# APPLICATION OF THE TRANSURANUS CODE TO HIGH BURN-UP LOCA TEST IN VIEW OF 10 CFR 50.46c

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## ABSTRACT

Nowadays, the implementation of new cladding materials and higher rod burn-ups have led to the necessity of re-examining the LOCA safety criteria and verifying their validity regarding the importance of hydrogen content on cladding embrittlement. U.S – NRC 10 CFR 50.46, “Acceptance criteria for emergency core cooling systems for light water nuclear power reactors,” is currently under revision to account for the influence of hydrogen on cladding embrittlement under LOCA conditions. In this work, the tests 191 and 192 conducted at the Hot Cell Laboratory of Studsvik Nuclear AB were simulated with TRANSURANUS code. Two base irradiation simulations were performed for both the father rod and the fuel rodlet to achieve consistent results. Consequently, to deal with the LOCA test, the restart option of TRANSURANUS was used to set the appropriate boundary conditions. The simulated data proved to be in agreement the experimental values for both phases of the exercise.

## 1. Introduction

During the past years, the extensive studies on the influence of hydrogen on cladding embrittlement under LOCA conditions have highlighted the importance of hydrogen content. In addition, new cladding materials and higher rod burn-up have generated a need to re-examine the LOCA safety criteria and to verify their continued validity. The U.S. Nuclear Regulatory Commission is currently revising its regulatory criteria in 10 CFR 50.46c, “Acceptance criteria for emergency core cooling systems for light water nuclear power reactors,” to account for the influence of hydrogen on cladding embrittlement under LOCA conditions [1]. At Studsvik, four integral LOCA tests concerning high burn-up fuelled rod segments were performed to investigate this problem measuring the mechanical behaviour of claddings which underwent ballooning and ruptures following LOCA conditions [2].

The purpose of this study is to simulate the tests 192 and 191 conducted at Studsvik with the TRANSURANUS fuel performance code [3]. Thanks to its flexibility in the fuel rod design, the TRANSURANUS code can address the thermal and mechanical analysis of fuel rods in nuclear reactors in a wide range of different situations, such as the ones given in experiments, under normal, off-normal and accident conditions.

Particular attention is given to the restart modification option available in the TRANSURANUS code in order to perform the base irradiation followed by re-irradiation after parameter changes and hence taking into consideration the different boundary conditions. Consequently, two base irradiation simulations have been carried out with full-length rod (the father rod) and fuel rod segment (the rodlet) in pursuance of checking the consistency between the models and the physical equivalences of the results after base irradiation. Some of the parameters considered were final burn-up, inner pin pressure, fission gas release and cladding integrity. Finally, to deal with the rod heating-up and quenching, the restart option was applied.

## 2. Description of the exercises

In this work the tests 191 and 192 conducted at the Hot Cell Laboratory of Studsvik Nuclear AB were reproduced with TRANSURANUS code. These two tests were part of a test campaign commissioned by the U.S. Nuclear Regulatory Commission (NRC) of four single-rod, out-of-pile, integral loss-of-coolant accident (LOCA) tests to assess the mechanical performances of ballooned and ruptured high-burn-up fuel rods. In each of these tests, a pressurized, high-burn-up, fuelled rod segment was subjected to a temperature transient in a steam environment to induce ballooning, rupture, and high-temperature steam oxidation.

The LOCA apparatus is designed to externally heat a 300 mm long fuel segment up to 1200 °C by infra-red radiation. The test segment temperature is measured with a thermocouple attached on the rod approximately 50 mm above the axial mid plane. The test segment is pressurized with argon and placed in a quartz glass chamber in a flowing steam environment [1].

The segments were taken from two rods which were irradiated at a U.S. PWR power plant and had a rod average burn-up of 68-69 GWd/MTU. The operating history for these rods was non-typical and defined by a mean Linear Heat Rate (LHR) of approximately 24 kW/m for cycle one, 23 kW/m for cycle two, 5 kW/m for cycle three, and 15 kW/m for cycle four. The base irradiation data are reported in Table 1 [5]. For each father rod, two rodlets were taken for the LOCA test. Therefore, in this study, only one rodlet case was analysed for each father rod, i.e. test 191 and 192.

Two base irradiation simulations were carried out with a full-length rod (the father rod) and a fuel rod segment (the rodlet) in pursuance of checking the consistency between the models and the physical equivalents of the results after the base irradiation. To deal with the LOCA test (rod heating-up and quenching) the restart option available in TRANSURANUS code was applied. Figure 1 and Figure 2 show the temperature and pressure history for the tests 191 and 192 [4].

The rodlets 191 and 192 were heated and maintained at 300 °C for approximately 15 minutes to achieve thermal equilibrium. Before initiating the temperature ramp, the desired filling pressures were established at 300 °C. Consequently, the rodlets were pressurized with argon between 82 and 110 bar. The rodlet was then heated at 5 °C/s until the rodlet temperature reached 1160 °C. The rodlets were held at 1160 °C for a few seconds. After this, the rods were cooled at a rate of 3 °C/s to 800 °C. At 800 °C, the quenching is initiated. At the quench, the test chamber is filled with room temperature water which rapidly lowers the test segment temperature. Table 2 summarises the post-irradiation evaluation (PIE) after the base irradiation and the specifications for the test rodlets. Besides, in Table 3 the experimental data of interest measured after the transient are indicated [4].

Table 1 – Base irradiation data. Reproduced from P. Raynaud, P.A.C., “NEC Studsvik LOCA test 192”, 2014, MS Excel data file contributed to the IAEA CRP FUMAC on December 8, 2014, U.S. Nuclear Regulatory Commission, Washington, DC, USA.

| Cycle | Time | | EPD (Equivalent power days) | Mean LHR [kW/m] |
|---|---|---|---|---|
| | Start | Stop | | |
| 7 | 01/07/1987 | 01/03/1989 | 579 | 24.5 |
| 9 | 09/03/1991 | 05/01/1993 | 491 | 23.1 |
| 10 | 10/04/1993 | 10/09/1994 | 518 | 5 |
| 14 | 09/10/1999 | 12/03/2001 | 520 | 14.8 |

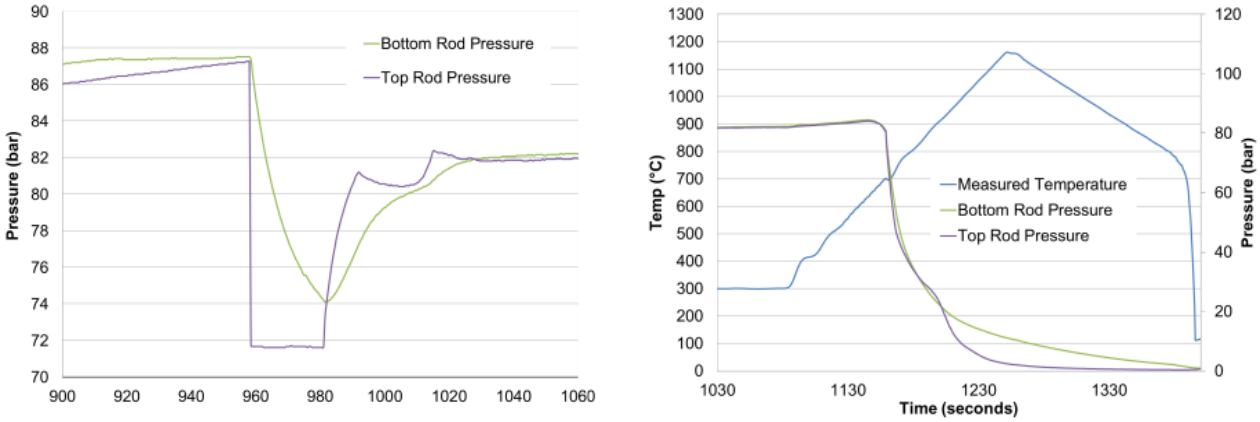

Figure 1 – Pressure adjustment (left) and LOCA data (right) for test 192. Reproduced from M. E. Flanagan, P. Askeljung, A. Puranen, "Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory", NUREG 2160.

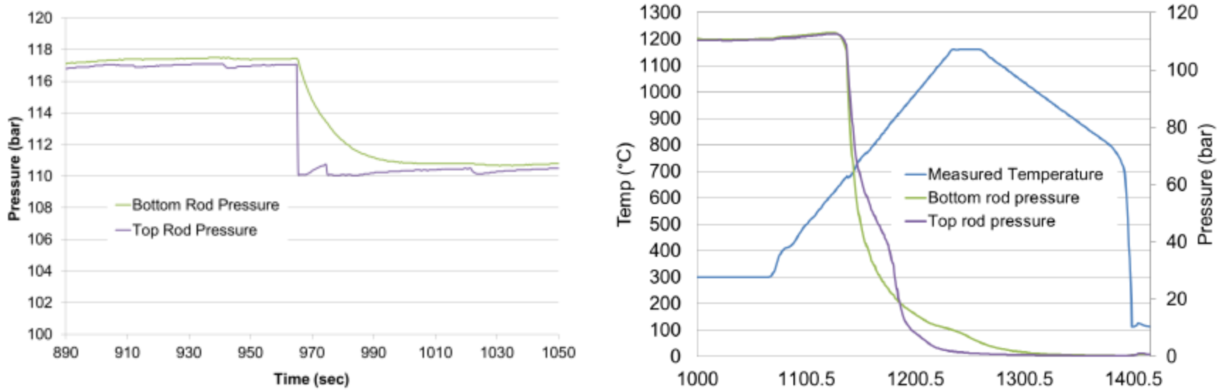

Figure 2 – Pressure adjustment (left) and LOCA data (right) for test 191. Reproduced from M. E. Flanagan, P. Askeljung, A. Puranen, "Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory", NUREG 2160.

Table 2 – PIE after base irradiation and specifications for the rodlet tests. Reproduced from M. E. Flanagan, P. Askeljung, A. Puranen, "Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory", NUREG 2160.

| **Parameter** | **Unit** | **Test 191** | **Test 192** |
|---|---|---|---|
| Hydrogen | wppm | 187 | 176-288 |
| Oxide | µm | 20-30 | 25-30 |
| Father rod average burn-up | MWd/kgU | 69.3 | 68.2 |
| Rodlet fill gas | - | Ar | Ar |
| Internal pressure at 300 °C | bar | 110 | 82 |
| Average rodlet burn-up | MWd/kgU | 75 | 78 |
| Rodlet length | mm | 300 | 300 |
| Position on father rod* | mm | 1800 | 1800 |

* from rod bottom

Table 3 – PIE after transient. Reproduced from M. E. Flanagan, P. Askeljung, A. Puranen, “Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory”, NUREG 2160.

| **Parameter** | **Unit** | **Test 191** | **Test 192** | **Note** |
|---|---|---|---|---|
| Max strain at clad failure position | % | 55 | 50 | At clad failure position |
| Maximum cladding diameter | mm | 18.5 | 16 | |

## 3. Computational domains

The TRANSURANUS model of the father rods includes 13 axial meshes for a total fuel stack length of 3.66 m. The radial zones considered are 5 for the fuel pellet and 2 for the cladding. Each radial zone is further subdivided into 15 finer meshes for both materials. Additional data are reported in Table 4 [5]. The heights of the axial slices are calculated in order to have a 300mm-height slice at 1400 and 1800 mm from the rod bottom, i.e. at rodlet cuts. The rodlet models for the base irradiation considered a 300 mm rod length with 15 axial meshes, 20 mm long each. All the other geometrical and material characteristics were maintained.

The base irradiation simulations were performed choosing the standard option for the determination of the heat transfer coefficient α between fuel rod and coolant, which is calculated by the code starting from the coolant bulk temperature. Moreover, this flag considers the corrosion of the outer cladding in the evaluation of the α coefficient multiplying it by a correction factor $f_{corr}$ accounting for the oxide thickness (s) and its thermal conductivity ($\lambda_{ox}$) [3]:

$$f_{corr} = \frac{1}{\left(1 + s\frac{\alpha}{\lambda_{ox}}\right)}$$

The LOCA tests were carried out using the restart option available in TRANSURANUS. This was done in order to have appropriate parameters and variables as boundary conditions for the LOCA exercises. In particular, the option for the calculation of the α coefficients were changed and it was set to infinity, which implies that the outer cladding temperature is equal to the coolant temperature. In fact, this flag is more accurate for this part of the transient since the data available refer to the temperature measured by thermocouples clamped attached to the cladding. In addition, the total free volume was modified to increase the lower and upper plenum volume consistently with test data (see Table 5 [2]). Consequently, the total amount of gas in the free volume was enlarged and the filling gas composition was switched to 100% Argon. Besides, the rod internal pressure was set to 82 and 110 bar at 300 °C for test 192 and 191 respectively.

Finally, a dynamic model for Zr-based cladding crystallographic phase transition was activated and a cladding failure criterion as well. For the latter, overstress is assumed if the average true tangential stress is larger than the failure stress calculated by the material property function $\sigma_B$ [3]:

$$\sigma_B = a \cdot exp(-bT) \cdot exp\left[-\left(\frac{x - x_0}{0.095}\right)^2\right]$$

for $x \geq x_0$, where:

$\sigma_B$ = true tangential stress [MPa],
T = temperature in K,
x = actual oxygen concentration [g($O_2$)/g(Zr)],
$x_0$ = oxygen concentration at the initiation of the LOCA ($x0 \geq 0.0012$),
a,b = material constants.

This choice enables the large strain treatment of TRANSURANUS which is considered in the second term of the generalised flow law of the effective creep rate $\varepsilon$ (J=r, t, a) [3]:

$$\frac{d\varepsilon_j}{dt} = \frac{\partial\varepsilon_j}{\partial t} + \frac{\partial\varepsilon_j}{\partial R} \cdot \frac{\partial R}{\partial t}$$

It should be noted that no modifications were introduced in TRANSURANUS ("as received" use of the code has been tested).

Table 4 – Father rod data for the base irradiation. Reproduced from P. Raynaud, P.A.C., "NEC Studsvik LOCA test 192", 2014, MS Excel data file contributed to the IAEA CRP FUMAC on December 8, 2014, U.S. Nuclear Regulatory Commission, Washington, DC, USA.

| Parameter | Unit | Value |
|---|---|---|
| Rod ID | - | AM2 |
| Rod Type | - | Westinghouse 17x17 |
| Cladding Material | - | ZIRLO® |
| Reactor | - | North Anna Westinghouse 3-loops PWR |
| Coolant pressure | MPa | 15.5 |
| Coolant inlet temperature | K | 560 |
| Coolant mass flux | kg/s*m$^2$ | 3500 |
| Active fuel length | mm | 3657.6 |
| Cladding Outside Diameter | mm | 9.5 |
| Cladding Inside Diameter | mm | 8.36 |
| Gap width | mm | 0.57 |
| Pellet Diameter | mm | 8.19 |
| Pellet Length | mm | 9.82 |
| Rod Fill Gas | NA | He |
| Rod Fill Pressure | bar | 65 |
| Pellet Enrichment | wt% U235 | 4.95 |

Table 5 –Total free volume contributors for the rodlet domain in the LOCA apparatus. Reproduced from M. Helin, J. Flygare, "NRC LOCA tests at Studsvik: Design and construction of test train device and tests with unirradiated cladding material", 2012, Report STUDSVIK/N-11/130, Studsvik Nuclear AB, Studsvik, Sweden.

| Parameter | Unit | Value |
|---|---|---|
| Total Rod Free Volume | cm$^3$ | 10.4 |
| Upper Pressure Line Volume | cm$^3$ | 6.1 |
| Upper Plenum Volume | cm$^3$ | 1.2 |
| Lower Pressure Line Volume | cm$^3$ | 2.4 |
| Lower Plenum Volume | cm$^3$ | 0.7 |

## 4. Discussion of the results

### 4.1 Base irradiation results

Particular attention was dedicated to the base irradiation since it characterises the mechanical status of the cladding prior to the experiment. Besides, the verification of the consistency between the father rod and the rodlet data is crucial to produce significative results in the transient phase of the exercise that usually refers to a different rod geometry. Finally, the pre-transient hydrogen concentration is fundamental in the framework of the revision 10 CFR 50.46c to establish the correlation ECR-hydrogen content [1]. The results of the base irradiation obtained with TRANSURANUS simulations are summarised in Table 6.

For what concerns the hydrogen concentration, a pick-up fraction of 15.3% (as suggested in [6]) was considered. This led to a rodlet average value of 222 wppm, which is in agreement with the measured data for tests 192 and 191 (see Table 2). Oxide layer, burn-up and rod internal pressure values are congruent with the PIE data shown in Table 2 as well.

Table 6 – TRANSURANUS results of the base irradiation simulations.

| **Parameter** | **Unit** | **Test 191** | **Test 192** |
|---|---|---|---|
| Hydrogen | wppm | 222.8 | 222.8 |
| Oxide | µm | 28.19 | 28.19 |
| Father rod average burn-up | MWd/kgU | 69.316 | 68.158 |
| Average rodlet burn-up | MWd/kgU | 75.551 | 78.174 |
| Father rod internal pressure at 300 °C | bar | 94.2 | 91.4 |

### 4.2 LOCA tests results

The first phase of the transient was the pressure adjustment. This was necessary since the total free volume in the LOCA apparatus was greater than the rod one. A filling-gas injection system was present in the testing machine to reach the desired pressure value at a specified temperature. Therefore, the rodlet was kept at 300 °C for almost 15 min, obtaining, for the two cases, pressure values of 82.1 and 110.5 bar (see Table 7). During this phase, a steam flow of 11 g/min and a null LHR were used.

The transient history reported in Figure 2 was then applied to test rodlet 191. A heating rate of 5 °C/s was imposed until 1160 °C were reached and it was held at that temperature for 85 s, when the quenching phase started. Figure 3 compares the cladding radius calculated by TRANSURANUS at onset of cladding failure with the one measured post-test [4]. At this point, the diameter of the rod was 13.3 mm, which refers to a strain value of around 41% against a measured value of 50% after the transient.

Likewise, the transient history reported in Figure 1 was then applied to test rodlet 192. A heating rate of 5 °C/s was imposed until 1160 °C were reached and it was held at that temperature for 5 s. Figure 4 compares the cladding radius calculated by TRANSURANUS at onset of cladding failure with the one measured post-test [4]. At this point, the diameter of the rod was 13 mm, which refers to a strain value of around 40% against a measured value of 56% after the transient.

Table 7 – TRANSURANUS results for the transient simulations.

| **Parameter** | **Unit** | **Test 191** | **Test 192** | **Note** |
|---|---|---|---|---|
| Rodlet internal pressure at 300 °C | bar | 110.5 | 82.1 | p adjustment |
| Max strain at clad failure position | % | 45 | 40 | At onset of cladding failure |
| Maximum cladding diameter | mm | 13 | 13 | |

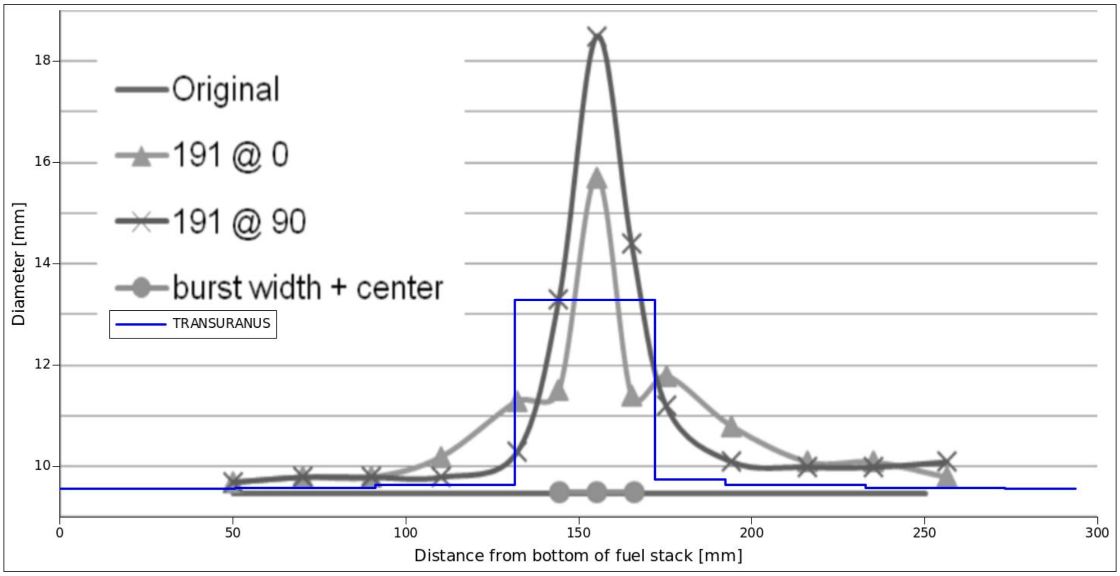

Figure 3 – Predicted diameter value by TRANSURANUS at onset of cladding failure compared to measured data after transient for test 191. Reproduced from M. E. Flanagan, P. Askeljung, A. Puranen, “Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory”, NUREG 2160.

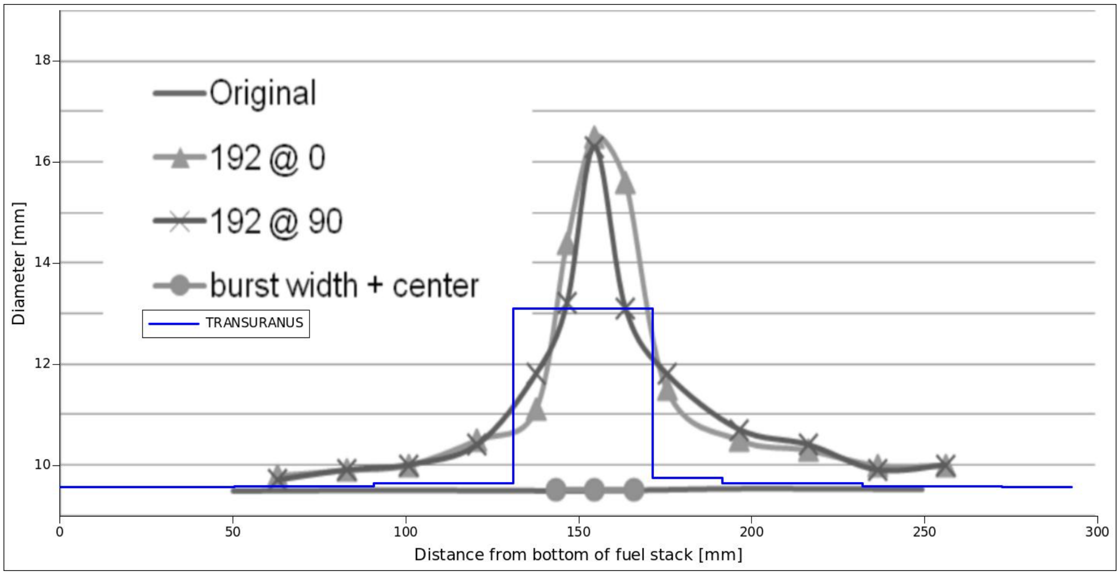

Figure 4 – Predicted diameter value by TRANSURANUS at onset of cladding failure compared to measured data after transient for test 192. Reproduced from M. E. Flanagan, P. Askeljung, A. Puranen, “Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory”, NUREG 2160.

## 5. Conclusions

The importance of hydrogen content on cladding embrittlement under LOCA conditions has become more and more important in the last years. The U.S. Nuclear Regulatory Commission is currently revising its regulatory criteria in 10 CFR 50.46c, “Acceptance criteria for emergency core cooling systems for light water nuclear power reactors,” to take it into consideration.

The purpose of this study was to simulate tests 192 and 191 concerning high burn-up fuelled rod segments, conducted at Studsvik, with the TRANSURANUS fuel performance code. Test 191 and 192 had been chosen as test cases (among those included in the test matrix) since they come from different father rods and have slightly different initial test conditions (e.g. internal pressure).

Two base irradiations were performed, one for the father rod and one for the rodlet, to obtain consistent results for both cases. The test was performed using the restart option of TRANSURANUS, in order to appropriately change the boundary conditions.

The results of the base irradiation simulations are in agreement with the measured data. The irradiation history has produced a rodlet average burn-up of 78.174 and 75.551 MWd/kgU for test 192 and 191 respectively (the equivalent father rod burn-ups are 68.158 and 69.316 MWd/kgU). The oxide thickness is around 28 $\mu$m in both cases and the hydrogen content is 222 wppm, calculated considering a pick-up fraction of 0.15 (average value for Zircaloy 4 in PWR).

Thanks to the pressure adjustments, the internal rodlet pressure was set at 82.1 and 110.5 bar for tests 192 and 191. TRANSURANUS code proved itself to be capable of simulating properly the LOCA exercises, predicting the failure characteristics and positions. In fact, at onset of cladding failure, the strain rate was between 40% and 50% and the deformed rodlet diameter was around 13.5 mm, which is quite consistent with the measured data.

Due to the growing importance of hydrogen content on cladding embrittlement under LOCA conditions, a model to predict H2 concentration in the cladding is under study for TRANSURANUS. As future developments, it is advisable to perform these exercises again once the model is ready.

## Acknowledgements

The authors gratefully acknowledge Dr Joakim Karlsson (Studsvik) and Dr Patrick Raynaud (NRC) for the suggestions, discussions and the useful materials provided.

## 6. References

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