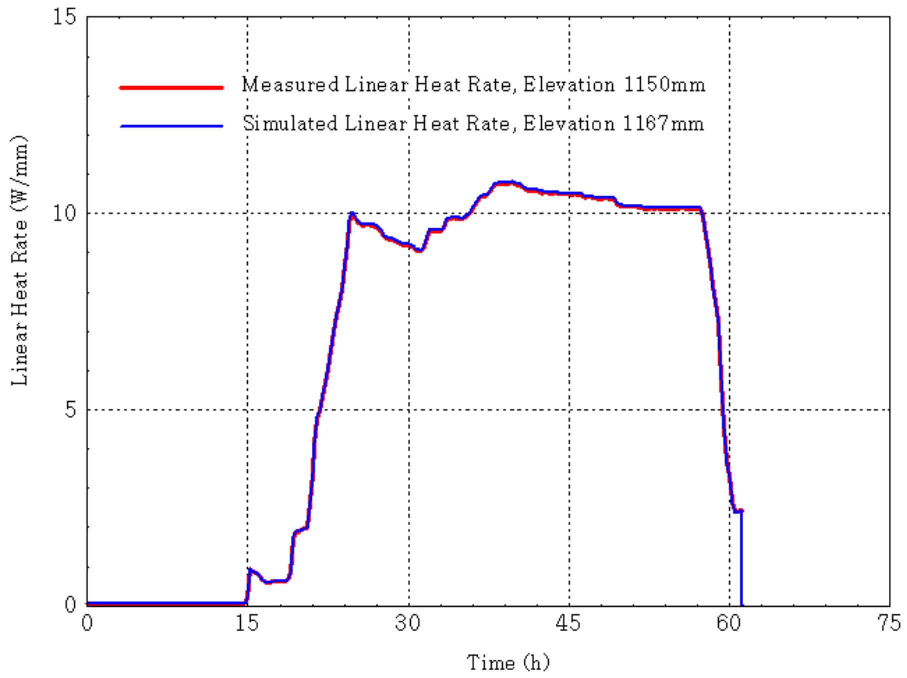

Figure 2. The comparison of modelled and measured linear heat rate.

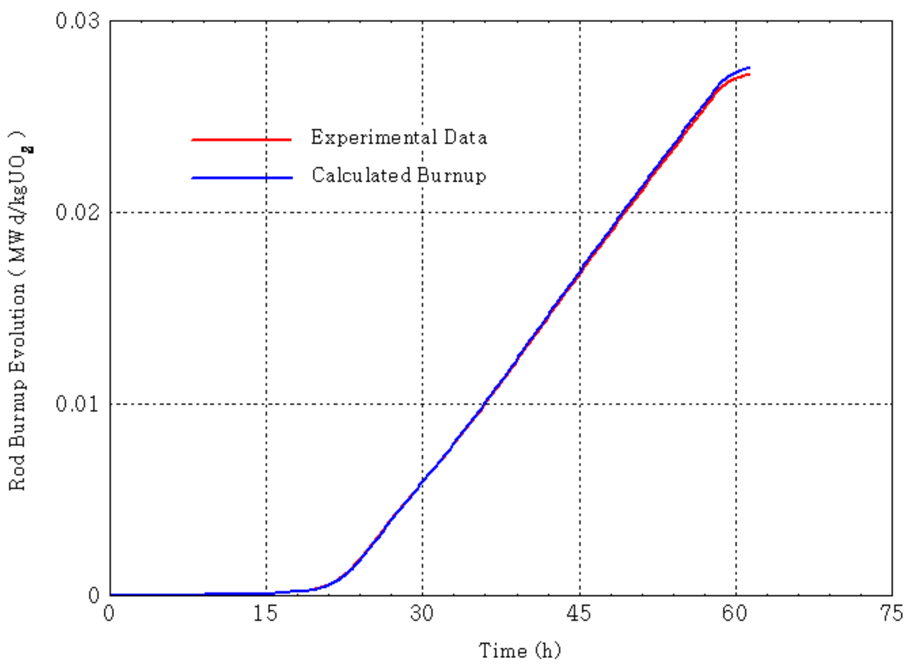

Figure 3. Comparison of the calculated and measured average Burnup.

A good indicator of rod failure is the drop of inner pin pressure. Calculated coolant pressure after the blow down start together with calculated inner pin pressure for the same time period are presented on the Figure 5. Measured rod pressure is presented on the same figure. Pressure transducer stuck at 5.6 MPa after rod rupture but the time of burst could be compared. The calculated inner pin pressure underestimated in the blow down phase and overestimated in the dry out phase. Time of failure is calculated with good accuracy. The difference between the calculated inner pin pressure and the measured data might be caused by a not well known plenum temperature used in the calculation.

4 Conclusion

The results of first post calculation of the IFA-650.2 Halden LOCA test show that the TRANSURANUS code including the LOCA extension can be used well to predict rod failure.

It was found that the time of burst is very sensitive to calculated inner pin pressure and to given axial temperature distribution of the cladding.

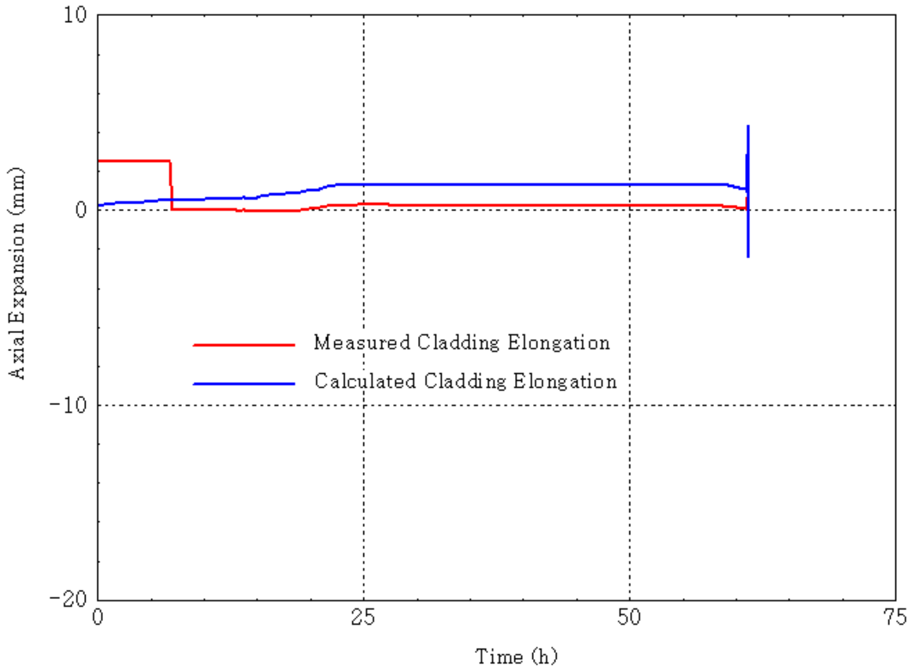

Figure 4. Cladding elongation.

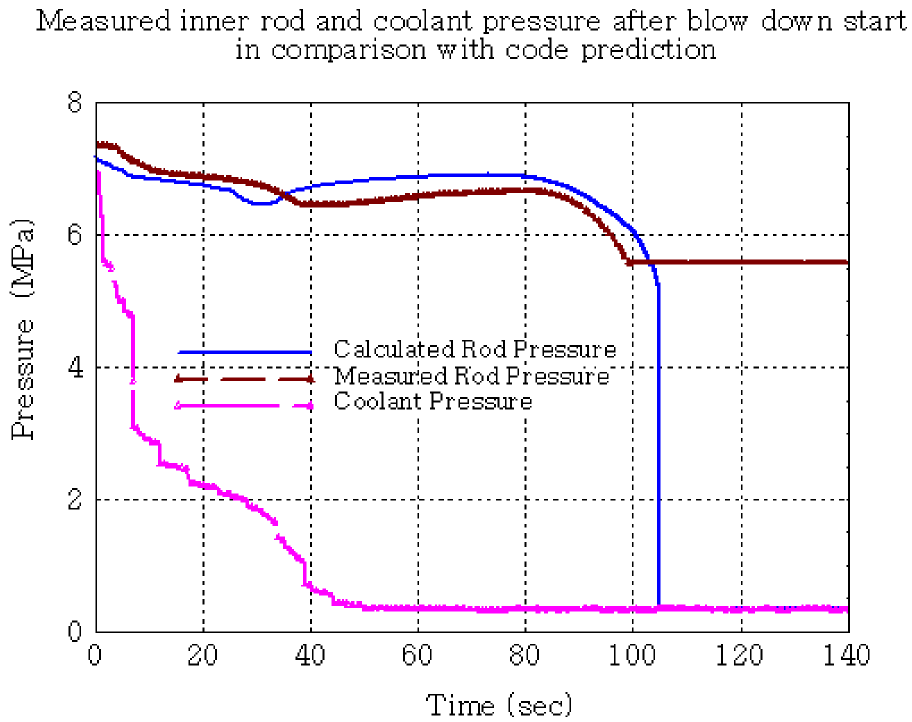

Figure 5. Gap pressure comparison after blow down start.

References

[1] K. Lassmann: The TRANSURANUS Code - Past, Present and Future (Review Article), in: *ITU Activity Report 2001 - EUR 20252*, ISBN 92-894-3639-5, 2001, p. 16, http://itu.jrc.cec.eu.int/annual_reports/annual_report_2001/index.htm.

[2] P. Van Uffelen, Cs. Győri, A. Schubert, J. van de Laar, Z. Hozer, G. Spykman: Extending the application range of a fuel performance code from normal operating to design basis accident conditions, *J. Nucl. Mater*. **383** (2008) 137.

[3] LOCA testing at Halden, Trial runs in IFA-650, V. Lestinen, E. Kolstad, W. Wiesenack OECD Halden Reactor Project, *Nuclear Safety Research Conference*, Washington October 20th - 22nd, 2003.

[4] G. Spykman, D. Maertens, D. Bour: Blind and post calculation of the Halden LOCA experiments with theTransuranus LOCA Extension, in: *Proceedings of International workshop "Towards nuclear fuel modelling in the various reactor types across Europe"*, P. Van Uffelen (Ed.), Institute for Transuranium elements, Karlsruhe, 25-26 June, 2007.