TRANSURANUS Capabilities for Uncertainty Analyses of Fuel Performance

M. Mitev, N. Mihaylov, S. Boneva, M. Manolova

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

Abstract. Uncertainty analysis of important parameters that characterize nuclear fuel behavior during accident conditions were performed using the TRANSURANUS code. The possible values of these parameters during transients in the fuel vicinity were evaluated. The most critical among the parameters are presented by means of fractional frequency in this paper. The obtained results are in good agreement with the experimental values measured in the IFA 650 LOCA experiments in Halden Research Reactor.

Keywords: TRANSURANUS fuel modelling, WWER fuel, fuel behavior, nuclear safety, uncertainty analysis, Monte Carlo simulation.

1 Introduction

The safe operation of nuclear power plants is of great importance for future development of nuclear energy production and it's acceptance of the public as well. This topic became particularly important after the Fukushima incident that 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). The detailed knowledge of the fuel behavior in normal conditions contributes to other important areas in the nuclear reactors research such as these described in Ref. [1].

IAEA had initiated a Coordinated Research Project (CRP) "Fuel Modelling in Accident Condition" (FUMAC) to support different Member States in their efforts to develop reliable tools for modelling of fuel behavior during accidents. This task is tackled by share of experimental data and comparison of modelling predictions acquired with different computer codes. INRNE participate in this CRP. The main purpose of the contract is the application of the developed TRANSURANUS WWER version, to cover exercises included in the joint NEA-IAEA Fuel Performance Experimental database as well as the specific WWER fuel. One of the tasks [2] was to perform an uncertainty analysis based on one chosen LOCA experiment performed in Halden reactor, Norway.

Among all the available uncertainty analysis methods, the probabilistic input uncertainty propagation method is the most widely used in the nuclear safety analysis. The uncertainty of each input parameter is quantified by a probability density function based on experience feedback from code applications. The input uncertainties are propagated to the simulation model output uncertainties via the code calculations. In Monte-Carlo simulation the computer code is run repeatedly each time using different values for each of the uncertain parameters. The results of MC simulations lead to a sample of the same size for each output quantity. A number of input uncertainty parameters that cover fuel manufacturing data, properties and models, as well as operating and test conditions were applied.

The IFA-650.10 test with PWR fuel pre-irradiated in France together with the simplified T/H boundary conditions i.e. coolant temperature and heat transfer coefficients was simulated and compared. The objective is to verify the quantified uncertainties impact on the predicted key physical parameters (cladding temperature, plenum gas temperature, plenum gas pressure, burst time, strain, elongation, equivalent cladding reacted, hydriding of cladding alloy, etc.), to identify the important input parameters.

The IFA 650 LOCA experiments in Halden are integral in-pile tests on fuel behavior such as fuel fragmentation and relocation, cladding ballooning, burst (rupture) and oxidation during typical LOCA transient for PWR, BWR and WWER high burnup fuels. In the frame of the FUMAC project the LOCA experiment IFA650.10 was simulated by means of TRANSURANUS code. IFA650.10 experiment [3] is a test on PWR fuel behavior, pre-irradiated up to 60 MWd/kgU. The modified version of the TRANSURANUS code with incorporated specific LOCA models [4] was applied and predicted fuel behavior was analyzed and compared.

Applying the Monte-Carlo technique, TRANSURANUS code allowed statistical variations of large number of input quantities to be simulated according to Gaussian distribution. Results of the calculation with nominal value of input parameters and with sufficient large number of Monte-Carlo simulations are enclosed in this report as well.

2 Short Description of the IFA650.10 Experiment and TRANSURANUS Model

In the IFA-650 LOCA tests, a single fuel rod is located in a high-pressure flask connected to the heavy water loop of the Halden reactor. The fuel power is controlled by reactor power. Nuclear power generation in the fuel rod is used to simulate decay heat, whereas the electrical heater surrounding the rod is simulating the heat from surrounding rods. The detailed description of IFA-650.10 can be found in Ref. [3]. The test segment was cut from a standard PWR fuel rod which had been irradiated in the PWR Gravelines 5 (France) during five cycles up to burnup of 60 MWd/kgU. The length of refabricated fuel stack was ~ 440 mm. The rodlet was filled with a gas mixture of 95% argon and 5% helium at 40 bars. Argon was chosen to simulate the fission gases.

The LOCA test started with steady state operation at high power in the rig, it was connected to the outer loop and forced circulation flow. Nuclear power calibration is done during this period. Shortly before the start of the LOCA test, power is decreased to test level and the heater is turn on. The time of blow-down, i.e. start of LOCA conditions, is taken 0 seconds. The cladding burst, detected by pressure transducer is at ~ 249 seconds. Target peak cladding temperature was 850°C. Slight clad ballooning and burst were detected in-pile and verified by the gamma scanning performed at Halden.

The new TRANSURANUS version v1m1j17 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 IFA-650.10. The calculations were performed for base irradiation as well as for the LOCA test irradiation, using restart option of TRANSURANUS code for account rod cutting and refilling [5].

The test fuel rod was modelled by a steady state simulation of the base in-reactor irradiations. In both steady state and transient fuel rod input models were set according to the specifications of IFA-650.10 tests (UO_2 PWR fuel and Zircaloy 4 cladding). The thermo-hydraulic boundary conditions during LOCA test calculated from SOCRAT code system [6], are used in the TRANSURANUS input file: the coolant temperature and appropriate it axial distribution; the power in the fuel stack (average LHR and axial distribution); and coolant pressure are prescribed.

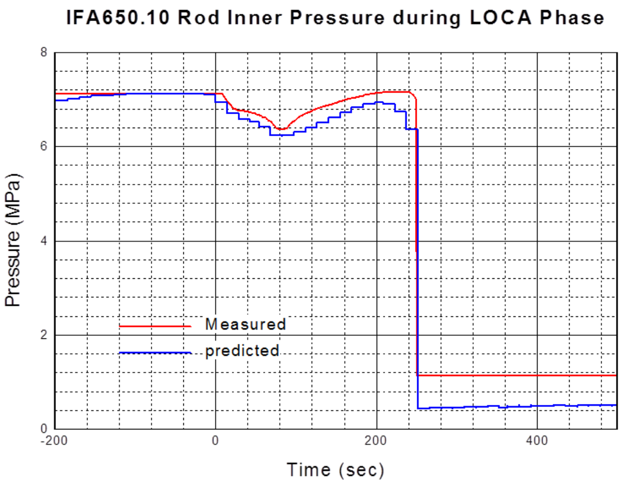

Figure 1. Rod inner pressure during LOCA phase of IFA-650.10 test compared with pressure transducer records.

An indicator of rod failure during LOCA test is the drop of inner pin pressure. Calculated inner pin pressure is compared with the pressure transducer records and is presented in Figure 1. The TRANSURANUS prediction of the time of burst according the inner pin pressure is 251 s after blow-down and the pressure evolution during LOCA test is presented as well.

The agreement between measured and predicted time of burst is acceptable.

The cladding outer diameter after rod burst is presented in Figure 2.

The place of rod burst is compared with measured ones as well. A reasonable agreement between predicted and measured values of this parameter is observed.

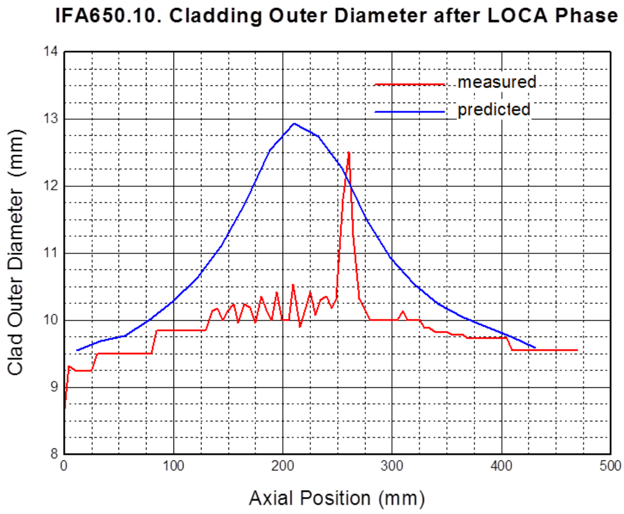

Figure 2. IFA-650.10 LOCA test. Outer cladding diameter comparison.

3 Uncertainty Analyses of Fuel Rod Performance by TRANSURANUS

Applying the Monte-Carlo technique, already the first versions of TRANSURANUS allowed statistical variations of a large number of input quantities to be simulated according to normal (Gaussian) distributions [7]. The corresponding code input options cover the fuel rod geometry at beginning of life, all prescribed time-dependent quantities (e.g. linear heat rate and coolant or cladding outside temperatures) as well as all material properties (e.g. thermal conductivity, creep) that are applied in the code for fuel, cladding and coolant. By introducing additional types of input distributions (uniform, log-normal) as well as by allowing user-defined lower and upper bounds of the input quantities the code capabilities were extended. The applications to WWER fuel were outlined in Ref. [8].

Statistical uncertainty analysis of the above mentioned LOCA experiment IFA-650.10 with pre-irradiated PWR

UO_2 fuel was performed. Uncertainties in fuel rod operation and test boundary conditions, e.g. time dependent prescribed quantities as linear heat rate, coolant temperature and inner pin pressure as well as material properties of the fuel and cladding were considered. The input parameters as well as the information related to their uncertainties are provided in Table 1. For each of uncertainty parameters, it includes a mean value, a standard deviation (σ) and a type of distribution. A normal distribution has been assigned for simplicity to all the considered input parameters.

Table 1. Specification for Uncertainty Analysis on Modelling of the Halden IFA-650.10 LOCA test

	Input uncertainty parameter		
	Mean	Standard deviation	Type of distribution
Operation and test boundary conditions			
Relative power during base irradiation	1	0.01	Normal
Relative power during test	1	0.02	Normal
Coolant temperature – base	1	0.01	Normal
Coolant temperature – test	1	0.2	Normal
Inner pin pressure – base	1	0.0125	Normal
Inner pin pressure – test	1	0.025	Normal
Model Parameters			
Gap conductance	1	0.125	Normal
Minimum porosity at the end of thermal and irradiation induced densification	1	0.05	Normal
Eff. diffusion coefficient	1	0.25	Normal
Corrosion rate	1	0.15	Normal
Material Properties of the Fuel			
Fuel swelling	1	0.05	Normal
Fuel thermal strain	1	0.05	Normal
Fuel thermal conductivity	1	0.05	Normal
Fuel specific heat	1	0.015	Normal
Fuel density	1	0.0048	Normal
Fuel emissivity	1	0.05	Normal
Material Properties of the Cladding			
Clad elasticity module	1	0.05	Normal
Clad thermal strain	1	0.05	Normal
Clad thermal conductivity	1	0.05	Normal
Clad yield stress	1	0.05	Normal
Clad burst stress	1	0.1	Normal
Clad specific heat	1	0.015	Normal
Clad emissivity	1	0.05	Normal
Clad rupture strain	1	0.05	Normal

The impact of realistic input uncertainties has been tested for the output parameters specified in Ref. [9]:

•Fuel rod internal pressure;

•Cladding inner side temperature;

•Cladding surface temperature;

•Fuel centreline temperature;

•Fuel surface temperature;

•Cladding outsider oxidation layer thickness;

•Equivalent cladding reacted (ECR);

•Cladding outside diameter;

•Cladding effective stress.

4 Results

Results for the mean value of the listed parameters over time were obtained. The results' uncertainty due to the varied input parameters was evaluated by means of fractional frequency.

4.1 Fuel central temperature

Graphical representations of important results from the calculation at burst node for the time of interest are shown below. The mean value and the upper and lower boundaries at 5% and 95% correspondingly are presented. The start time of the LOCA is chosen for start time of the diagrams. The time at which the fractional frequency is presented is shown. Graphical representation of Monte Carlo calculations results for Fuel Central temperature (FCT) at burst node for the time of LOCA start is shown on Figure 3. Next two figures shows the probability density of at time

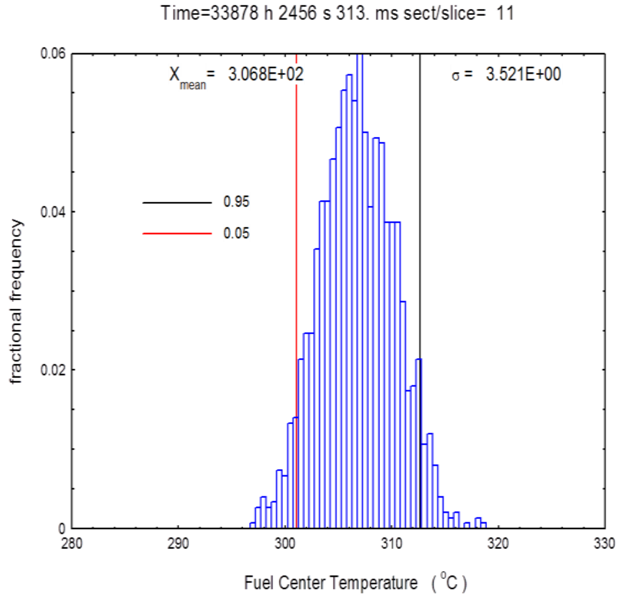

Figure 3. FCT at time of LOCA start.

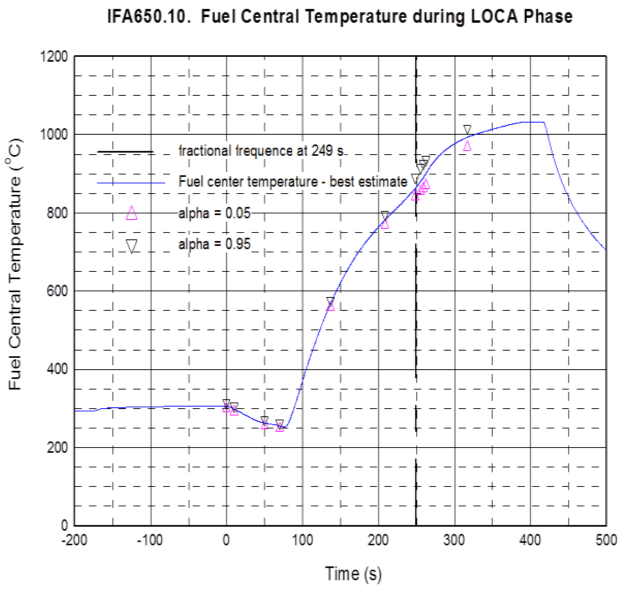

Figure 4. Mean value and its boundaries over time.

of burst and time dependent changes of FCT as well as its 5% and 95% percentage boundary.

4.2 Outer cladding diameter

Outer cladding diameter evolution during time of LOCA test is assessed and presented in Figure 5 together with its lower, resp. upper bounds associated with all the time trend of the parameter.

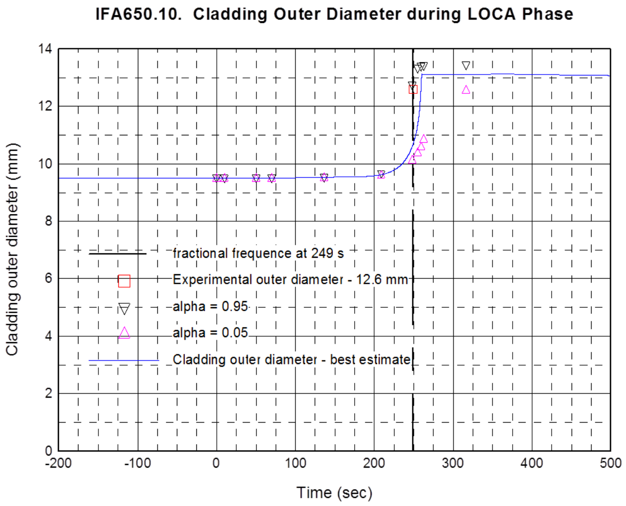

Figure 5. Cladding outer diameter v/s time of LOCA process.

During time of transient (time of burst) a great uncertainty in some of the fuel parameters as cladding diameter and rod inner pressure have to be expected. The calculated probability densities of the cladding outer diameter at the beginning of the LOCA test (Figure 6) and at time of burst (Figure 7) are presented and confirm this assumption.

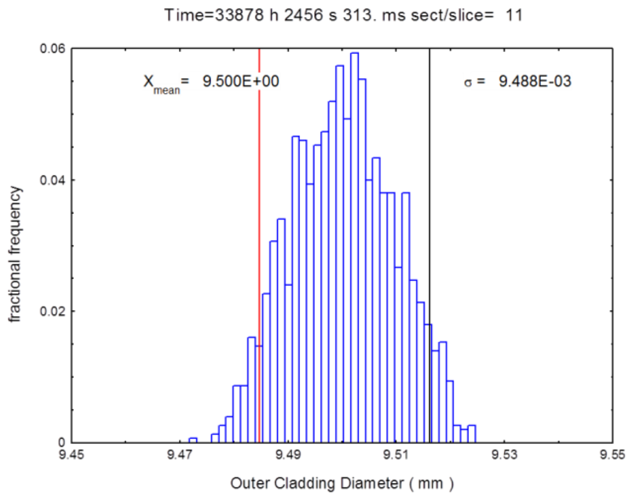

Figure 6. Fractional frequency of outer cladding.

5 Conclusions

The uncertainty of input parameters that impact most on the code predictions have to be carefully evaluated. Further precise analyses on the uncertainty sources are necessary in order to better predict the fuel behaviour under transient conditions.

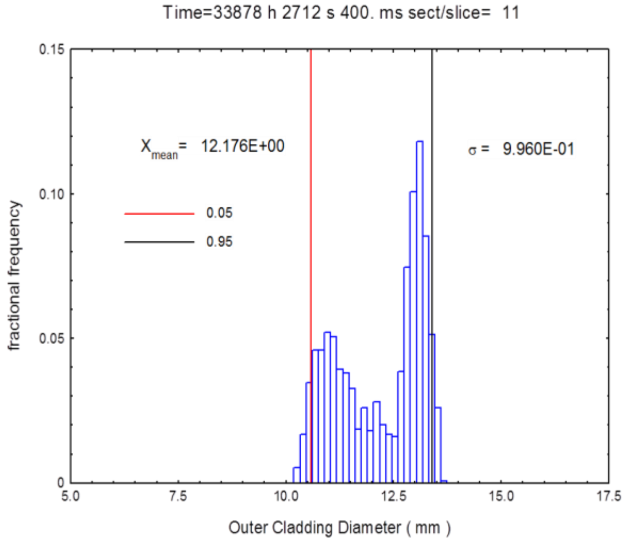

Figure 7. Fractional frequency of outer cladding.

The work in the field of uncertainty analysis with develop TRANSURANUS code is just started in INRNE and we hope this new develop version of the code will be very useful for further work.

Acknowledgements

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