1D and 2D analyses of the IFA-610 lift-off experiments with the fuel code ALCYONE

C. Bassi, J. Sercombe, B. Petitprez

1D and 2D analyses of the IFA-610 lift-off experiments with the fuel code ALCYONE

C. Bassi, J. Sercombe, B. Petitprez
CEA, DEN, DEC, F-13108 Saint-Paul-lez-Durance, France
(+33) 442 38 25, christophe.bassi@cea.fr

Abstract

This paper presents finite elements analyses of the lift-off experiments performed in the HALDEN reactor: IFA-610.3/.5 for UO_2-Zy4 fuel rods, IFA-610.2/.4 and IFA610.7 for MOX-Zy4 fuel rods. The 1D and 2D(r,θ) schemes of the multi-dimensional fuel performance code ALCYONE are both used to study the overpressure conditions leading to the onset of temperature increase in the experiments. The 1D scheme is based on a rather standard axisymmetric description of the complete fuel rod discretized axially in slices. The 2D(r,θ) scheme allows one to study the plane strain thermo-mechanical behaviour of a pellet fragment (usually 1/8th of the complete pellet) and its contact with the overlying cladding bore. It accounts explicitly for the additional free surface associated to pellet radial fractures and provides an estimation of the evolving pellet crack opening during loading sequences. In the proposed application to lift-off experiments, the impact of overpressure applied on the radial pellet crack borders has been studied.

In the first part of this paper, the main features of ALCYONE 1D and 2D(r,θ) modelling schemes are presented. In the second part, simulations of the lift-off experiments performed with the ALCYONE 1.4 release are presented (in particular this release allows changing the nature of the filling gas in order to assess its impact on the fuel thermal behaviour). Generally, for the lift-off experiments simulated with ALCYONE code 1D scheme, a rather good agreement is obtained between predicted and measured temperature evolutions and rod axial elongations, especially when a clad-pellet bonding hypothesis is retained. Since the same material models are used in 1D and 2D, a good agreement with the measured temperature is also obtained from the 2D simulations. It is however shown that the application of the overpressure on the radial pellet crack borders has a strong impact on the onset of pellet-clad gap re-opening. The resulting tangential stressing of the pellet fragment leads to radial fuel creep which tends to increase the external radius of the pellet and hence delay re-opening with respect to 1D simulations results. The "mechanical lift-off" is thus better estimated when the pellet fragmentation is considered in the simulations.

1. Introduction

Fission Gas Release (FGR) and the resulting rod internal pressure are important aspects of fuel behaviour and are therefore included in current fuel safety criteria. The first concerns the amount of FGR that accumulates in the rod free volumes. The main consequence of this release is a reduced thermal conductivity of the filling gas. If the gap has not been closed by fuel swelling, this causes the fuel temperature to rise, which in turn results in an increase of the release. Afterward, with further irradiation, a potential adverse thermal feedback condition may arise due to excessive fuel rod internal pressure. If the added gas causes the pressure to exceed the coolant pressure, the cladding "lifts off" the fuel, thereby increasing the gap size and its thermal resistance. An increase in the pellet-cladding gap will reduce the pellet-cladding thermal conductance thereby increasing fuel temperatures. This will then result in further fuel pellet FGR, greater fuel rod internal pressure, and correspondingly a faster rate of cladding creep-out and gap opening.

From safety point of view related to this topic, two alternative criteria for acceptable internal gas pressure are currently used in various countries by their regulatory authorities [1]. In the first option, the rod internal pressure is maintained below the nominal pressure in the Reactor Coolant System (RCS) during normal operation and incidental conditions in order to prevent outward creep of the cladding. In the second option, the rod internal pressure may exceed the RCS pressure, but is limited so that the cladding creep-out rate due to a greater internal rod pressure is not expected to exceed the fuel swelling rate (this is the so-called “no lift-off” criterion) [2].

The cladding lift-off experiments performed at HALDEN aim at providing data for the maximum pressure above system pressure to which a rod can be operated without causing a lasting fuel temperature increase [3]. The experiments carried out in IFA-610 (Instrumented Fuel Assembly) are performed with test rods containing UO_2 or MOX high burn-ups fuels pre-irradiated in commercial LWRs (to nearly 50-60 MWd/kg).

This paper presents Finite Elements (FE) analyses of the lift-off experiments performed in the HALDEN reactor: IFA-610.3/.5 for UO_2-Zy4 fuel rods, IFA-610.2/.4 and IFA610.7 for MOX-Zy4 fuel rods. The 1D and 2D(r,θ) schemes of the multi-dimensional fuel performance code ALCYONE that were both used to study the overpressure conditions are first presented in this paper. Then, after a short description of the test device and of the experimental conditions retained, the results of the calculations are presented and compared to the main results gathered on-line during the experiments performed at HALDEN.

2. The ALCYONE fuel code

ALCYONE is the multi-dimensional fuel code co-developed in the PLEIADES platform [4][5] for non-accidental [6] and accidental situations [7] by the CEA, EDF and AREVA. It incorporates three different calculation schemes which describe the thermo-mechanical behaviour of a complete fuel rod (1D axisymmetric) or that of a single fuel pellet fragment and overlying cladding (2D plane strain or 3D representation) during irradiation in commercial Light Water Reactors (LWR) or power ramps in experimental reactors.

2.1 General description of schemes and models

ALCYONE is a multi-dimensional application which consists of four different schemes concerned with:

- the complete fuel rod discretized in axial slices (1D), see Figure 1,
- half of the pellet and the overlying cladding (2D(r,z)), see Figure 2 where the Mid-Pellet (MP) plane is situated at the top of the mesh,
- one quarter of a pellet fragment and associated cladding (3D), see Figure 2, where the MP plane is situated at the top of the mesh,
- the MP plane of the 3D scheme as reference for the (2D(r,θ)), see Figure 2.

The different schemes use the same Finite Element (FE) code CAST3M to solve the thermo-mechanical pellet-gap-cladding problem and share the same physical material models at each node or integration points of the FE mesh. This makes the comparison of simulated results from one scheme to another possible with no dependency on the constitutive models.

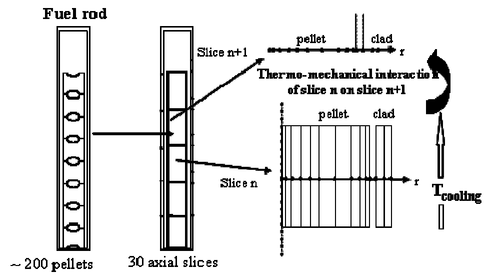

Figure 1: 1D scheme of ALCYONE modelling the complete fuel rod

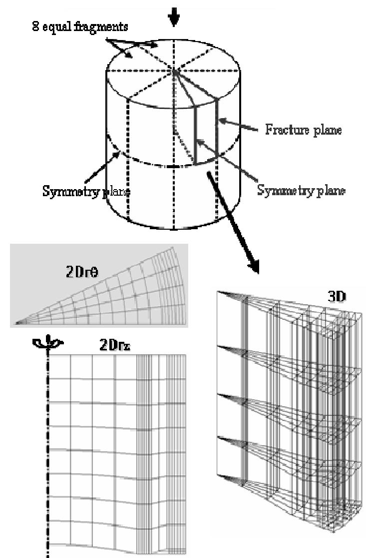

Figure 2: 2D and 3D schemes of ALCYONE modeling a pellet fragment and overlying cladding

The 1D scheme is based on a rather standard axisymmetric description of the complete fuel rod discretized axially in slices. The 2D(r,θ) scheme allows one to study the plane strain thermo-mechanical behaviour of a pellet fragment (usually 1/8th of the complete pellet) and its contact with the overlying cladding bore. It accounts explicitly for the additional free surface associated to pellet radial fractures and provides an estimation of the evolving pellet crack opening during loading sequences [8]. In the proposed application to lift-off experiments, the impact of overpressure applied on the radial pellet crack borders has been studied.

The main phenomena considered in the simulations are:

- Irradiation creep, thermal creep and plasticity of the cladding;
- Creep and cracking of the fuel pellet;
- Evolution of the thermal and mechanical properties of the materials with temperature, porosity and burn-up;
- Coupled thermo-mechanical analysis of the fuel pellet-gap-cladding system (the gap size depends on the deformation of the rod and on the FGR);
- Generation of, diffusion of FG in intra-granular, inter-granular and connected pores, release of FG in the plenum (internal pressure update);
- Pellet densification, pellet FG-induced swelling (stress-dependent);
- Relocation of pellet fragments after pellet cladding contact.

Performing 1D simulations of the complete fuel rod is a preliminary step before using the other schemes of ALCYONE simulations provide information on the FGR kinetics and hence on the internal pressure in the fuel rod, axial temperature and pressure distribution in the coolant, and also on clad elongation. ALCYONE 1D predictions in terms of axial clad profilometry, FGR or elongation are validated on experimental data concerning 200 base irradiations and 50 ramp tests performed on rods with UO_2, MOX or Cr-doped UO_2 fuels and Zy4 or M5® cladding tubes with mean burn-ups up to 80 MWd/kg [9].

2.2 Specificities regarding the lift-off tests simulation

As expressed above, 1D simulations of mother rods were performed in order to determine the conditioning state of the rod segments re-irradiated in the HALDEN reactor.

For the calculation of the lift-off tests with ALCYONE, some of the new features of the ALCYONE 1.4 were used. In particular, this new release allows the user to define, and eventually to modify during the irradiation, the nature and the pressure of the rod filling gas (it is worth noticing that in the following, the pellet-clad gap is free to reopen in the so-called “reference calculation”). Another point concerns the possibility to prescribe a strong mechanical bond when the pellet-clad gap is closed. This feature was implemented in order to simulate the potential bonding layer between the pellet and the clad that can be observed in fuel rods, irradiated at burn-ups exceeding 40 MWd/kg. In ALCYONE 1.4, a user-defined criterion based upon the maximum radial stress at the clad-pellet interface is implemented to simulate the potential breaking of the bonding layer (the radial stress limit equals 120 MPa in the simulations, roughly the tensile strength of UO_2).

The boundary conditions considered in the 2D calculations are shown in figure 3. They account for the geometrical symmetries of the problem and for the pellet-cladding interactions. Generalized plane strain conditions are assumed when solving the mechanical problem which allows modelling the out-of-plane stresses and strains. Concerning loading conditions, the internal rod pressure is applied to the cladding inner surface (green arrow) and to the pellet fragment outer surface (green arrow), and also to the radial fracture plane of the pellet (red line). In case of pellet-clad gap closing or radial fracture closing, the pressure boundary conditions are replaced by unilateral contact conditions (such as the constraint condition Uy = 0 on the pellet fracture plane). Note that the unilateral contact conditions can be applied on all or parts of the surfaces (partial closing of the gap or radial fracture). The external pressure (water pressure) is applied to the cladding outer surface.

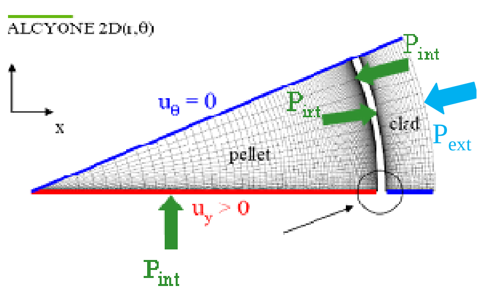

Figure 3: Mesh and boundary conditions in the 2D(r,θ) scheme used in the lift-off simulations with ALCYONE

To minimize the uncertainty of calculations associated with the input data, the measured and/or estimated (e.g. for Linear Heat Rate, LHR) test conditions were introduced as faithfully as possible. The following chapter recalls the main experimental conditions of the different lift-off tests that were retained to build ALCYONE input data files.

3. IFA-610 test design and experimental conditions

Usually, the fuel segments are re-fabricated in the IFE Kjeller hot cells and are equipped with a fuel thermocouple and a cladding extensometer. Gas lines are attached to the end plugs and connected for pressurisation of the rod (with helium at low overpressure, below +100 bar overpressure, or with argon at high overpressure, up to +500 bar). The low pressure system in helium is also used for hydraulic diameter measurements (see figure 4). The test rig is equipped with vanadium and cobalt neutron detectors for monitoring the axial flux distribution and rod power. An example of the axial power distribution estimated with the Helios code is provided in figure 4. The rod instrumentation is connected to a fast scanning system for noise measurements, which are performed at regular intervals during overpressure operation [3].

The in-pile pressure flask is surrounded by booster rods to provide a representative fast neutron flux in the test section. The test rig is connected to an outer loop operating under PWR conditions (pressure between 155 and 160 bar, inlet temperature of 310℃).

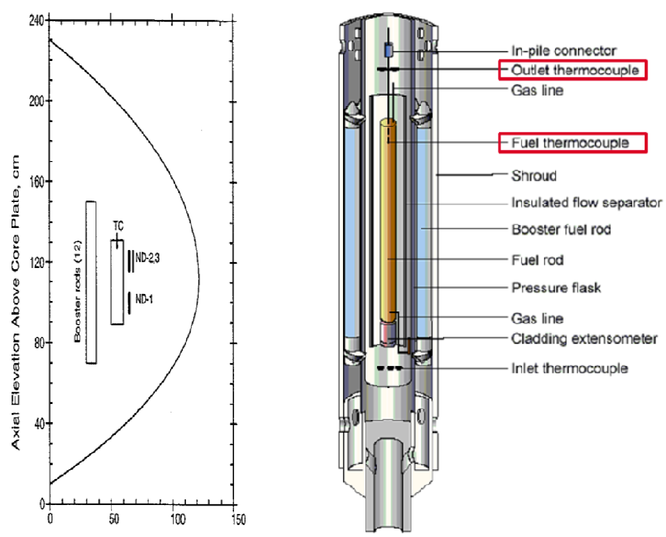

Figure 4: Axial flux distribution and layout of the irradiation rig

IFA-610.1 (UO_2):

The first lift-off test was performed from July 1997 with a UO_2 fuel segment that had been pre-irradiated during 4 cycles in the Gösgen PWR, up to a burn-up of 52 MWd/kgU [3]. The cladding material is zircaloy 4 (Zy4). The test was operated for two reactor cycles (around 4400 fph, full power hours) under representative PWR conditions. Different overpressure levels were achieved, from +50 bar (rod pressure around 210 bar) up to +300 bar, in successive steps of 50 bar. The rod was initially pressurised with argon, in order to simulate representative conditions of a gap filled with helium and released fission gas (the thermal conductivities being in the same order of magnitude).

IFA-610.2/.4 (MOX):

For the second lift-off test, a fuel segment prepared from MOX-MIMAS, provided by EdF was re-irradiated in the HALDEN reactor. This fuel segment was previously irradiated four cycles in the Gravelines 4 French PWR to a burn-up close to 50 MWd/kgU. The fuel rod (Zy4 cladded), re-fabricated and instrumented by IFE Kjeller, has been irradiated for about 1230 fph (IFA-610.2) to reach an average burn-up of 51,4 MWd/kgU [10] [11]. The rod was filled with helium during the first 93 fph. The pressurisation was continued with Argon to successive overpressure levels of +20, +75, +100, +150 and +175 bar. Because of a leakage detected in the device, the IFA-610.2 test was stopped. The fuel segment was then re-fabricated with a new set of instrumentation and new gas lines for a further re-irradiation lasting 2480 fph in the IFA-610.4 test [12]. The pressurisation began with helium for 20 fph and then was switched to argon lines for three successive overpressure levels of +20, +50 and +150 bar. After 1220 fph, during the +150 bar plateau, the thermocouple failed and the test was terminated with a +20 bar overpressure level. The figure 5 presents a simplified sketch of the test conditions, with regard to the linear heat rate at thermocouple position (TF) and rod overpressure.

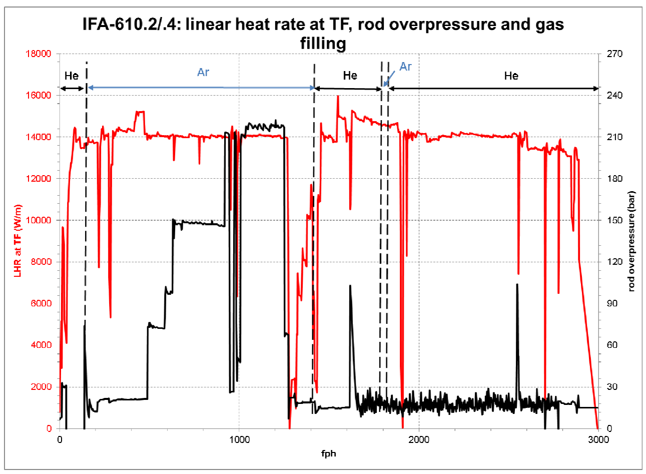

Figure 5: IFA-610.2/.4 power and overpressure histories

IFA-610.3/.5 (UO_2):

The third lift-off test was performed with a fuel segment provided by EdF and coming from a fuel rod that had been irradiated for five cycles in the Gravelines 5 PWR, to a burn-up of approximately 54 MWd/kgU. The cladding material is made of Zy4. After a re-fabrication and instrumentation setting made by IFA Kjeller, the fuel rod experienced 1860 fph in the HALDEN reactor [12]. The first step of overpressure at +50 bar revealed that the rod was leaktight and it was decided to reduce the overpressure at +20 bar with helium filling. As for the IFA-610.2/.4 tests, the rod was re-fabricated and experienced a further irradiation in the HALDEN reactor for about 2700 fph [13]. The overpressure level was increased stepwise (+30, +100, +175) to a final plateau of +175 bar that was sustained approximately for 2000 fph. It is worth to notice that at the midterm of the holding period with +175 bar (1575 fph after the beginning of the IFA-610.5 lift-off test), the average inlet coolant temperature was raised from 306 to 316℃ in order to assess the influence of this parameter on the cladding creep-out rate. Hereafter, in figure 6, are summarised the main conditions of this lift-off test.

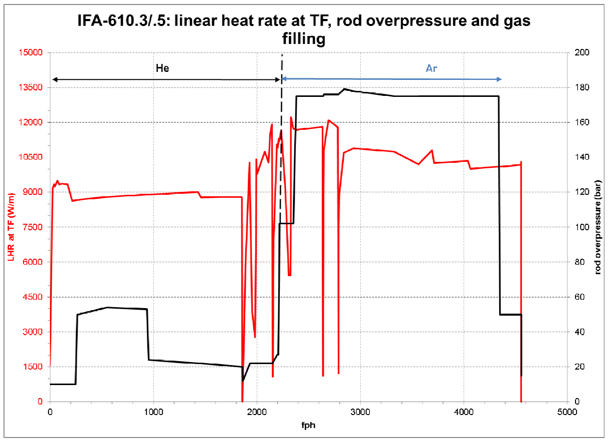

Figure 6: IFA-610.3/.5 power and overpressure histories

IFA-610.7 (MOX):

The last test of the IFA-610 lift-off series was completed with a fuel segment provided by EdF from a fuel rod that was pre-irradiated up to 50 MWd/kgU in the Gravelines 4 PWR [14]. This fuel segment came from the same fuel rod that was selected for the IFA-610.2/.4 test. The overpressure level was initially set to +150 bar and maintained for about 1000 fph with argon as filling gas. The overpressure was raised to +175 bar and then reduced to +40 bar. The re-irradiation lasted around 3100 fph (see Figure 7).

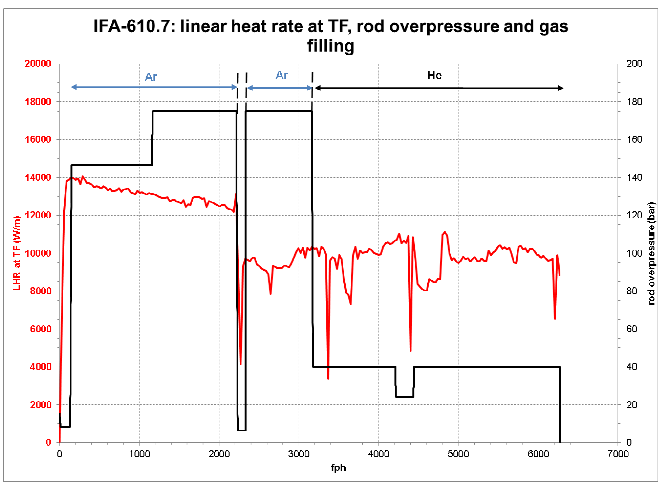

Figure 7: IFA-610.7 power and overpressure histories

4. Results of ALCYONE simulations

4.1 UO_2 fuel (IFA-610.3/.5)

In figure 8 is depicted the comparison of the measured and calculated temperatures in the hollow pellets (upper part of the UO_2 fuel rod) of the IFA-610.3/.5 lift-off test. Owing to ALCYONE 1.4 new features, the reference calculation (in green) is performed with the assumption that the test rod is pressurised with argon up to an overpressure above +100 bar. Knowing that argon has a thermal conductivity comparable to a mixture of original helium gas and FGR, it is worth noticing that the predicted temperature in the hollow pellets is overestimated by about 100K. During the high overpressure period (2300 to 4500 fph), the thickness of the gap between the pellet and the cladding is estimated to be between 1 and 4 µm in the reference calculation (see figure 9), leading to a temperature gradient in the gap of roughly 50-90 K (depending on the gap thickness as reported in figure 9).

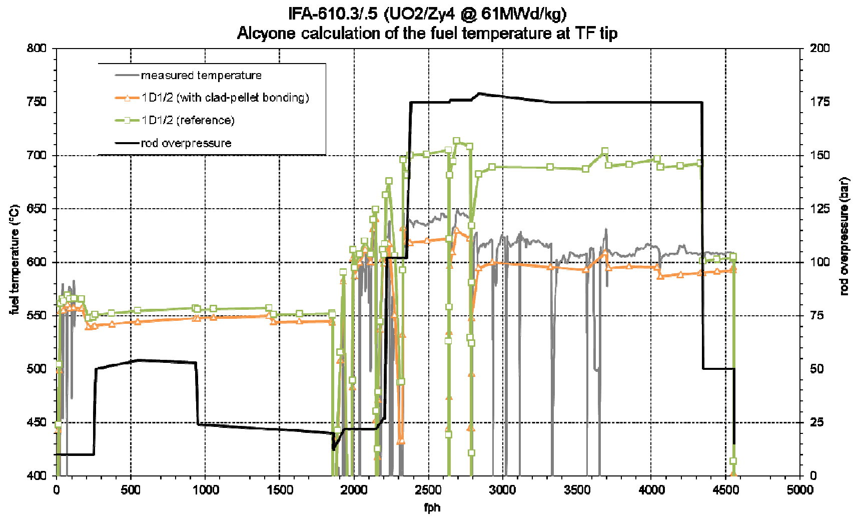

Figure 8: IFA-610.3/.5 temperature calculation with ALCYONE 1D scheme

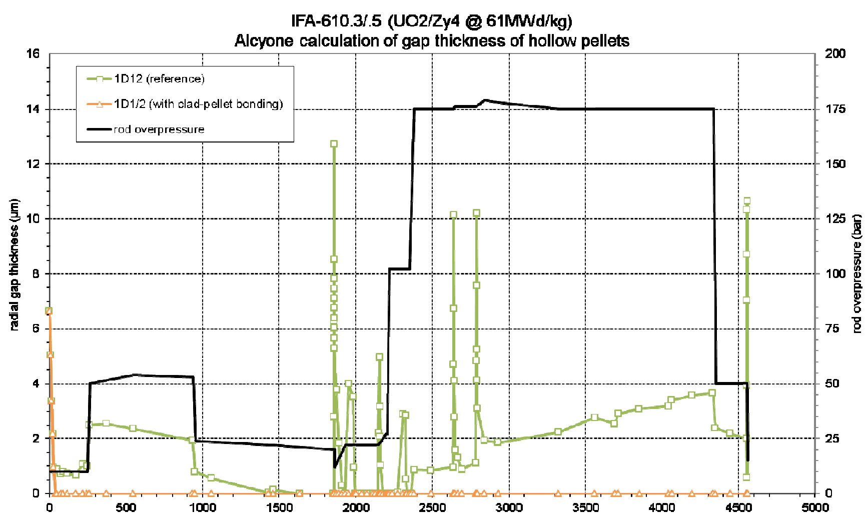

Figure 9: IFA-610.3/.5 gap thickness estimations

To check the importance of the small pellet-clad gap, a calculation was performed with the 1D scheme of ALCYONE assuming that bonding occurred in case of pellet-clad contact. The temperature estimation in the hollow pellets (in orange) reported in figure 8 exhibits that the bonding hypothesis leads to a rather good agreement with the measured temperature during the argon filling phase (underestimation below 20 K). Moreover, these ALCYONE calculations are clearly showing the impact of the filling gas on temperatures: when pure helium is used (IFA-610.3, up to 2200 fph), the calculated temperatures are very close whatever the gap thickness (above 2 µm for the reference calculation, 0 when clad-pellet bonding is simulated), owing to the rather good thermal conductivity of this gas. However, when argon is employed (IFA-610.5, form 2200 to 4600 fph), the temperatures differ even if the gap thickness is in the same order of magnitude as during the helium filling phase. This result should mean that no clad lift-off occurred under these experimental conditions owing to the fact that the measured temperature did not exhibit a “sharp” increase during the argon filling phase (at high overpressure level). This result is consistent with the ALCYONE calculation where re-opening of the pellet-clad did not occur (the radial stress at the pellet-clad interface never reached the 120 MPa limit).

ALCYONE calculations were also performed with the 2D(r,θ) scheme considering a solid pellet (the hollow pellet was not simulated). In figure 10 are depicted the pellet-cladding radial gaps estimated for the IFA-610.3/.5 lift-off test. These simulations were performed with helium only. In red is represented the gap thickness evolution with time during the 1D calculation. The reference 2D(r,θ) calculation (blue curves) differ significantly from the 1D estimates of the gap thickness. During the +175 MPa overpressure step, the 2D calculation does not give any increase of gap thickness. Another 2D calculation was then performed in which the pressure loading imposed as boundary condition on pellet cracks borders was suppressed (see the red line in Figure 3). The results, in orange in figure 10, are now consistent with the gap size provided by the 1D simulation.

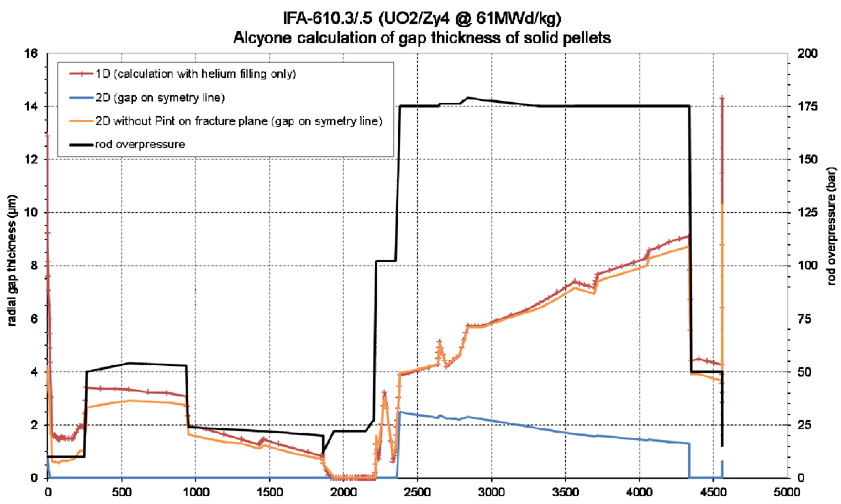

Figure 10: IFA-610.3/.5 gap thickness estimations with ALCYONE 2D scheme

These results show that the application of the overpressure on the radial pellet crack borders has a strong impact on the evolution of the pellet-clad gap. The additional loading of the pellet fragment induced by the pressurization of the crack borders leads to fuel creep that tends to increase the external radius of the pellet fragment and hence reduce the gap re-opening with respect to the 1D simulation of the complete pellet geometry. Figure 11 gives the calculated deformations of the pellet fragment with and without application of the overpressure on the crack border. In the first case, the radial crack is closed only at the pellet periphery owing to the important solid swelling of the rim. In the second case, the crack is closed everywhere along the radius.

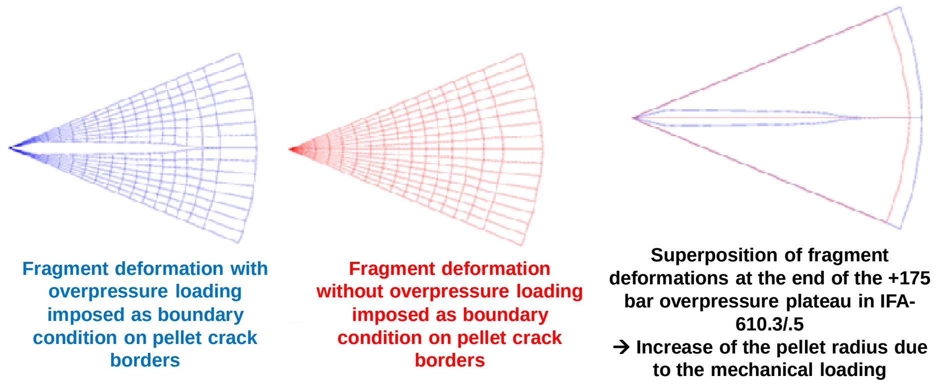

Figure 11: ALCYONE 2D(r,θ) pellet deformations with and without application of the overpressure on the radial crack

4.2 MOX fuel

4.2.1 IFA-610.2/.4

The IFA-610.2/.4 lift-off test was simulated with ALCYONE code using the 1D and 2D schemes. A description of MOX fuel as an homogeneous material was used in the calculations. During the IFA-610.2 test (up to 1300 fph), the overpressure was increased step-by-step from +20 to around +220 bar, and argon was mainly used as rod filling gas (see figure 5). The results were confronted to the temperature measurements gathered on-line during the experiment (see figure 12). For the 1D reference calculation (in blue), the maximum fuel temperature estimated in hollow pellets underestimates the measure by roughly 50K. However, an interesting point is related to the shape of fuel temperature evolutions during the IFA-610.2 test: the measured temperature decreases continuously during the irradiation. Knowing that the LHR at TF position was kept at nearly constant level close to 14 kW/m (see figure 5 providing results obtained by Helios calculations based on ND measurements), the expected trend would be a slight increase of the maximum fuel temperature owing to fuel thermal conductivity degradation with burn-up acquirement. In the ALCYONE calculation, the overpressure loading leads to an incremental increase of the gap thickness (see figure 13). Consequently a continuous increase of the maximum fuel temperature during IFA-610.2 (up to 1300 fph) is observed. This result is confirmed by 2D(r,θ) calculations of the solid pellets: temperature and gap thickness evolutions are similar in all calculations (1D and 2D).

When a pellet-clad bonding is considered, the trend is consistent with the measured temperature (see figure 12, results in orange), but ALCYONE gives a temperature level underestimated by around 150K (when the pellet-clad bonding is assumed, a perfect contact is considered between the pellet and the clad which tends to lower the fuel temperature compared to the reference calculation even if, in this latter case, the gap thickness is weak or null). However, owing to this large underestimation in comparison with the measure, it could be useful to investigate the accuracy of the LHR estimation at TF tip provided for the IFA-610.2 test.

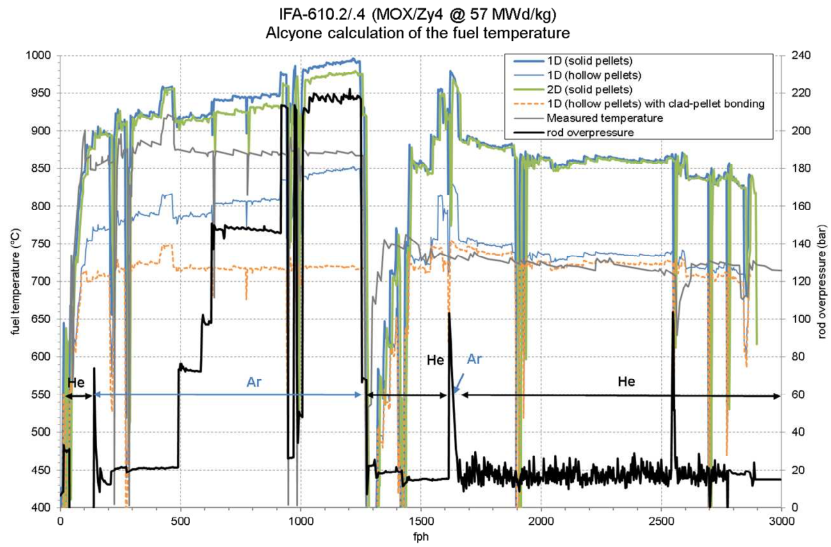

Figure 12: temperature history during IFA-610.2/.4 lift-off test

For the second phase of the lift-off test (IFA-610.4, from 1300 to around 3000 fph), and due to a malfunction in the high pressure argon filling line, helium was utilized and a small overpressure was applied to the fuel rod (close to +20 bar). As depicted in figure 12, the temperature evolutions with time are now consistent with the measure (differences are below 20 K all along the irradiation). Regarding the gap thickness estimation with ALCYONE (see figure 13), there are no significant discrepancies between 1D calculations (without or with clad-pellet bonding) owing to the low level of overpressure imposed: the gap remains closed or insignificantly opened to get noteworthy fuel temperature rise until the end of the test.

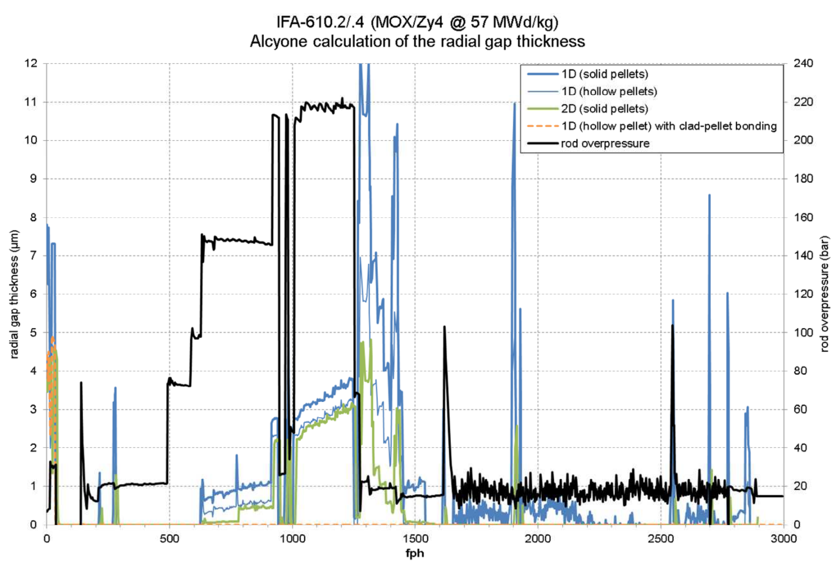

Figure 13: gap thickness evolutions during IFA-610.2/.4

4.2.2 IFA-610.7

Compared to the previous lift-off test for MOX fuel, the IFA-610.7 was performed by imposing a high level of overpressure at the beginning of the experiment. As reported in figure 7, during the first cycle of irradiation, an overpressure of +145 bar was maintained for almost 1000 fph and then increased to +175 bar under argon gas filling. During these two periods, the linear heat rate at TF position ranged from 14 to 12 kW/m.

As for the IFA-610.2/.4 test, the trend is showing a continuous decrease of the measured temperature, whatever the imposed overpressure level. This could be directly related to the decrease of the LHR during the first part of the test, even if the fuel thermal conductivity degradation will tend to counterbalance this decreasing LHR. ALCYONE 1D calculations for hollow pellets (at TF position) are providing results in accordance with the previous ones for IFA-610.2/.4: the maximum fuel temperature is increasing due to the pellet-clad gap opening when high-level overpressures are maintained for large duration (around 1000 fph). For the reference calculation, the calculation overestimates the measured temperature by 30 to 80K and the gap thickness ranges from 1 to 6 µm. Sensitivity studies, reported in figure 14 were also performed with ALCYONE to estimate the effect of the pellet and cladding roughness on the thermal gradient in the gap, as implemented in the URGAP model [15]. Then, clad-pellet bonding was considered in the calculation and it clearly lead to the same tendencies as reported for IFA-610.2/.4: when the gap is maintained closed, the decrease of the maximum fuel temperature is reproduced and the results are in good agreement with the measures (discrepancy below 20K at the end of the first cycle).

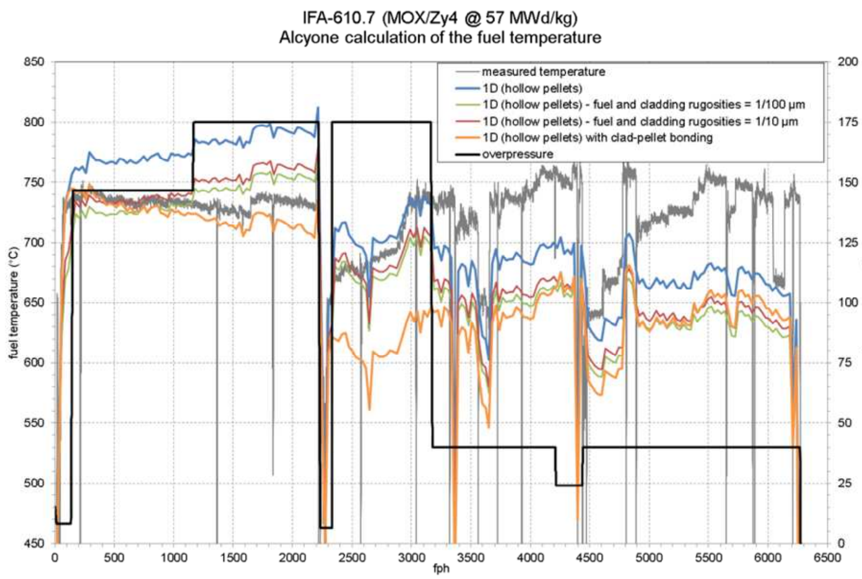

Figure 14: Fuel temperature history for IFA-610.7

During the second cycle of irradiation (from 2200 to 6300 fph), a high overpressure level of +175 bar was imposed and maintained for a long duration (around 700 fph) before switching to a helium gas filling at +40 bar till the end of the lift-off test. During the high overpressure plateau, the fuel temperature histories reported in figure 14 are now in good agreement with the measured temperature when the pellet-clad bonding is not prescribed. It obviously shows that gap re-opening took place during the very low overpressure period between the two reactor cycles. It is worth recalling that a pellet-clad bonding is maintained until a radial stress criterion of 120 MPa is reached. This clearly does not append in the simulation with ALCYONE. For the helium gas filling phase, the results gathered with ALCYONE are showing an underestimation by 50 to 100K of the measure. However, one can notice that the temperature evolution is well reproduced when a pellet-clad bonding is assumed. On the contrary, in the reference calculation where the pellet-clad gap is opened, the maximum fuel temperature is slightly decreasing. Then, it can be concluded that only a closed gap is able to furnish temperature evolutions as recorded during the lift-off test. Only at the beginning of the second reactor cycle, a gap re-opening seemed to occur (from 2200 to roughly 2300 fph).

In figure 15 is depicted the comparison of the gap evolutions assessed with 1D and 2D(r,θ) simulations. As for the previous calculations, discrepancies between their time evolutions are observed as the additional stressing of the pellet fragment due to the internal pressure in 2D leads to fuel creep that tends to increase the external radius and hence delay re-opening of the gap (see after 3200 fph for example) compared to 1D simulations results. When this boundary condition is suppressed, the results provided by ALCYONE 1D and 2D schemes are identical.

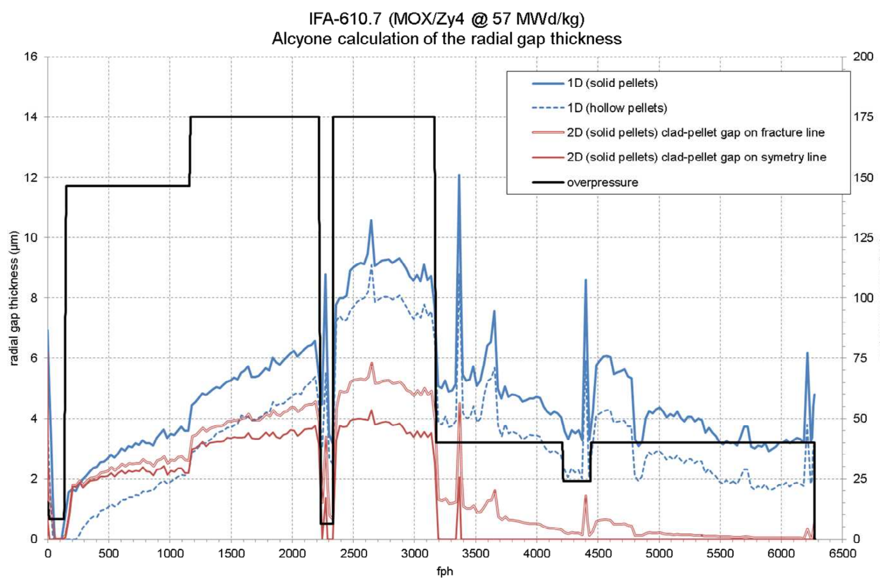

Figure 15: gap thickness estimations for IFA-610.7 (reference calculations)

Finally, 1D simulations of the IFA-610.7 can provide insights regarding the fuel and cladding elongations. In Figure 17 are drawn the calculated variations of fuel and cladding elongations with time, with or without clad-pellet bonding. For the reference case (in blue in figure 16), elongation of the fuel column and of the cladding are respectively consistent with LHR and overpressure variations. When clad-pellet bonding is considered (see orange curves), elongations of the two components are obviously correlated and their variations are more consistent with the measured cladding elongation. This result provides valuable insights regarding the accuracy of ALCYONE to characterise the whole fuel rod behaviour, in complement with more specific or local assessments

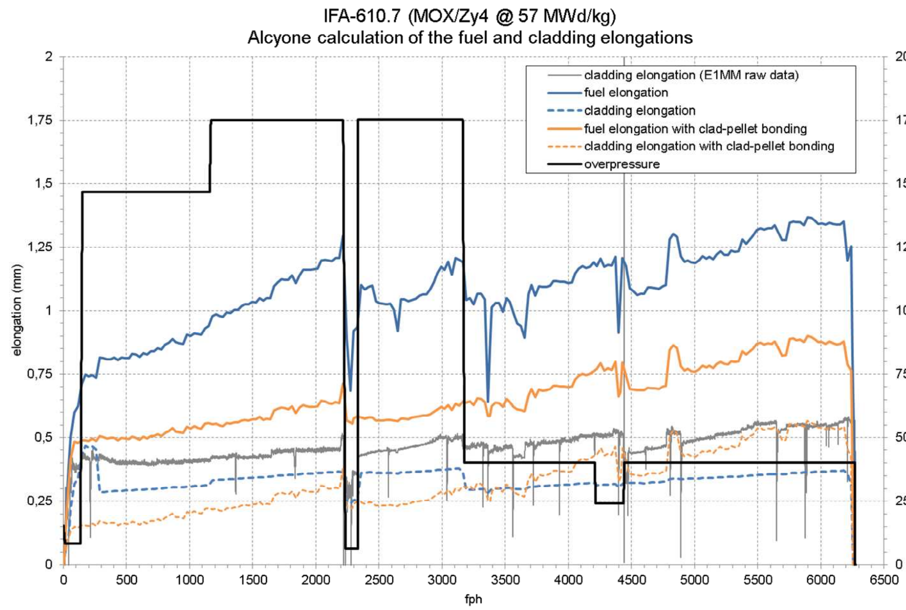

Figure 16: fuel and cladding elongations in IFA-610.7

5. Summary

In this paper, 1D and 2D(r,θ) simulations of lift-off experiments performed in the HALDEN reactor have been presented. The new functionalities of ALCYONE 1.4 release have been employed in order to acquire knowledge regarding the impact of the gas filling nature and of the overpressure, and also of the potential clad-pellet bonding, on fuel temperature evolutions ("thermal lift-off") and gap thickness ("mechanical lift-off"). The different modelling schemes and models of ALCYONE, combined with the validation on a wide range of burn-ups that comes from its extensive use over the last years, make it now a powerful simulation tool for interpreting or defining experimental tests for industrial application purposes.

Specifically, for the lift-off experiments simulated with ALCYONE 1D scheme, a rather good agreement is obtained between predicted and measured temperature evolutions and rod axial elongations when a clad-pellet bonding hypothesis is retained. Since the same material models are used in 1D and 2D, a good agreement with the measured temperature is also obtained from the 2D simulations. It is however shown that the application of the overpressure on the radial pellet crack borders has a strong impact on the onset of pellet-clad gap re-opening. The resulting additional stressing of the pellet fragment leads to fuel creep that tends to increase the external radius of the pellet and hence delay re-opening with respect to 1D simulations. The "mechanical lift-off" is thus better estimated when the pellet fragmentation observed prior to the test is considered in the simulations.

Perspectives for ALCYONE could be now to improve modelling of the kinetics of gap re-opening due to bounding conditions at the pellet-clad interface, thus providing more confidence in the simulation of some lift-off tests.

Acknowledgements

The authors would like to thank EDF and AREVA for their financial and technical support to this research.

M5® is a trademark of AREVA-NP

References

[1] Nuclear Fuel Safety Criteria (second edition) – NEA OECD 2012

[2] B. Petitprez, B. Delhaye, and S. Béguin, “”No clad lift-off” criterion and associated methodology developed by EDF and Framatome-ANP on the basis of IFA-610 experiments”, EHPG meeting, Lillehammer, October 2005

[3] W. Wiesenack, T. Tverberg, M. Mc Grath, E. Kolstad and S. Béguin, “Rod overpressure / lift-off testing at Halden - In-pile data and analysis”, *Journal of Nuclear Science and Technology*, 43, n°9, p1037-1044 (2006)

[4] B. Michel, C. Nonon, J. Sercombe, F. Michel and V. Marelle, “Simulation of Pellet-Cladding Interaction with the PLEIADES fuel performance software environment”, Nuclear Technology, In Press

[5] V. Marelle, J. Sercombe, B. Michel and R. Tawizgant, “Thermo-mechanical modelling of PWR fuel with ALCYONE”, Proceedings of the 2011 Water Reactor Fuel Performance Meeting, Chengdu, China, September 2011

[6] J. Sercombe, J. Julien, F. Michel, B. Michel and E. Fédérici, “3D modelling of strain concentration due to PCI within the fuel code ALCYONE”, Proceedings of Top Fuel 2013, Charlotte, NC USA, September 2013

[7] J. Sercombe, E. Fédérici, M. Le Saux, B. Michel and C. Poussard, “1D and 3D modelling of PCMI during a RIA with ALCYONE V1.1”, Top Fuel 2010, Orlando, September 2010

[8] J. Sercombe, R. Masson and T. Helfer “Stress concentration during pellet cladding interaction: Comparison of closed-form solutions with 2D(r,θ) finite element simulations. *Nuclear Engineering and Design, 260*, 175-187, 2013

[9] C. Struzik and V. Marelle, “Validation of fuel performance CEA code ALCYONE, scheme 1D, on extensive database”, Proceedings of Top Fuel 2012, Manchester, UK, September 2012

[10] S. Béguin, “The lift-off experiment with MOX fuel rod in IFA-610.2 - Initial results”, HWR-603, April 1999

[11] C. Jean and E. Muller, “The lift-off experiment with MOX fuel in IFA-610.2 - Results of the second cycle”, HWR-620, December 1999

[12] H. Fujii and J. Claudel, “The lift-off experiments, IFA-610.3 (UO2), and IFA-610.4 (MOX) - Evaluation of in-pile measurement data”, HWR-650, February 2001

[13] T. Sugiyama, “The lift-off experiment IFA-610.5 with UO2 fuel rod - Evaluation of in-pile results”, HWR-713, July 2002

[14] L. Klecka, “The lift-off experiment IFA-610.7 with high burn-up PWR MOX fuel rod - In-pile results from 3-cycles irradiation”, HWR-814, December 2006

[15] K. Lassmann and F. Hohlefeld, “The revised URGAP model to describe the gap conductance between fuel and cladding”, *Nuclear Eng. and Design*, 103, 215-221 (1987)