Analysis of the LOC-C-4 LOCA test with the FRAPTRAN and TRANSURANUS fuel performance codes

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Abstract:

This work presents a comparative analysis of the models of two advanced traditional 1½D fuel performance codes, TRANSURANUS and FRAPTRAN, applied to pre-test simulations of a Loss-of-Coolant Accident (LOCA) scenario defined within the international LOC-HBu benchmark framework of FIDES-II. The benchmark focuses on a sensitivity analysis of fuel rod ballooning and burst behaviour in relation to rod internal pressure and rod free volume, specifically for fresh fuel. The key objectives of this work were to improve the understanding of the behaviour and the limitations of the codes in modelling LOCA scenarios, as well as to improve their applicability and accuracy for nuclear safety assessments. In the presented comparative study, the calculated key fuel quantities (hoop stresses, fuel and cladding temperatures) showed good agreement, while the hoop strains predicted by FRAPTRAN exhibited greater sensitivity to temperature variations. The experienced deviations were explained, and the key conclusions were drawn.

1 INTRODUCTION

In the early 2000s, a series of LOCA tests carried out in the framework of the Halden Reactor Project (HRP) demonstrated that high-burnup fuel, with burnups of up to 92 MWd/kgU, is subject to a new type of fragmentation yielding much finer fragments than what had been seen earlier at lower burnups, axial relocation and, in the case of cladding burst after ballooning, dispersion of these fragments in the primary circuit [1].

With the aim of obtaining more information about fuel fragmentation, relocation and dispersal (FFRD), a series of high-burnup LOCA tests in the Transient Reactor Test (TREAT) research reactor at the Idaho National Laboratory (INL) was planned in the frame of the joint experimental programme LOC-HBU of the OECD NEA FIDES-II project [2]. Before the high-burnup real tests, five commissioning tests on fresh fuel, known as LOC-Commissioning (LOC-C), are planned to establish, demonstrate, and qualify the experimental system. For the fourth test (LOC-C-4), an international benchmark, with the participation of various technical support organisations (TSOs), consisting of a pre-test modelling and simulation exercise (M&S) was organised to assess the sensitivity of cladding ballooning and possible burst to a change in the rod internal pressure and the rod free volume.

The work presented in this paper was developed in this context. Based on the results obtained from the simulation of the LOCA scenario specified in the benchmark, a comparative analysis was carried out using the modelling approaches implemented in the two advanced 1½D fuel performance codes, TRANSURANUS and FRAPTRAN. The paper contributes to the broader objective of understanding how different modelling approaches, different levels of physical details, correlations, and considered burst criteria, can influence the prediction of critical safety-relevant phenomena. Such comparative studies are essential in evaluating the robustness and reliability of fuel performance codes, especially when they are to be applied to safety assessments involving accident conditions.

2 LOC-C-4 PROBLEM DESCRIPTION

2.1 The LOC-C-4 experiment

The LOC-C-4 experiment is the fourth fresh fuel commissioning test to be performed in the Transient Reactor Test Facility (TWIST). TWIST consists of an upper capsule, containing the fuel rod, and a lower expansion tank operated by a remotely actuated motorised ball valve, Fig. 1. The goal of the LOC-C-4 test is to perform the full TWIST LOCA experiment evolution and drive the test fuel rod to balloon and burst. The LOC-C-4 experiment will contain a PWR-type fuel rodlet consisting of 24 fresh UO2 fuel pellets in Zircaloy-4 cladding with a ceramic insulator pellet on the top and bottom of the active fuel stack. The reactor power is controlled via the movement of transient control rods. The evolution of the experiment is planned as follows:

1. **State Point 1 (SP-1):**
    - the upper capsule is filled with static water, pressurised with argon to ~3.5 MPa at 20°C;
    - the lower expansion volume is at atmospheric pressure;
    - the TREAT reactor power is ramped up and held constant a few tens of seconds to create a radial temperature profile in the fuel rod similar to an LWR in operation.
2. **LOCA Simulation (blowdown):**
    - The valve between the capsules opens after 29 s, causing rapid depressurisation and drainage of the upper capsule, and simultaneously the TREAT reactor power is reduced by control rods;
    - the loss of coolant reduces heat transfer, causing a rapid temperature increase.
3. **State Point 2 (SP-2):**
    - The upper capsule is empty of water at 31 s, leaving the fuel rod surrounded by some steam and non-condensable gases;
    - the TREAT reactor power is adjusted to match decay heat conditions seen in an LWR during a LOCA.

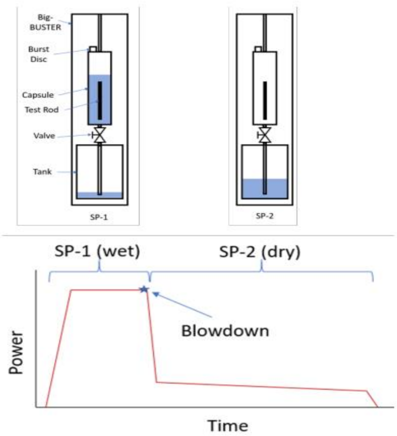

Figure 1: Schematic of the TWIST LOCA operation and TREAT power [3].

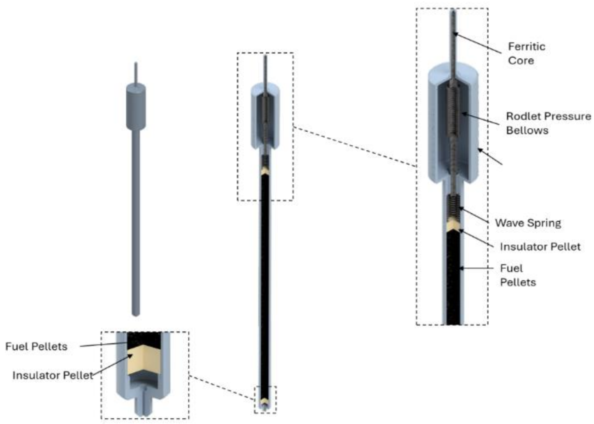

Figure 2: LOC-C-4 fuel rodlet *[3].*

2.1 LOC-C-4 M&S exercise

The exercise consists of the pre-test simulation of the LOC-C-4 fresh fuel commissioning test. Overall, there are six cases included in it. The five cases in Tab. 1, subjected to analysis in this work, from case 2 to 6, are specific to the fuel performance simulation, while the one omitted, case 1, also included a thermal-hydraulic performance simulation. Cases 2 to 6 aim to study how rod pre-pressurisation and plenum volume affect cladding ballooning and bursting behaviour.

Table 1: Cases of the M&S exercise

Case #	Fuel length (cm)	Rod Free Volume (cm^3)	Rod Internal Pressure, 20°C (MPa)	Targeted Peak Cladding Temperature (°C)
2	25	15.9	10	900
3			5	
4			15	
5		10	10	
6		5	10	

3 METHODOLOGY

3.1 Boundary conditions

In order to draw meaningful conclusions regarding the discrepancies between the predictions of the two codes, the simulations must be based on identical thermal-hydraulic boundary conditions. Ensuring consistent boundary conditions is the fundamental first step when comparing the performance and modelling approaches of different fuel performance codes.
As strongly recommended by the benchmark organisers, particular attention was given to this aspect: the cladding surface temperature was calculated using the provided heat transfer coefficient and the bulk coolant temperature, while the linear heat rate was calculated according to the given TREAT power and Power Coupling Factors (PCFs) of each pellet.

Figures 3 and 4 are used as a reference.

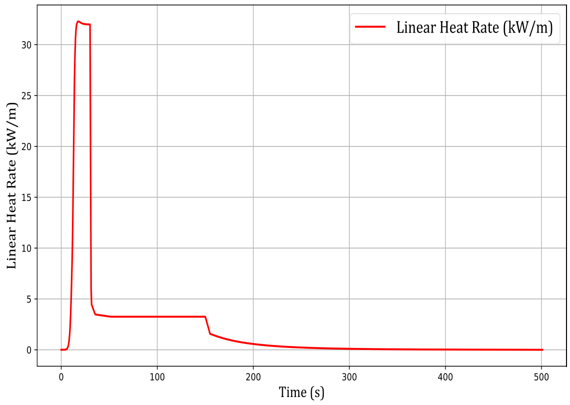

Figure 3: Linear heat rate history

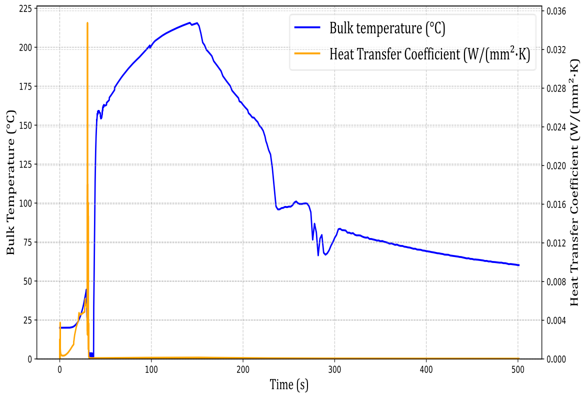

Figure 4: Heat transfer coefficient and bulk coolant temperatures histories

3.2 Models and failure criteria applied

In TRANSURANUS, cladding deformations were treated using the small-strain approximation. This is the preferred approach for analysing deformations during LOCA transient conditions, as the parameters of the creep law and of the failure criteria were tuned for the small-strain model. The creep behaviour of Zircaloy is described by a Norton law as a function of stress and temperature [4]. To predict cladding burst, TRANSURANUS provides four possible burst criteria: a stress-based criterion, a permanent strain criterion, a permanent strain rate criterion, and a criterion based on the radially averaged permanent true tangential strain [4]. In this work, a conservative approach was adopted, allowing all four criteria to be considered simultaneously.
FRAPTRAN uses the FRACAS-I small-strain approximation, rigid pellet model (also present in the FRAPCON and FAST codes), which ignores the stress-induced deformation of the fuel pellets [5]. Following the calculation of the cladding deformation, FRAPTRAN checks whether the cladding effective plastic strain is greater than the cladding instability strain given by MATPRO [6]. If the cladding effective plastic strain is greater than the cladding instability strain, the BALON2 ballooning model for large strains is invoked [7].
FRAPTRAN has two high-temperature failure criteria for ballooning and burst: cladding hoop stress and plastic strain. The hoop stress limit is only active when ballooning occurs and the BALON2 model is invoked, while the strain limit is only valid above 667°C average cladding temperature.

3.3 Nodalisation

The axial and time discretisation of the power and of the thermal-hydraulic boundary conditions provided for the benchmark were different. The approaches adopted by the participants to tackle this were the following.
For TRANSURANUS, the safest way to preserve all the information was adopted. The two sets of axial coordinates were merged and interpolated, obtaining 56 axial nodes. The time points were merged and interpolated in the same way as the axial nodes. For the radial discretisation, 14 coarse zones were selected, of which 3 were for the cladding, each one divided into 5 mesh points.
For FRAPTRAN, 24 uniform axial nodes were applied, with 20 equal-area radial nodes in the fuel and 5 in the cladding. The latter two are close to the upper limit of the recommended (usually used) values. Considering the time nodalisation, 0.1 s was used (FRAPTRAN recommendation ranges between 0.2 s and 5 s, depending on the size and the phase of the LOCA).
The presence of insulators was considered only for TRANSURANUS.

4 RESULTS AND DISCUSSION

The benchmark analysis revealed that, for both FRAPTRAN and TRANSURANUS, the fuel rod undergoes ballooning followed by burst in all five analysed cases. Moreover, the axial location at which the burst occurs is identical.

Comparing the cases, both codes show that the time at which the burst occurs is highly influenced by the variation of the rod internal pressure. The increase in the rod internal pressure leads to a significantly shorter time for the burst. The burst time is, on the contrary, only slightly influenced by the variation of rod free volume. This limited sensitivity is related to the size of the fuel rod and its free volume. Even the smallest upper plenum, case 6, is very large and relatively cool, so it dominates the behaviour of the rod.

The key elements determining the ballooning and burst are the outer cladding temperature and the rod internal pressure. Both codes predicted the same evolution of the pressure. Consequently, the ballooning and burst are driven, mainly, by the evolution of the temperature.

In all the simulated cases, rod failure was prompted by the stress limit in FRAPTRAN, while it was caused by the permanent strain in TRANSURANUS.

Since all the cases exhibit similar behaviour, in order to develop a thorough understanding of the differences, the analysis below only refers to the base case, i.e. to Case 2. The curves are taken up to the burst time.

4.1 Hoop stress and strain evolution.

Figure 5 shows the evolution of hoop stress and permanent strain, while Fig. 6 shows the evolution of the Normalised Failure Criteria (NFC), a parameter described below.

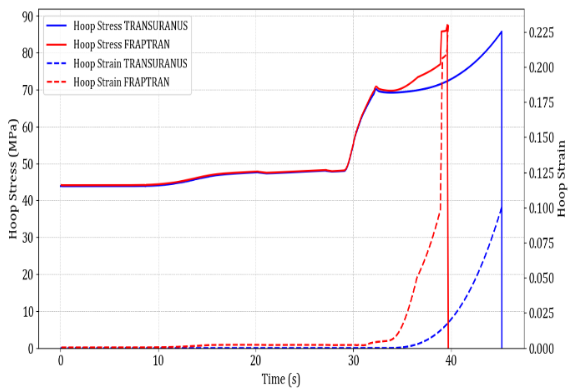

Figure 5: Hoop stress and strain evolution at burst height

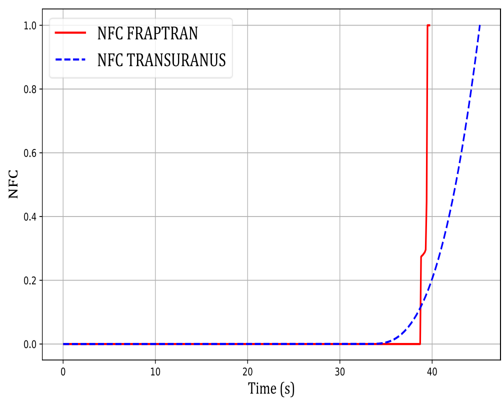

Figure 6: Normalised failure criterion evolution at burst height

TRANSURANUS calculated strain shows an exponential increase. The code predicts rod ballooning and failure for a 10 % permanent strain, a value suggested by the developers.

FRAPTRAN, instead, shows a discontinuity in the estimation of the cladding permanent hoop strain from 5 % to around 10 % when switching between the FRACAS-I and BALON2 models. It is related to the initialisation of the strain components in BALON2, which does not directly come from the previous strain calculation in FRACAS-I, that are based on constitutive laws between strains and stresses. The initial strain in BALON2, instead, is calculated from the cladding geometry at the end of the pre-ballooning phase [8]. Once BALON2 is invoked, a new radial and axial nodalisation is automatically imposed by the model in the specific node that shows the balloon.

The hoop stress evolutions shown in Fig. 5 correspond to those reported in the output files of both codes. They reflect the general behaviour of the rod internal pressure, up to the point at which the strain calculated by FRACAS-I starts to increase abruptly. At the time of the burst, the stresses are comparable, but FRAPTRAN predicts burst due to the local stress exceeding the limit in one of the newly introduced radial nodes by BALON2 (not shown in the figure). Furthermore, the strain limit is not triggered because the outer cladding temperature at that moment is still below 940 K.

The normalised failure criteria, proposed in Fig. 6, is a useful parameter used as a measure to indicate how close the cladding is to failure. It has been defined as the ratio between the failure parameter and the failure parameter criterion. For FRAPTRAN, the NFC value is fixed at 0.0 when the simulation is outside of the criteria ranges (BALON2 calculation) and evaluated on the basis of the hoop failure stress, while for TRANSURANUS, it is calculated based on the limit imposed for the permanent strain.

4.2 Fuel centerline and outer cladding temperature evolution

Figure 7 shows the evolution of the fuel centreline temperature and the outer cladding temperature during a LOCA.

From the licensing perspectives, the fuel centreline temperature plays an important role. For this reason, the radial power density profile of the TREAT facility was used as input for both codes. This profile comes from INL through FIDES-II and was calculated by the MCNP Monte Carlo code.

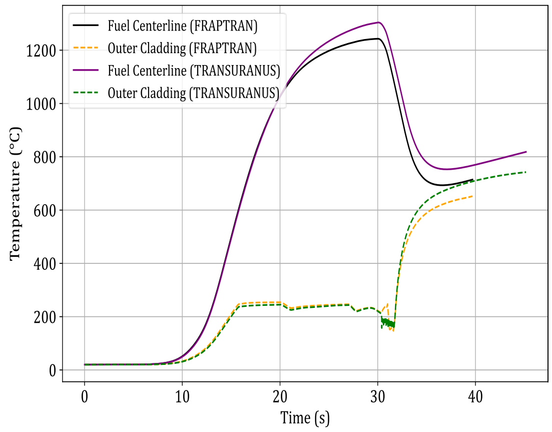

Figure 7: Temperature evolution at the fuel mid-height

The results show a difference of tens of degrees in the temperatures of the pellet. Following several simulations, the study revealed that the reason for the observed difference lies in the different correlations used for the thermal conductivity of the fuel pellet: the fuel thermal conductivity model in FRAPTRAN is based on the expression developed by the Nuclear Fuels Industries with modifications by PNNL [5]; in TRANSURANUS, instead, the thermal conductivity was calculated with the MATPRO correlation [6].

The two curves of the outer cladding temperature differ significantly in the post-blowdown phase due to the change in cladding geometry resulting from the deformations calculated with the model FRACAS-I. Indeed, an increase in the outer cladding radius leads to a reduction of the heat flux, which results in a decrease in the outer surface temperature.

4.3 Axial profiles

Figures 8 and 9 show the axial profiles of the outer cladding surface temperatures and the hoop strains, taken at the respective burst times (45.2 s for TRANSURANUS and 39.7 s for FRAPTRAN).

For the profiles of both quantities, the codes predict similar trends and magnitudes. In accordance with the results of Figure 7, the cladding outer surface temperature profile of FRAPTRAN is consistently lower than that of TRANSURANUS.

The deformations predicted by FRAPTRAN exhibit increased sensitivity to slight changes in temperature compared to those calculated by TRANSURANUS.

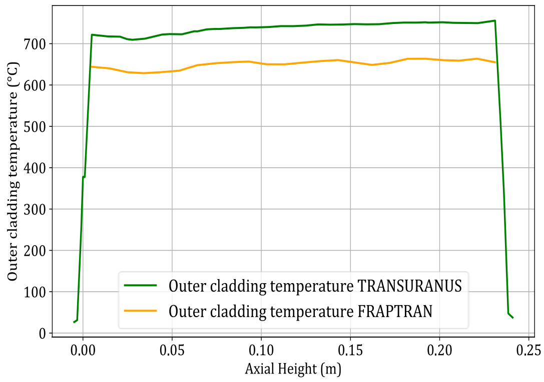

Figure 8: Temperature axial profile at the burst time

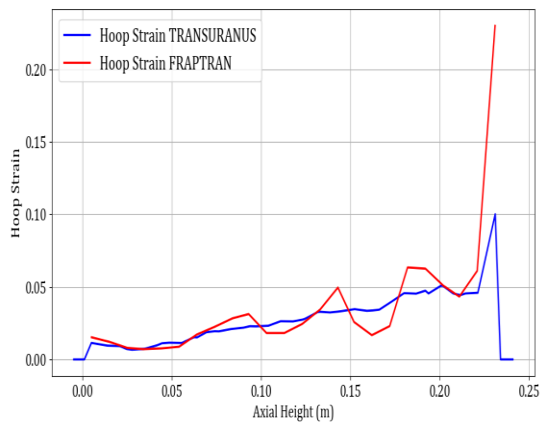

Figure 9: Strain axial profile at the burst time

5 CONCLUSIONS

In this paper, a comparative numerical fuel performance analysis was presented on the pre-test LOC-C-4 LOCA benchmark exercise. The measurement setup and the case matrix of the problem were briefly described. The simulations were carried out with the FRAPTRAN and TRANSURANUS traditional 1½D fuel behaviour codes. During the modelling, special attention was given to the utilisation of the same power history and the same thermal-hydraulic boundary conditions.

Both codes predicted rod burst for each case within a few seconds of difference at the same axial location. The trends of the cladding hoop stresses and strains were similar. Also, systematic deviations were seen between the fuel centreline temperatures due to the different heat conductivity models and between the cladding outer surface temperatures of the post-blowdown phase due to the different calculated deformations. Despite the significant differences in the models and in the failure criteria, the simulation results yielded close agreement and provided a good opportunity to study the underlying physical phenomena to explain the experienced discrepancies.

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References

[1] NEA/CSNI/R(2016)16, Report on Fuel Fragmentation, Relocation and Dispersal, OECD Publishing, 2016.

[2] "https://www.oecd-nea.org/jcms/pl_70867/second-framework-for-irradiation-experiments-fides-ii".

[3] R. Armstrong, C. Folsom and C. Jensen, "LOC-HBu M&S Exercise Problem Description Report," 2025.

[4] J. R. C. European Commission, TRANSURANUS handbook, 2023.

[5] K. J. Geelhood, W. G. Luscher, J. M. Cuta, I. A. Porter, FRAPTRAN-2.0: A Computer Code for the Transient Analysis of Oxide Fuel Rods, PNNL, 2016.

[6] A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior. MATPRO Version 11 (Revision 2).

[7] D. L. Hagrman, Zircaloy cladding shape at failure (BALON2), Idaho Falls, Idaho: EG&G Idaho, Inc., 1981.

[8] F. Feria, P. Aragón, L.E. Herranz, "Assessment of cladding ballooning during DBA-LOCAs with FRAPTRAN," Elsevier, p. 8, 2024.