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MODELLING AXIAL RELOCATION OF FRAGMENTED FUEL PELLETS INSIDE BALLOONED CLADDING TUBES AND ITS EFFECTS ON LWR FUEL ROD FAILURE BEHAVIOUR DURING LOCA

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ABSTRACT

Downward axial relocation of fuel pellet fragments may occur when overheated and internally overpressurized cladding tubes of light water reactor fuel rods distend due to creep during a loss-of-coolant accident (LOCA). The relocation is of safety concern, since it changes the axial distribution of heat load along the rod and also has the potential to increase the amount of fuel material dispersed into the reactor coolant, should the cladding fail. Here, we present a computational model that calculates the fuel relocation on the basis of estimated fuel fragment size distributions and the calculated cladding distension along the fuel rod. The model has been implemented and fully integrated with the FRAPTRAN-1.5 computer program, such that thermal feedback effects of fuel relocation on the axial redistribution of fuel mass, stored heat and power are accounted for in FRAPTRAN's calculations of the fuel rod thermo-mechanical behaviour. The model has been validated against the IFA-650.4 integral LOCA test in the Halden reactor, Norway, which was done on a very high burnup UO_2 fuel rodlet and resulted in extensive fuel pellet pulverization, axial relocation and dispersal into the coolant. Our simulations of this test suggest that thermal feedback effects from axial fuel relocation are strong enough to significantly affect the dynamics of cladding ballooning and rupture, in spite of the short duration of these processes. Moreover, for the considered LOCA test, the axial relocation has a strong effect on the calculated peak cladding temperature and oxidation after rupture.

INTRODUCTION

Over the last decade, integral LOCA tests on high burnup light water reactor (LWR) fuel rods have been carried out in Halden, Norway, and Studsvik, Sweden (Kolstad et al., 2011, Flanagan et al., 2013). The results of these tests have revived interest in the phenomena of fuel pellet fragmentation and subsequent axial relocation and dispersion of fuel fragments into the primary reactor coolant upon cladding failure. The downward axial relocation of fuel fragments, which is mainly driven by gravity, occurs when the overheated and internally overpressurized cladding tube distends due to creep. The fuel relocation is of safety concern, since it may localize the heat load to "ballooned" parts of the rod, thereby increasing the risk for cladding failure and aggravating local oxidation. It may also increase the amount of fuel dispersed into the coolant, should the cladding fail. Fuel fragmentation, axial relocation and dispersal were observed already in the early 1980s, when in-reactor experiments on fuel rod behaviour during LOCA were carried out on low to medium burnup (< 35 MWd/kgU) test rods (Karb et al., 1983, Broughton et al., 1981), but the more recent tests suggest that the phenomena are more pronounced for high burnup fuel. This is related to the fact that high burnup fuel may "pulverize" into very fine (< 0.2 mm) fragments when the fuel is overheated during LOCA (Turnbull et al., 2014). The fine fragments have a higher potential for axial relocation and subsequent dispersal into the coolant than the fairly large (> 1 mm) fragments that are typically observed in LOCA tests on low to medium burnup fuel. This has been identified as a high burnup fuel issue by regulators (Wiesenack, 2010, Raynaud, 2012). In comparison with the 1980s, the regulatory focus has somewhat shifted from the effects of fuel relocation on the local heat load to its effects on fuel dispersal upon cladding rupture. The fuel dispersal is a potential issue with regard to energetic fuel-coolant interaction, radiological consequences, criticality and long-term coolability of the material ejected into the coolant.

To our best knowledge, the first computational model for axial fuel relocation was presented at the 1983 SMiRT conference by Siefken (Siefken, 1983). This model, which was implemented in the SCDAP computer program for severe accident analyses, was based on experimental results and data available at that time. Since then, along with the more recent LOCA tests on high burnup fuel, various computational models for fuel relocation have been proposed and used for evaluations of the tests (Aounallah et al., 2006, Khvostov et al., 2007, Govers and Verwerft, 2014). A common feature of these later models is that they are used as post-processors to computer programs for thermo-mechanical analyses of fuel rods: the cladding distension along the fuel rod during the LOCA is calculated with these programs and used as input to subsequent calculations of fuel relocation. However, the relocation models are not integrated with the computer programs, which means that effects of fuel relocation on the axial redistribution of stored heat and power are not accounted for in the thermo-mechanical analyses of the rod. The reason for this lack of integration can be understood from the typical “1 ½ D” computational approach used in fuel rod analysis programs (Lassmann and van Uffelen, 2004). The term alludes to the fact that most computer programs of this kind represent the fuel rod by a stack of axial segments, and that the heat transfer and deformations in each segment are calculated by solving one-dimensional (radial) equations. Axial interaction between the segments is merely by coolant heat transfer, a common internal fuel rod gas pressure, and possibly axial forces from pellet-cladding mechanical interaction. Adding axial fuel relocation to these programs is nontrivial, since the relocation introduces a significant interaction between the axial segments with regard to the fuel rod temperature calculations. In addition, the temperature calculations in fuel rod analysis programs are done on the basis of a geometrical configuration with cylindrical fuel pellets surrounded by an annular, gas-filled, pellet-cladding gap. These conditions do not apply when axial fuel relocation occurs, since the cylindrical pellets collapse into a porous particle bed with crumbled fuel in ballooned regions of the fuel rod.

In this work, we present a relocation model that is fully integrated with the FRAPTRAN-1.5 fuel rod analysis program (Geelhood et al., 2014). Hence, in contrast to hitherto presented relocation models for fuel rod analysis programs, the model considers thermal feedback effects from the fuel relocation. It also uses submodels to calculate the packing fraction and effective thermal conductivity of particle beds formed by crumbled fuel in ballooned regions of the fuel rod, based on the estimated state of fragmentation and pulverization of the fuel pellets.

MODEL DESCRIPTION

Our model is based on two postulated prerequisites for axial fuel relocation. Firstly, a sufficient pellet-cladding gap is required for fuel fragments to detach from the surrounding cladding and move downward. This threshold radial gap size, g^{th}, is set to 0.2 mm in our model, based on results from recent LOCA simulation experiments in Studsvik, Sweden, and Halden, Norway. Post-test examinations of test rodlets used in these experiments show that the local cladding hoop strain must exceed about 5 % to allow fuel fragment separation and axial movement (Raynaud, 2012, Oberländer and Wiesenack, 2014). No observable dependence on fuel pellet burnup is reported for this threshold strain over the investigated burnup range (44–92 MWd/kgU). The threshold pellet-cladding gap size used in our model corresponds to a cladding hoop strain of about 4.5–5.0 %, depending on the cladding tube dimensions. More experimental data are needed to determine whether the threshold gap size g^{th} depends on fuel burnup or any other parameter, e.g. the axial gradient in internal gas pressure.

Secondly, the cladding distension along at least one axial segment of the discretized fuel rod must be sufficient to accommodate relocated fuel fragments in a disordered (crumbled) configuration, which is assumed to contain a lot more void volume than the original, pellet-like configuration. In a specific axial segment of the fuel rod, henceforth referred to by subscript *k*, the fuel configuration is defined by the packing fraction of fuel fragments,

$$\phi_k = V_k^f / V_k \ . \tag{1}$$

Here, V_k^f is the volume occupied by fuel fragments and V_k is the total volume enclosed by the cladding tube in the k:th segment. In an axial segment of length L_k, this volume is $V_k = \pi L_k R_{cik}^2$, where R_{cik} is the cladding inner radius. Under normal reactor operation, ϕ_k is close to unity, since the fuel fragments are then densely packed and retained in the original, cylindrical configuration of the pellets, where the void volume is made up essentially of pellet dishes, cracks and possibly a narrow pellet-cladding gap. When the cladding tube distends under LOCA, the gap gradually widens and may reach a size that makes the fuel pellet column collapse. The fuel fragments then move radially outward and turn into a disordered pattern with ϕ_k significantly lower than unity. Here, we make the assumption that local collapse of the fuel pellet column in an axial segment occurs when more fuel can be accommodated in a crumbled configuration than in the original, pellet-like, configuration. This condition on fuel pellet column collapse can be written as

$$m_k^M > m_k^i , \tag{2}$$

where $m_k^M = \phi_k \rho_f V_k$, with ρ_f being the density of the fuel material, is the fuel mass in the k:th axial segment in case it is completely filled with crumbled fuel, and m_k^i is the initial (as-fabricated) fuel mass in the segment. We treat the packing fraction of crumbled fuel as a model parameter, which is correlated to the fragment size distribution. More specifically, we assume that the crumbled fuel consists of two different size classes of fragments: The first class includes large (> 1 mm) fragments, created by thermal stresses in the fuel during normal operation, whereas the second class comprises fine (< 0.2 mm) fragments, created during the LOCA by overheating high burnup fuel. The second fragment class thus exists only in high burnup fuel after overheating, and a recently proposed empirical "pulverization threshold" (Turnbull et al., 2014) is in our model used for estimating the mass fraction of small fuel fragments, based on the calculated distributions of burnup and temperature in the fuel. The fine fuel fragments are important, since they may effectively fill up voids between the mm-size fragments and thereby significantly increase the overall fragment packing fraction. This is illustrated in Fig. 1, which shows the calculated fuel fragment packing fraction of crumbled fuel versus the relative amount of small fragments, assuming four different sizes for the large fragments. The methods used for calculating ϕ_k from the estimated state of fuel fragmentation and pulverization are described in (Jernkvist et al., 2015, Jernkvist and Massih, 2015).

The condition defined by Equation (2) will preclude axial relocation until the cladding tube in some axial segment reaches a threshold deformation, roughly given by $\phi_k R_{cik}^2(t) \approx R_{cik}^2(0)$, where the right-hand-side quantity is the as-fabricated cladding inner radius. In terms of cladding hoop logarithmic (true) strain, $\varepsilon_{\theta\theta}(t) \approx \ln(R_{cik}(t)/R_{cik}(0))$, the condition in Equation (2) can thus be written

$$\varepsilon_{\theta\theta}(t) > \varepsilon_{\theta\theta}^{th}(t) \approx -\ln(\phi_k)/2 , \tag{3}$$

where $\varepsilon_{\theta\theta}^{th}$ can be interpreted as a cladding threshold strain (logarithmic) for fuel pellet column collapse and onset of fuel fragment relocation. This threshold strain is plotted in Fig. 2. It is clear that it is sensitive to the value assumed for the packing fraction of crumbled fuel.

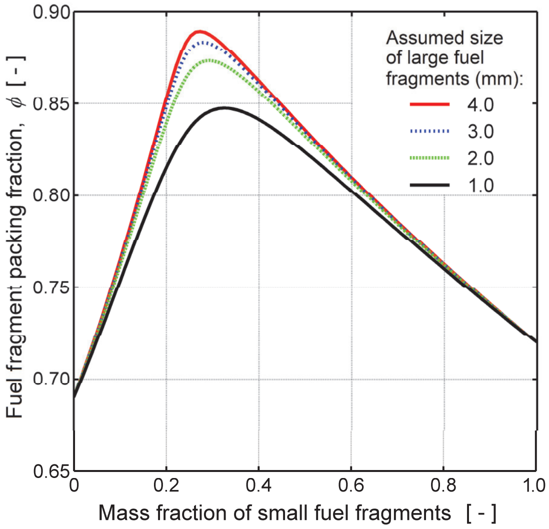

Fig. 1: Calculated packing fraction of crumbled fuel vs. relative amount of small fragments from pulverized high burnup fuel.

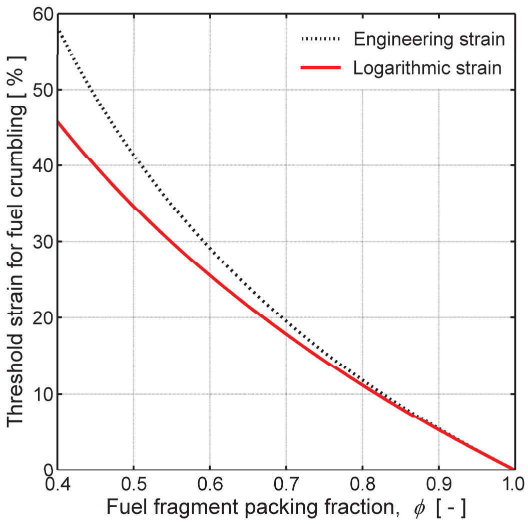

Fig. 2: Cladding threshold strain for fuel pellet column collapse and onset of axial fuel relocation, calculated through Equation (3).

The axial fuel relocation is calculated by a fairly simple algorithm, which comprises two loops over the N axial segments of the discretized fuel rod; see Fig. 3. Henceforth, the segment numbering is assumed to run bottom-up, and subscript k refers to the k:th segment from the bottom. We consider a time step that starts at time t_o, and assume that the fuel mass in each axial segment is known for this point in time. This mass is henceforth denoted m_k^o, whereas m_k denotes the sought fuel mass at end of the time step. In the first loop, the aforementioned requirement on a minimum pellet-cladding gap size for fuel mobility is used for calculating the amount of fuel, m_k^r, that each axial segment may receive from higher elevation segments. All fuel in an axial segment, except for a small residual fraction x^r, is allowed to fall down if $g_k > g_k^{th}$. The residual fraction represents small fuel fragments that are bonded to the cladding inner surface. Next, the condition from Equation (2) is applied in the second loop to "fill" ballooned axial segments, according to the calculated crumbled fuel packing fraction and cladding deformation that applies to the segment. Filling is possible only if sufficient moveable fuel is available above the segment, as determined in the first loop. Conditions are also imposed so that the total fuel mass in the rod is conserved and upward relocation precluded. The upper and lower limits for the sought end-of-timestep fuel mass m_k in Fig. 3 are given by

$$m_k^L = \sum_{j=1}^{k} m_j^o - \sum_{j=1}^{k-1} m_j \, , \tag{4}$$

$$m_k^U = m_k^r + \sum_{j=1}^{k} m_j^o - \sum_{j=1}^{k-1} m_j \, . \tag{5}$$

The cladding deformation, calculated with FRAPTRAN-1.5, is essential input to both loops in Fig. 3, and the relocation model is applied at the end of each time step taken by FRAPTRAN. The calculated results from the relocation model are used by FRAPTRAN for modifying the fuel rod temperature calculations in the next time step. Firstly, the changes caused by fuel relocation on the axial distributions of fuel mass, stored heat and power along the fuel rod are accounted for. Secondly, when the fuel pellet column collapses in ballooned segments of the fuel rod, we consider the changes in geometrical configuration as well as effective material properties. The pellet-cladding gap is significantly reduced, while gas-filled voids open up between the disorderly stacked fuel fragments. Since the volume fraction of gas is typically 20–30 %, the macroscopic thermal conductivity of the crumbled fuel in the balloon may be much lower than that of solid fuel material. This conductivity degradation is accounted for in our model (Jernkvist and Massih, 2015).

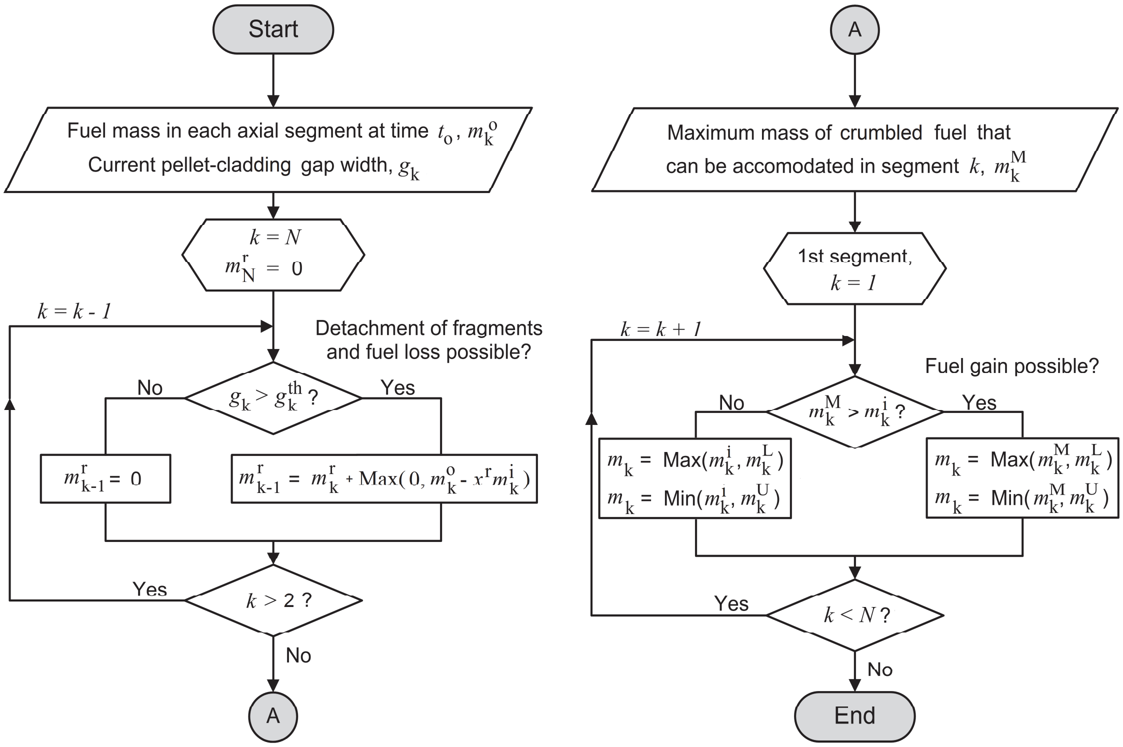

Fig. 3: Computational algorithm. First loop over the N axial segments determines mass of relocatable fuel, m_k^r. Second loop updates local fuel mass, m_k. All variables are defined in the running text.

MODEL VERIFICATION AND VALIDATION

Model Verification

The correctness of the computational algorithm in Fig. 3 has been verified by applying the relocation model to several test cases (Jernkvist and Massih, 2015). For illustration, we consider here a test case, in which a hypothetical axial profile for the cladding deformation is prescribed along a full-length fuel rod and the resulting fuel relocation is calculated as a function of time as the cladding distension is postulated to increase. The active length of the fuel rod is assumed to be 3.60 m, and the fuel pellet diameter is 9.0 mm. The fuel is assumed to be in a state such that a fragment packing fraction of 0.75 is obtained after fuel crumbling. For simplicity, this packing fraction is presumed to be independent of space and time. The fuel rod is discretized into 36 equal-length axial segments, and the prescribed cladding deformation is defined by

$$R_{ci}(t,z) \quad = \quad 4.5\times10^{-3} \; + \; 2.0\times10^{-5}\, t \left| \, \sin(2\pi\, z \,/\, L_a) \, \right|, \tag{6}$$

where R_{ci} is the inner radius of the cladding and z/L_a is the relative position along the active length (L_a) of the fuel rod. The time t is in units of seconds. The cladding deformation (evolution of R_{ci}) is shown by the solid black line in the upper panel of Fig. 4. The dotted red line in the same panel refers to the calculated fuel pellet radius. From this line, it is easily seen where the cladding deformation is large enough for collapse of the fuel pellet column to occur, i.e. where the condition $m_k^M > m_k^i$ is satisfied.

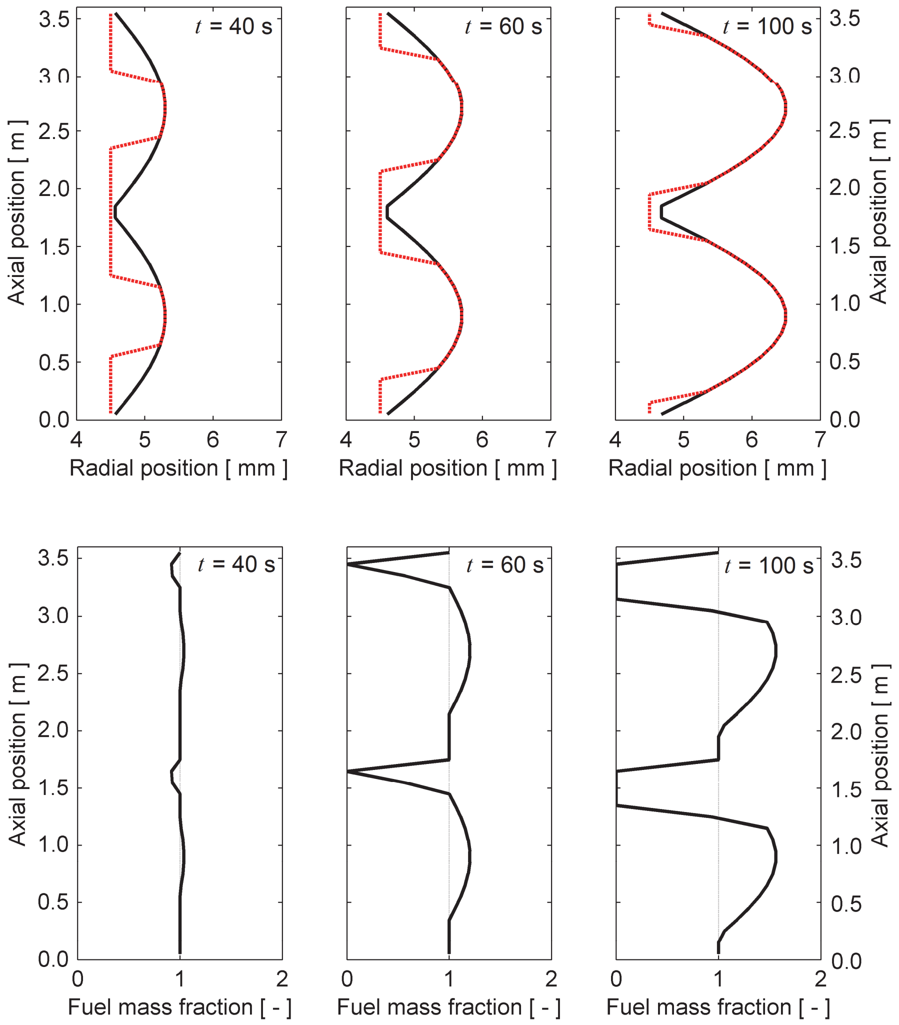

Fig. 4: Top panel shows deformation pattern. Solid black line: Cladding inner radius, as defined by Equation (6). Dotted red line: Calculated fuel pellet radius, indicating regions where collapse of the fuel pellet column may occur. Bottom panel shows calculated space-time variation in fuel mass.

The lower panel of Fig. 4 shows the axial fuel relocation that results from the postulated cladding deformation, presented in terms of calculated fuel mass fraction (local ratio of current mass to initial mass, m_k / m_k^i). At $t = 36$ s, the fuel pellet column collapses at the most distended cross sections of the rod and fuel starts to relocate independently and concurrently into the upper and lower balloon. There is a plug of immobile fuel fragments at the fuel rod mid-plane, where the cladding deformation is insufficient for the fuel fragments to detach from their original positions. The plug blocks any axial relocation of fuel fragments from the upper to the lower balloon. This kind of constraint may be expected at spacer grids in LWR fuel assemblies. We also note that for $t < 60$ s, there exist regions with invariant fuel mass fraction, located between the balloons and the axial segments from which fuel fragments are lost. In these regions, fuel moves downward without causing any net change of local fuel mass; the fuel just passes by on its way down, virtually in its original pellet-like configuration. This behaviour is confirmed by experiments (Oberländer and Wiesenack, 2014).

Model Validation Against the Halden IFA-650.4 LOCA Test

The Halden IFA-650.4 LOCA test was conducted on a 480 mm active length rodlet that had been sampled from a full length UO_2 fuel rod with Duplex-type Zircaloy-4 cladding after seven reactor cycles of operation in a commercial pressurized water reactor. The test is well suited for model validation, since it was carried out on an extensively instrumented fuel rodlet with very high fuel burnup (92.3 MWd/kgU) and resulted in cladding ballooning and burst, as well as significant axial fuel relocation and dispersal of pulverized fuel into the coolant. The IFA-650 test rig and typical testing procedures are described in (Wiesenack, 2013, Kolstad et al., 2011). In short, the test rodlet is instrumented and placed in the centre of the rig, which in turn is placed in one of the experimental channels of the Halden test reactor. The rodlet is surrounded by an electrically heated shroud and a pressure flask. The latter is connected to a water loop that may be depressurized into a large blowdown tank to simulate a LOCA. During most of the IFA-650.4 test, the linear heat generation rates of the rodlet and heater were held nearly constant at about 1.0 and 1.5 kW/m, respectively. The test was terminated by reactor scram 617 s after initiation of blowdown, which defines the starting point of the test (henceforth referred to as $t = 0$). Cladding rupture was detected at $t = 336$ s.

The first 500 seconds of the IFA-650.4 LOCA test were modelled with our extended version of FRAPTRAN-1.5. Since the power was held constant during this period and no water was sprayed into the test rig, the thermo-hydraulic boundary conditions for the rodlet were fairly simple and could be derived from temperatures and pressures measured in different parts of the test rig; details on the methodology are given in (Jernkvist and Massih, 2015). The initial conditions of the rodlet were determined by modelling the pre-test operating life of the fuel rod sample by use of the FRAPCON-3.5 program (Geelhood and Luscher, 2014). Based on the fuel operating life, the packing fraction of crumbled fuel is expected to be 0.72 in ballooned regions of the test rodlet. It should be noted that our extended version of FRAPTRAN-1.5 includes not only the axial fuel relocation model described here, but also a set of models that treat cladding high temperature metal-water reactions, solid-solid phase transformation, creep and failure in a unified fashion (Manngård and Massih, 2011). All computations were carried out with best-estimate models, but the cladding high temperature creep rate was scaled by a constant to match the calculated and measured time to cladding rupture. The test was simulated twice, with and without the model for axial fuel relocation, in order to assess the importance of the relocation to the thermo-mechanical behaviour and high temperature degradation of the test rodlet. Other models were identical for the two cases.

According to our simulations, cladding ballooning, collapse of the fuel pellet column, and axial relocation of fuel took place in a fairly short (7–8 s) period of time before cladding rupture in the IFA-650.4 test. Yet, thermal feedback effects from the axial fuel relocation were strong enough to affect the rupture process. Fig. 5 shows the calculated evolution of cladding deformation and axial fuel relocation during the last seven seconds before cladding rupture, i.e. from the time when the balloon started to grow and fuel started to relocate. The fuel mass fraction reached about 3 in the most distended cross section of the test rod, and the uppermost 120 mm long part of the rodlet was emptied of fuel, according to our calculations. In reality, the missing fuel length was 190 mm. The difference is due to the fact that a significant amount of fuel was expelled through the cladding breach (Oberländer and Wiesenack, 2014); this fuel loss was not accounted for in our simulations. According to our model, the entire fuel pellet column had been pulverized into fine fragments before the relocation started, resulting in a fragment packing fraction of 0.72 in all regions with crumbled fuel.

The calculated time to cladding rupture was 335.2 s with fuel relocation and 352.1 s without, which means that the calculated time to rupture was shortened by no less than 17 s as a result of thermal feedback effects from fuel crumbling and relocation. These feedback effects are illustrated in Fig. 6, which shows the cladding outer surface temperature versus axial position, calculated with and without consideration of axial fuel relocation.

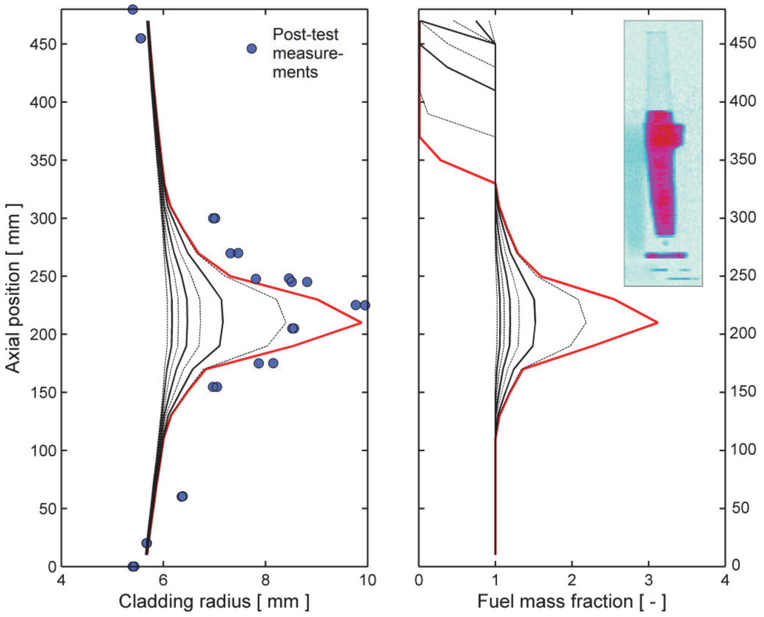

Fig. 5: Calculated evolution of cladding deformation (left) and fuel relocation (right) during the last seven seconds before cladding rupture. The rightmost (red) curve represents the conditions at time of cladding rupture, while the seven curves to the left show the calculated state 1,2,3,...7 seconds before rupture. Data from post-test cladding diameter measurements are included for comparison (left). A post-test gamma scan image of the IFA-650.4 test rig, showing the amount of fuel loss from the upper part of the rodlet, is also included (right).

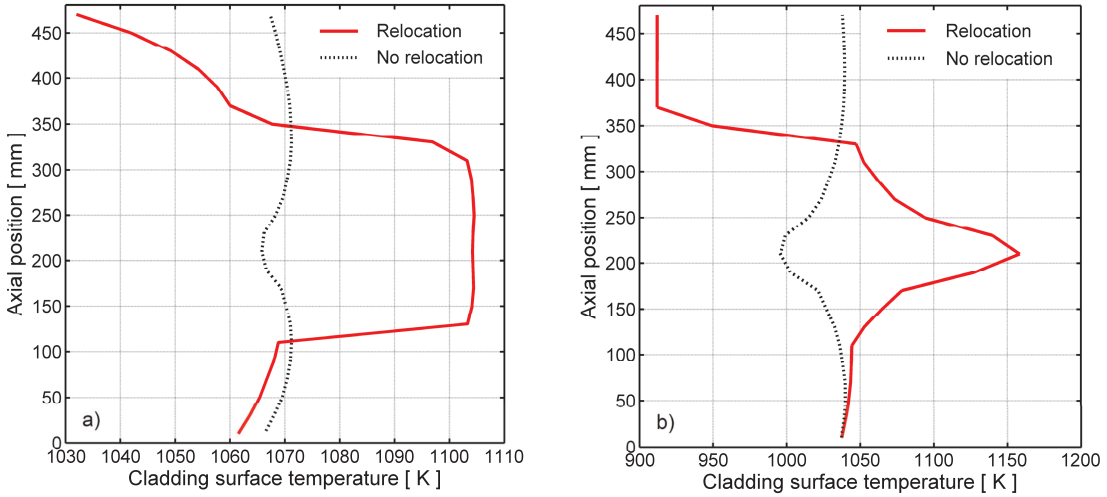

Fig. 6: Calculated cladding outer surface temperature vs. axial position at time of cladding rupture (a) and at time $t = 500$ s (b). Calculations were made with and without consideration of fuel relocation.

For the case with relocation in Fig. 6, there is a significant difference between the calculated cladding temperature distributions at time of rupture and at $t = 500$ s. Somewhat surprisingly, the calculated temperature along the balloon is almost uniform at time of cladding rupture. This is because the instantaneous cladding temperature increase in the balloon just after fuel crumbling is caused not so much by the local increase of fuel mass as such, but by closure of the pellet-cladding gap as the fuel pellet column collapses and hot fuel fragments come into contact with the cladding inner surface. The local increase of fuel mass in the balloon results in only minor thermal feedback effects *before* cladding rupture, but it has significant impact on the local cladding temperature and oxidation rate *after* rupture, as shown by Fig. 6b. The temperature peaking shown in Fig. 6b has a strong localization effect on cladding oxidation, and the calculated peak value for equivalent cladding reacted (ECR) during the IFA-650.4 LOCA test is doubled when axial fuel relocation is considered in the simulations (Jernkvist and Massih, 2015).

CONCLUSIONS AND OUTLOOK

In conclusion, some unique features of the presented relocation model should be emphasized. Firstly, the model is fully integrated with the equations used for calculating the space-time variation of fuel and cladding temperature in FRAPTRAN-1.5. This means that thermal feedback effects from the axial redistribution of power and stored heat that the fuel relocation brings about are fully accounted for in FRAPTRAN's calculations of the fuel rod thermo-mechanical behaviour. Also, the changes in fuel geometry and effective thermal conductivity caused by collapse of the fuel pellet column into a porous particle bed of crumbled fuel in ballooned regions of the fuel rod are considered in the calculations. Our simulations of the Halden IFA-650.4 LOCA test suggest that these thermal feedback effects from fuel crumbling and relocation are strong enough to significantly affect the dynamics of cladding ballooning and rupture, even though the calculated duration of these processes is no more than 7–8 s. Moreover, for the considered test, the axial relocation has a strong effect on the calculated peak cladding temperature and oxidation after cladding rupture. Secondly, the packing fraction of crumbled fuel in ballooned regions of the fuel rod is in our model estimated from the state of fuel fragmentation and pulverization. This packing fraction is a key model parameter that controls the degree of fuel relocation, given the deformed configuration of the cladding tube. It also makes an impact on the concentration of heat load to ballooned regions.

Finally, it should be remarked that the presented relocation model may be extended for predicting the fuel mass that would be ejected into the coolant upon cladding rupture at any axial position. Such predictions must consider that spacer grids act as choke points for axial fuel relocation, thereby limiting the relocatable and dispersible amount of fuel. Also, it is necessary to correlate the amount of ejected fuel to the fuel fragment size distribution and to the expected area of the cladding breach. The latter would require a significant experimental effort in order to widen the available database.

ACKNOWLEDGEMENT

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