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A DAMAGE MODEL TO DESCRIBE FUEL FRAGMENTATION AND PREDICT FISSION GAS RELEASE DURING REACTIVITY INITIATED ACCIDENT

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ABSTRACT
In this paper, we propose the use of a damage model to describe the mechanical behaviour of nuclear fuel (UO_2) during a Reactivity Initiated Accident. It describes cracking and crushing of the material depending on the loading mode (tension or compression dominated) and on temperature. This model allows one to model fuel's fragmentation and the subsequent Fission Gas Release by coupling the local damage to the release of the intergranular gas inventory. The simulation of the CABRI REP-Na4 and REP-Na5 test pulses showed that the extent of the fragmented zones and the values of the %FGR are in good agreement with the experimental data. The calculations were performed with the fuel performance code OFFBEAT developed at the Ecole Polytechnique Fédérale de Lausanne in Switzerland.

INTRODUCTION
The release of fission gases remains a difficult phenomenon to accurately simulate as pointed out by a recently published synthesis report from NEA (NEA – Working Group on Fuel Satefy, 2022). The main mechanism by which fission gases are released during a fast transient is thought to be grain boundary cracking, as diffusion-based process are too slow to explain the level of release measured after experiments conducted in test reactors. Traditionally, this fuel fragmentation has been attributed to over-pressurisation of the gas bubbles due to the rise of temperature, ultimately leading to grain boundary decohesion (Lemoine, 1997). As a result, in most fuel performance codes, transient fission gas release is often due to grain boundary fragmentation is driven by a stress criterion linked to the bubble internal pressure needed to break the grain boundary (Moal, Georgenthum and Marchand, 2014; Khvostov, 2018; Jernkvist, 2019). Another approach is to directly use a temperature (driving gas bubbles over-pressurisation) threshold triggering the opening of closed porosities at the grain boundaries (Moal, Georgenthum and Marchand, 2014; Pastore *et al.*, 2017). However, grain boundary cracking has been observed after strain-driven compression tests, compression creep tests or bending creep tests on fresh fuel (Byron, 1968; CANON, ROBERTS and BEALS, 1971; Dherbey *et al.*, 2002; Salvo, Sercombe, Helfer, *et al.*, 2015). Moreover, significant grain boundary cracking have been observed on almost the totality of the fuel radius in low burnup (around 30 GWd/tU) fuel rods tested in CABRI such as REP-Na2 (Schmitz and Papin, 1999a). The Fission Gases (FG) inventory for such a burnup is small and cannot explain the extent of the grain boundary fragmentation. Thus, fuel fragmentation cannot be attributed only to gas over-pressurisation.

In this paper, we propose the use of a damage model to simulate grain boundary cracking and fuel fragmentation. The model parametrization is based on the experimental data from Salvo and coworkers (Salvo, Sercombe, Ménard, *et al.*, 2015) that reported significant grain boundary cracking after uniaxial compressive tests performed on fresh fuel at a strain rate of 10^{-1} /s and at temperatures above 1623 K, which are conditions typically encountered during a RIA Transient. Thus, the damage variable of the model is thought to directly represent grain boundary cracking and is used to trigger transient fission gas release when a certain threshold of damage is reached. A threshold of temperature is also considered for the gas release from the restructured zone of the fuel. This methodology is then applied to simulate fuel fragmentation and fission gas release during the CABRI REP-Na4 and REP-Na5 tests.

DAMAGE MODEL FOR UO_2
To model the mechanical behaviour of UO_2 in tension and in compression, the μ-model proposed by Mazars (Mazars, Hamon and Grange, 2015) and classically used for concrete is considered hereafter. It

was previously used for the simulation of out-of-pile high-power laser heating experiments (Reymond *et al.*, 2021) conducted on UO_2 samples leading to fast localized heating of the material similar in terms of kinetics to a RIA. The model was able to accurately predict the location and time of cracking within the sample due to thermal stresses. In this paper, we now propose to extend its use to the simulation of in-pile experiments, such as RIA-tests performed in research reactors.

In this model, the local damage is described by a scalar variable *d* (ranging from 0 to 1) that represents the effective damage of the material and is used to describe the loss of stiffness of the material. Two damage modes are considered for traction and compression, i.e., cracking and crushing, respectively. In our case, crushing damage is directly linked to grain boundary cracking and fragmentation due to compressive loads. Finally, one of the main interests of this model is its ability to model effects such as cracks opening and closure if the loading is reversed.

In the μ-model, the stress-strain relation is given by:

$$\underline{\sigma} = (1-d)\mathbf{C}\colon \underline{\varepsilon} \tag{1}$$

With $\underline{\sigma}$ the standard Cauchy stress tensor, **C** the elastic tensor and $\underline{\varepsilon}$ the elastic strain tensor. The material is assumed isotropic, and all the properties are defined at the macroscopic scale.

To model damage, the μ-model uses the equivalent strain concept. Cracking and crushing are associated to the following equivalent strains:

$$\varepsilon_t = \frac{I_\varepsilon}{2(1-2\nu)} + \frac{\sqrt{J_\varepsilon}}{2(1+\nu)} \tag{2}$$

$$\varepsilon_c = \frac{I_\varepsilon}{5(1-2\nu)} + \frac{6\sqrt{J_\varepsilon}}{5(1+\nu)} \tag{3}$$

With I_ε, J_ε the first and second invariants of the strain tensor and ν the Poisson's ratio.
Then, two thermodynamic variables, Y_t and Y_c, related to the maximum equivalent strains reached during the loading sequence, are considered:

$$Y_t = Sup[\varepsilon_{0t}, max(\varepsilon_t)] \quad and \quad Y_c = Sup[\varepsilon_{0c}, max(\varepsilon_c)] \tag{4}$$

Before damage onset, Y_t and Y_c are equal to the initial thresholds ε_{0t} and ε_{0c}. The Y driving variable combine Y_t and Y_c, corresponding to tensile and compressive loads, as:

$$Y = rY_t + (1-r)Y_c \tag{5}$$

With r the triaxial factor indicating the nature of the stress. $r = 0$ corresponds to a purely compressive load and $r = 1$ to a purely tensile load.
The effective damage is then computed as:

$$d = 1 - \frac{(1-A)Y_0}{Y} - A\exp\big(-B(Y-Y_0)\big) \tag{6}$$

With Y_0 the corresponding initial threshold for Y:

$$Y_0 = r\varepsilon_{0t} + (1-r)\varepsilon_{0c} \tag{7}$$

The internal variables A and B are computed as:

$$A = A_t\left(2r^2(1-2k) - r(1-4k)\right) + A_c(2r^2 - 3r + 1)$$
$$B = r^{(r^2 r+2)}B_t + \left(1 - r^{(r^2-2r+2)}\right)B_c$$

(8)

When $r = 1$, $A = A_t$ and $B = B_t$ and when $r = 0$, $A = A_c$ and $B = B_c$. As one can see from equations 6 to 9, it is easy to split every variables between their compressive or tensile contribution. Finally, the five parametersA_t, B_t, A_c, B_c and k can be easily identified from strain-stress curves obtained from uniaxial compression and tensile or bending tests. Two strain thresholds activating the damage evolution need also to be defined for tension and compression, i.e., ε_{0t} and ε_{0c} , respectively.

UO_2 exhibits a brittle to ductile transition that is not only dependent on temperature but also on strain rate. Generally speaking, the higher the strain rate, the higher the temperature of transition will be. For example, Salvo et al (Salvo, Sercombe, Helfer, *et al.*, 2015) reported a brittle to ductile transition between 1373 K (1100 °C) and 1623 K (1350 °C) at a strain rate of 10^{-1} /s during uniaxial compression tests. A ductile behaviour was reported for a temperature of 1623 K (1350 °C) while pronounced grain boundary cracking observed by SEM examination was observed at temperatures ≥ 1823 K (1550 °C). At moderate temperature (1373 K), a brittle behaviour with cracks parallel to the stress direction was reported. No grain boundary cracking was observed for strain rates below 10^{-1} /s, indicating that this phenomenon can only happen under high strain rates.

Similar observations have been reported for the tensile domain by Evans and Davidge (Evans and Davidge, 1969) who identified a temperature of transition around 1473 K (1200 °C) from three-point bending tests. Similarly, Canon and coworkers (CANON, ROBERTS and BEALS, 1971) found a temperature of transition of 1473 K from four-point bending tests leading to an ultimate tensile stress of ~120 MPa at a strain rate of 9.2 /h (2.10^{-3} /s). With strain rate usually exceeding 1/s during RIA transients, a brittle behaviour is expected in tension even at high temperatures at which the behaviour would normally be ductile at lower strain rates.

As we aim to model the fragmentation of the fuel -due to grain boundary cracking-, we hereafter propose a parametrization of the μ-model based on the strain-stress curves of Salvo et al (Salvo, Sercombe, Helfer, *et al.*, 2015) obtained during uniaxial compression tests at high strain rates (10^{-1} /s) and high temperatures (1373, 1623, 1823 and 1973 K) representative of RIA loading conditions. This parametrization assumes an elastic behaviour (i.e, no damage onset) for low temperatures and low strain rate and a combination of elasticity and damage at high temperatures and high strain rate. In the model, it corresponds to a threshold of temperature and of equivalent strain rate above which the internal variable Y_c of the model is updated.

To reproduce the behaviour observed by Salvo et al with grain boundary cracking occurring at and above 1823 K (1550 °C) at a minimum strain rate of 10^{-1} /s, the strain rate threshold was set at 10^{-1} /s and the temperature threshold at 1623 K and. This temperature threshold is lower than the temperature at which grain boundary cracking was observed since higher strain rates can be reached in the fuel pellet during a RIA (up to 10 /s). If no significant grain boundary cracking was reported by Salvo et al 1623 K with a strain-rate of 10^{-1} /s, it is expected that the temperature interval in which grain boundary cracking can happen would be larger at high strain rate. Unfortunately, no experimental data at a strain rate superior to 10^{-1} /s are available in the literature to give us a better understanding of the relation between strain rate / temperature and the onset of grain boundary cracking. The equivalent strain rate concept is considered for the threshold on the strain rate and is expressed as:

$$\dot{\varepsilon_{eq}} = \sqrt{\dot{\varepsilon_{xx}^2} + \dot{\varepsilon_{yy}^2} + \dot{\varepsilon_{zz}^2}}$$

(9)

As we assume an elastic behaviour below 1623 K (no update of the internal variables relative to the compressive load) and a quasi-perfect plastic behaviour at or above 1623 K, the A_c parameter is set to 0. Consequently, The B_c parameter can also be set to 0 as it has no impact on damage evolution if A_c is set to 0. Thus, the only parameter that needs to be defined is ε_{0c}, corresponding to the strain at which damage is activated. Salvo's experiments clearly led to a stress plateau which is thought to correspond to the flow stress. Thus, ε_{0c} decreases on the 1623 K-2500 K interval to reproduce the decrease of stress with increasing temperatures, the stress calculated at the ε_{0c} strain being the asymptotic one when $A_c = 0$.

The tensile behaviour is assumed to remain brittle whatever the temperature reached and is characterized by a constant ultimate tensile stress of 140 MPa. Finally, the asymptotic shear stress has been assumed null, leading to $k = 1$. The resulting parameters expressions of the μ-model are given in Table 1.

At	3.5
Bt	1750
ε_{0t}	0.000013
k	1
Ac	0
Bc	0
ε_{0c}	$-3.0226 \times 10^{-10} \times T^2 - 1.8109 \times 10^{-6} \times T + 0.0029$ If $\varepsilon_{0c} < 0.0002 : \varepsilon_{0c} = 0.0002$

Table 1: Parameters of the μ-model for the simulation of grain boundary cracking and tensile cracking. In compression, no values for the parameters are prescribed below 1673 K as damage onset cannot occurs.

Figure 1 (left graph) presents the stress-strain curves obtained by imposing a uniaxial strain on a single cell. As can be seen, in compression, the behaviour below 1623 K is elastic with no damage onset. At temperatures equal or above 1673 K, the behaviour is characterized by a stress peak reached at less than 1% of axial strain followed by a plateau. The stress peak decreases with temperature increase. The tensile behaviour is described by a single curve since no temperature dependency is assumed. The maximum stress reaches ~140 MPa and is followed by a fast decrease of the stress towards a 0 value.

The corresponding damage-strain curves are given in Figure 1 (right graph). The most important aspect of this parametrization is the significant damage obtained in compression even at low strain level (less than 0.5 %), which is consistent with the pronounced grain boundary cracking reported by Salvo et al for the samples tested at high temperatures. As one can see, the proposed parametrization results in an increase in damage with temperature for a given strain level, corresponding to the decrease with temperature of the flow stress observed by Salvo and co-workers.

Fission Gas Release coupling to grain boundary cracking

We relate the fission gas release to grain boundary cracking which is represented in the model by the local damage caused by compressive stresses d_c.

This coupling is based on the following assumptions:

- Grain boundary cracking is associated to the crushing damage d_c. When a threshold of d_c is reached in a given cell, the local inter-granular gas inventory is released from the fuel.
- In case of high burnup fuel, characterised by a fine grain structure and a high fraction of the gas inventory at the grain boundaries, a threshold of temperature is considered. This so-called High Burnup Structure (HBS) forms during the nominal irradiation at the periphery of the pellet. If the temperature threshold is reached, the total gas inventory (intergranular and intragranular) is released. This is consistent with annealing tests which showed FGR from the HBS for temperatures as low as 900 K (Hiernaut *et al.*, 2008). In the following simulations, this threshold was set at 1000 K.

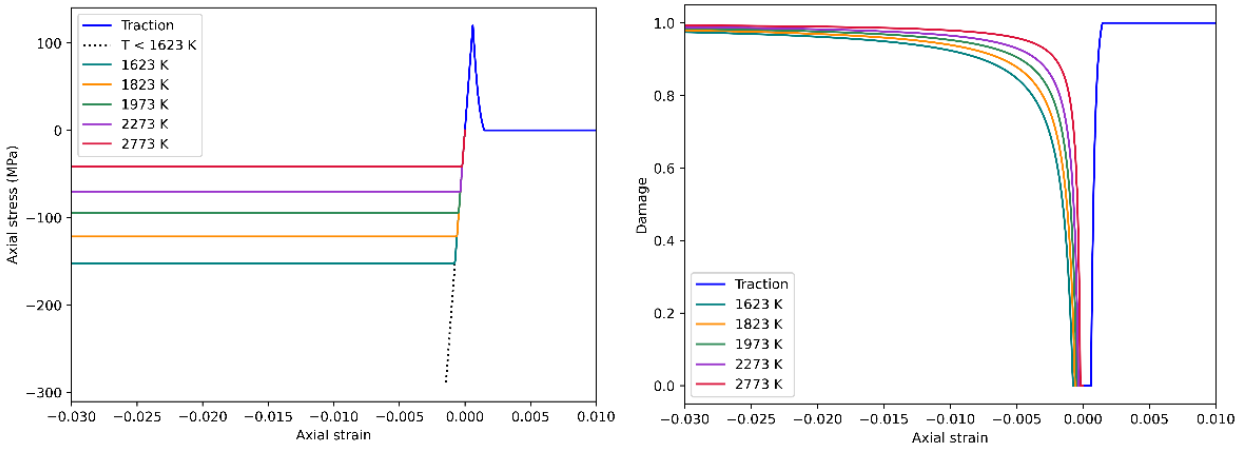


Figure 1: Left: Stress-strain curves at constant temperatures during uniaxial tensile or compressive loading. Right: Corresponding damage-strain curves.

The OFFBEAT fuel performance code

OFFBEAT (Scolaro *et al.*, 2020) is an open-source fuel performance code based on the OpenFOAM C++ library developed at the EPFL and PSI in Switzerland. Until recently, main developments efforts were aimed at modelling fuel behaviour during base irradiation conditions. OFFBEAT has recently been enhanced for RIA simulations on LWR fuel rods. This includes for example the implementation of a specific behaviour law for the clad mechanical behaviour (Le Saux *et al.*, 2008), in addition to the fuel mechanical model presented in this paper for transient fission gas release. We believe all relevant models for RIA simulations on irradiated fuel rods are now available in OFFBEAT. The μ-model and its parametrization have been implemented in OFFBEAT as well as the handling of the FGR based on the local damage of the fuel during a RIA transient. One important feature of OFFBEAT is its ability to perform the base irradiation prior to transient simulations. Continuity between the two simulations is ensured since the code will use the state calculated at the end of the base irradiation to initialize the transient calculation. As this study is focused on the fuel fragmentation during the transient, the simulations presented hereafter were performed on the axial slice located at Peak Power Node (PPN). This choice also reduce computational time

TEST CASES

The CABRI REP-Na program (Papin *et al.*, 2007), carried out between 1993 and 2000, submitted a total of 12 rodlets to simulated RIA transients in the CABRI experimental reactor (France). In this paper, we consider the REP-Na 4 and REP-Na 5 tests as to validate our model and the methodology to estimate the FGR. A comparison between these two tests is of particular interest since the two rodlets had the same father rod (identical burn-up and FG inventory) and were tested with equivalent deposited energy (397 J/g and 430 J/g for REP-Na 4 and 5, respectively), but with different pulse-widths (76.4 ms and 8.8 ms for REP-Na4 and 5, respectively).

This difference led to a noticeable difference in the measured FGR (8.3% for REP-Na4 and 15.1% for REP-Na5), and the post-mortem examination of the rodlets showed that significant fragmentation occurred at the periphery of the fuel for REP-Na 5 but not for REP-Na 4. Thus, these two cases are ideal to test the simulation of fuel fragmentation with the proposed parametrization of the μ-model coupled to FGR. The main characteristics of the tests are summarized in Table 2.

	REP-Na4	REP-Na5
Maximum Burnup (GWd/t)	62.0	64.0
Cladding type	Std Zy-4	Std Zy-4

Energy deposit (J/g)	397	430
Pulse Width (ms)	76.4	8.8
Peak fuel enthalpy (J/g)	364	451
Maximum mean hoop strain (%)	0.4	1.1
Fission gas release (%)	8.30	15.1
Grain boundary cracking	Not visible	Outer periphery

Table 2: Main characteristics of the REP-Na 4 and REP-Na5 test pulses. From (Papin et al.*, 2007).*

BASE IRRADIATION SIMULATION

During base irradiation, the coupling of OFFBEAT with the 0D gas model SCIANTIX (Pizzocri, Barani and Luzzi, 2020) was activated and gas evolution (gas production, diffusion, bubbles growth and coalescence, etc.) and repartition (intergranular, intragranular or released) were calculated in each cell at each time-step. The fuel pellet was discretized with 55 radial elements with a refinement at its periphery to well capture the HBS formation. The cladding was discretized with 15 radial elements.

A single base irradiation simulation considering one axial slice at Peak Power Node was performed for both test cases as the rodlets for REP-Na 4 and REP-Na 5 were refabricated from the same father rod. Even though they were not refabricated from the same level of the father rod, we do not expect significant differences in the fission gas inventory at the end of the base irradiation. The calculated gas inventory and the radial profiles of the total, intragranular, intergranular and released gas contents at the end of the base irradiation are given Figure 2. They are typical of an UO_2 fuel rod irradiated to 60 GWd/tU with a majority of gases located in the grain boundaries at the periphery of the pellet due to the fine grain structure of the High-Burnup Structure.

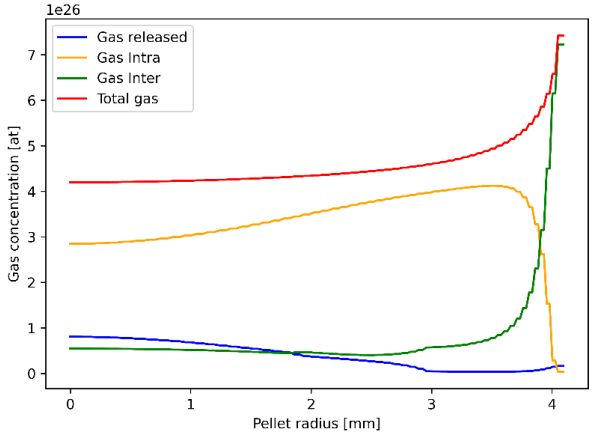


Figure 2: Gas concentration (at) as a function of pellet radius calculated with SCIANTIX at the end of the base irradiation.

RIA TRANSIENT SIMULATIONS

1.5D RIA transient simulations were performed with OFFBEAT for REP-Na 4 and REP-Na 5. The simulations were carried out on a single axial slice located at Peak Power Node. The following modelling hypotheses were considered:

- The parametrization of the μ-model proposed above was used to model the fuel thermo-mechanical behaviour.
- The clad mechanical behaviour is described by the viscoplastic model of Le Saux (Le Saux *et al.*, 2008), established on a large database of tests performed on fresh and irradiated clad samples at temperatures and strain rates typically encountered in RIA conditions.
- The REP-Na tests were performed in a flowing liquid sodium coolant. As OFFBEAT does not have a separate coolant channel model, the clad external temperature evolution was calculated with the ALCYONE fuel code developed by the CEA, EdF and FRAMATOME in the PLEIADES platform (Sercombe et al., 2010)(Guénot-Delahaie et al., 2018) and used as an input in OFFBEAT.

- During these transient simulations, the coupling with SCIANTIX was deactivated as it was not expected that the thermal diffusion of fission gas atoms would have a significant impact during a RIA. Instead, the fission gas release during the transient is handled in a simplified manner by a dedicated module. First, the gas released during the base irradiation is subtracted from the total gas inventory and is reinitialised at 0 at the beginning of the RIA simulation. In the RIA simulations, cells were considered as restructured (i.e., mainly consisting of HBS) if the local burnup was > 80 000 MWd/kgU. This criterion is consistent with the reported thickness of the restructured rim region in the father rod of the REP-Na4 and 5 samples (~200 um) (Schmitz and Papin, 1999b).

Simplified power profiles

As the REP-Na irradiation histories are not publicly available, simplified power pulses were used for the RIA simulations. They are based on the following Gaussian function:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{1}{2}\frac{(t-t_m)^2}{\sigma^2}\right) \quad (10)$$

Where t_m is the time of peak power. The σ value if dependant on the Full Width Half Maximum (FWHM) of the pulse. The resulting power evolutions as a function of time are given in

Inversely, for REP-Na5, significant grain boundary cracking was obtained at the periphery of the pellet on roughly one third of its radius. Figure 5 (left) shows the evolution of the crushing damage, of which the quasi-totality occurred at the end of the pulse. The red colour in the pellet mesh indicates the extent of the area that contributes to fission gas release for a threshold of crushing damage of 0.75 or 0.87. (top).

RESULTS

The radial average peak fuel enthalpies calculated with OFFBEAT and the simplified power pulses reach 375 J/g and 461 J/g for REP-Na 4 and REP-Na 5, respectively. They are consistent with the reported values of 364 J/g and 451 J/g (Papin *et al.*, 2007).

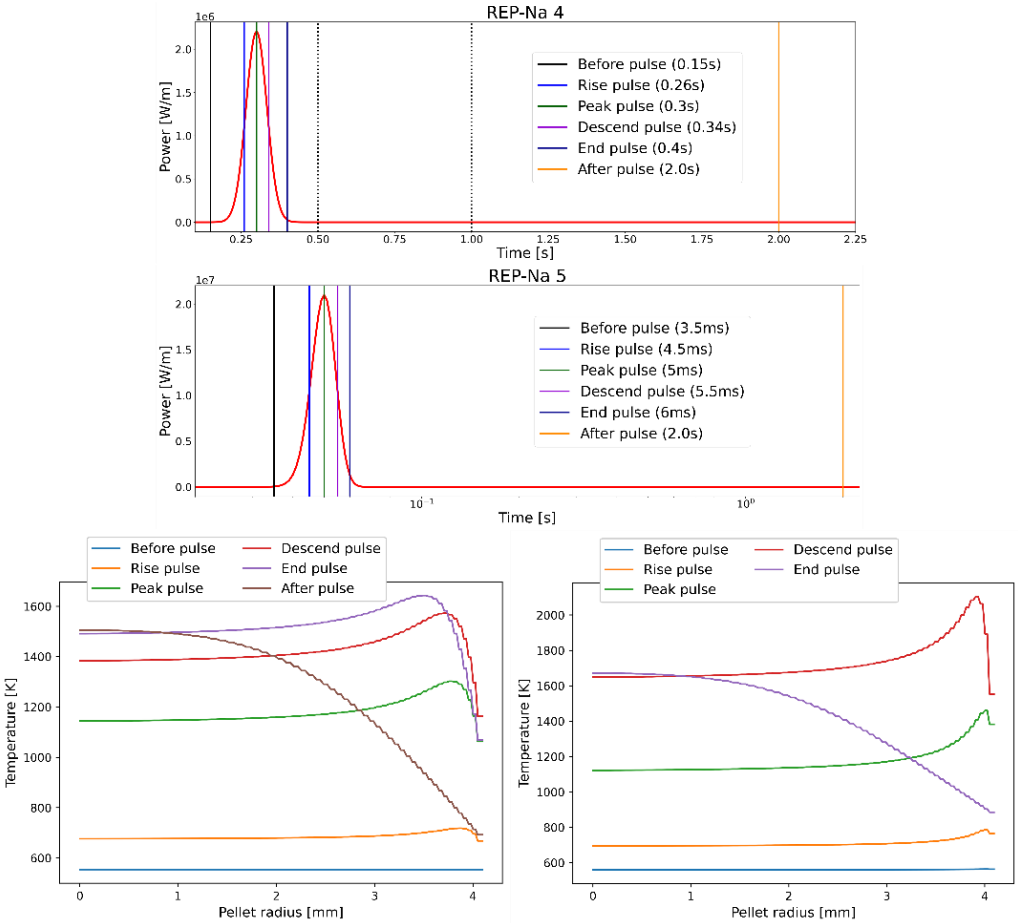
The radial temperature profiles calculated at different times are shown in Figure 3. One stricking difference between the pulse simulations is the peak of temperature induced near the pellet periphery by the fast transient of REP-Na 5 while the temperature profiles of REP-Na 4 are quasi-flat, in accordance with the slow kinetic of the power transient. The maximal temperature reached at the center of the pellet are 1510 and 1678 K for REP-Na4 and REP-Na5, respectively, which is consistent with the deposited energies (430 J/g for REP-Na 5 vs 397 J/g for REP-Na 4).

Evolution of microcracking and resulting fission gas release

The evolution of the local crushing damage, d_c, that is directly linked to grain decohesion is of particular interest as it directly represents the fragmentation of the fuel contributing to FGR. For REP-Na4, a small peak of crushing damage is visible in the area where the thresholds of temperature and strain rate were reached, as one can see on Figure 4 (left). It is however interesting to note that these calculations were made at Peak Power Node, at which the conditions were the most likely to lead to fuel fragmentation. Two damage thresholds were considered to quantify the importance and potential contribution of this damaged zone to the fission gas release: 0.87, at which no fission gas release induced by grain boundary cracking is obtained in REP-Na4 and 0.75, at which the peak of damage visible on Figure 4 (left) contributes to the FGR. The resulting fission gas release as a function of time is plotted in Figure 4 (right). When considering a threshold of 0.87, only the HBS contributes to the calculated FGR and its value is close to the experimental one (9% predicted by OFFBEAT vs the measured 8.1%). When considering a threshold of 0.75, the damaged region also participates to the FGR. The resulting value of 10.7% is nevertheless still consistent

with the experimental one, considering also the probable overprediction due to the choice of PPN for the entire rod, and the typical uncertainties in the measurement of the released volume.

Inversely, for REP-Na5, significant grain boundary cracking was obtained at the periphery of the pellet on roughly one third of its radius. Figure 5 (left) shows the evolution of the crushing damage, of



which the quasi-totality occurred at the end of the pulse. The red colour in the pellet mesh indicates the extent of the area that contributes to fission gas release for a threshold of crushing damage of 0.75 or 0.87.

Figure 3: Top: Timeline of the power histories of REP-Na4 and REP-Na5 with the chosen time of plotting for each. Bottom: Radial temperature profiles for REP-Na4 (left) and REP-Na5 (right)

The resulting fission gas release is plotted Figure 5 (right). As for REP-Na4, almost all of the release took place during the power pulse. For a threshold of 0.87, the calculated FGR of 15.2% is in excellent agreement with the measurement of 15.1%. For a threshold of 0.75, the calculated value of 20.8% is still consistent with the measured value. Moreover, the discrepancy between the two pulses is consistent whatever the used damage threshold. It is again worth noting that the simulations were carried at PPN and it is possible that carrying out the same simulation with the same threshold on the whole fuel rodlet would lead to a smaller %FGR as it would be averaged on the whole length of the rod.

CONCLUSION

In this article, we introduced a damage model (the so-called µ-model) coupled to a fission gas model (SCIANTIX) in the OFFBEAT fuel performance code to represent grain boundary cracking and FGR during a RIA transient on UO_2 pellets with. These is models were used to simulate two RIA transients performed at the CABRI facility, i.e., REP-Na4 and REP-Na5.

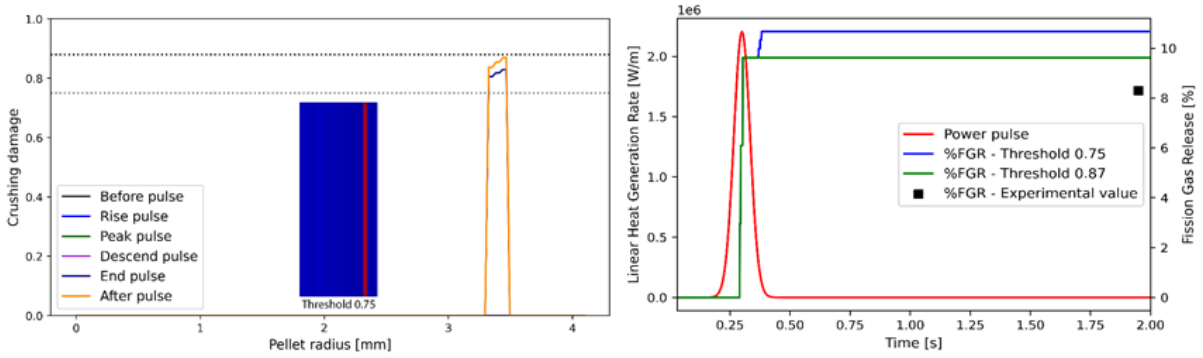


Figure 4: Left: Radial profile of the crushing damage for REP-Na4. The red color in the pellet mesh indicates the extent of the area that contributes to FGR (i.e., that is considered as fragmented) for a threshold of crushing damage of 0.75. Right: Fission gas release as a function of time for REP-Na4. The power pulse is given as a reference.

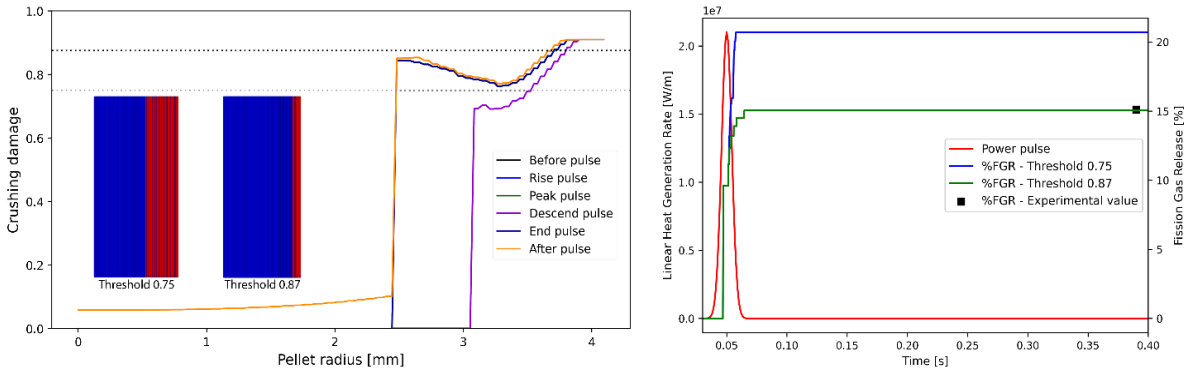


Figure 5: Left: Crushing damage evolution during REP-Na. The black dotted line refers to a damage threshold of 0.85 and the grey dotted line to 0.75. The red color in the pellet meshes indicates the extent of the area that contributes to FGR (i.e., that is considered as fragmented) for the two different thresholds of crushing damage. Right: Fission gas release as a function of time for REP-Na5. The power pulse is given as a reference.

Calculation results have shown that using a mechanistic approach based solely on experimental data obtained on fresh UO_2 is pertinent to accurately model: 1) the onset and radial extent of fuel fragmentation and 2) fission gas release by linking the release to the internal variables of the model representing local grain boundary cracking. Of course, the calculated fission gas release during the transient also greatly depends on the gas inventory and its repartition obtained at the end of the base irradiation. In this regard, OFFBEAT is coupled to the 0D gas model SCIANTIX but the use of others gas models could lead to a different inventory and repartition, thus affecting the transient fission gas behaviour.

Future work could aim at improving the model by, for example, expressing the temperature threshold at which crushing damage can occur as a function of the strain-rate. Its application on other REP-Na test cases for further validation is also envisioned.

Finally, these results also outline the new capabilities of OFFBEAT for the simulation of accidental transients on irradiated fuel rods and its ability to perform both base irradiation and transient behaviour analysis on LWR fuel rods.

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