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Abstract

During the initial rise to power in light water reactors (LWR), thermal gradients within a pellet cause radial and axial cracks to form in the fuel. The effect of these cracks is to reduce the pellet-cladding gap and accelerate the interaction between the fuel and cladding. This process is known as fuel relocation and may also include contributions from pellet eccentricity and cladding ovality. Since the cladding experiences both elevated temperatures and high external pressure due to the coolant, the cladding typically creeps inward further reducing the pellet-cladding gap. Once the gap is closed and pellet cladding mechanical interaction (PCMI) begins, both the thermal and mechanical behavior of the fuel is affected. The compressive forces exerted on the fuel due to contact with the cladding cause the fractured fuel sections to move back toward their original position which is termed relocation recovery. A model for this phenomena is implemented in the Bison fuel performance code and applied to a set of validation test cases. The predicted fuel rod diameter is compared to experimental measurements to evaluate the influence of relocation recovery over a range of operating conditions.

Keywords: Fuel relocation, Fuel recovery, Cladding, Creep

1. Introduction

The Bison fuel performance code is developed at Idaho National Laboratory (INL) and has been used to simulate a variety of fuel and cladding materials within a reactor environment [1]. A significant effort has been made to verify [2] and validate [3] Bison. The most recent validation activity identified several areas where additional development could improve the code predictions. In this work, the focus is on the implementation of a model for relocation recovery into Bison.

During the operation of a nuclear reactor, thermal gradients are generated in the fuel rods, which cause fracture in the fuel pellets. A consequence of these primarily radial cracks in the fuel is an effective increase in the pellet radius and the reduction or closure of the pellet-cladding gap (i.e., fuel relocation).

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Initially, many fuel performance codes did not include the effect of fuel relocation on the fuel/clad gap behavior and during the beginning of life (BOL) only considered the difference in thermal expansion coefficient between the fuel and cladding. This resulted in a consistent over-prediction of the fuel centerline temperature compared to experiment [4]. Therefore, fuel relocation models were implemented that caused the fuel/cladding gap conductivity to increase during BOL analyses and the predicted centerline temperatures then decreased to more closely match experimental values.

During continued operation, the cladding creeps inward and, following contact, exerts compressive mechanical forces on the fractured pellet. These forces tend to move the fractured sections of the pellet back into their original positions, which is known as relocation recovery. However, due to the random nature of the crack shapes and sizes, the pellet sections do not move perfectly back into a cylindrical shape. Therefore, the relocation recovery is typically not complete and how much recovery actually occurs in a given situation is stochastic due to the random nature of the fracture and relocation processes [5]. A number of factors have been identified that influence fuel relocation. These include geometric effects such as initial pellet diameter and gap thickness, and operating conditions including power level, number of power cycles and burnup [6].

A variety of relocation models exist and have been implemented in fuel performance codes [7]. The models contain both experimentally determined constants as well as dependencies on the factors mentioned above. A straightforward approach for modeling relocation recovery is proposed below and implemented in Bison.

2. Background

Relocation and relocation recovery models have been developed as part of a more general objective to accurately calculate the thermal stored energy of the fuel in a LWR. The thermal energy of the fuel is a major factor controlling the peak cladding surface temperature, which is limited to 1204°C by requirement [8], during the design basis accident scenario of a loss-of-coolant-accident (LOCA) [9]. The thermal energy in a fuel rod is a function of the rod power, the fuel thermal conductivity and the gap conductance [10]. Reducing the uncertainty in the gap conductance has been an aim of both experimental [10–14] and modeling [4–7, 15–18] efforts for several decades.

Relocation models have addressed the change in gap conductance inferred from experiments by introducing equations which increase the radius of the pellet or an equivalent form which reduces the gap size. The relations proposed have many different forms and can be as simple as [19]

$$u^{rel} = 2/3g_o$$

with

u^{rel} = radial deformation at the outer surface of the pellet

g_o = initial gap size

or as complex as [18]

$$G(B) = C_1'(2 - C_3)e^{-C_2 A} - C_1'(1 - C_3)e^{-(C_2 A + C_4 B)}$$

with

$G(B)$ = gap size (μm)

A = $(P - 60)$

P = rod power (W/cm)

B = burnup (GWD/T)

C_1' = $G_o - (\Delta D_j + K)$

G_o = initial gap (μm)

ΔD_j = amount of pellet jump (μm)

= $3.6D$, where D is pellet diameter (mm)

K = gap change (μm) due to other phenomena (i.e., swelling, creep)

C_2 = 0.0039, $C_3 = 1.41$ and $C_4 = 0.95$

The amount of relocation can vary by an order of magnitude [7] depending on the correlation used. The benefits of a relocation model with a more complicated form and additional empirically determined constants is not readily apparent. Therefore, the model used in Bison [17] was chosen to account for the experimentally observed dependencies for relocation which are initial geometry (i.e., pellet diameter and gap size), burnup and linear heating rate [7, 10]. The model is described in more detail in the next section.

Relocation recovery is the process during which the PCMI transitions from a "soft" to a "hard" contact behavior [18]. After the initial pellet cracking occurs, the pellet fragments can move in response to additional power increases and/or decreases and the related fuel thermal expansion, swelling and densification. However, as the cladding continues to creep inward due to the elevated temperature and pressure on the cladding, eventually the pellet-cladding gap completely closes. Once the pellet fragments and cladding are in mechanical contact, the pellet fragments move in response to the cladding creepdown until "hard" PCMI is attained. The mechanisms involved in this process are not well understood and the assumptions of different fuel performance codes range from ignoring relocation recovery [7] to allowing for full recovery of all the relocation strain [20].

The above equation for the gap size as a function of burnup also includes the effects of relocation recovery. The author argues that the transition between "soft" and "hard" PCMI behavior is similar to the compaction of granular materials and derives an expression for the gap size as a function of power which is incorporated into the overall equation. However, in a subsequent section of the paper, the onset of "hard" PCMI under some conditions is shown to be inconsistent with the compaction of granular material assumption. This illustrates how difficult it is for a single model of relocation with or without recovery to satisfactorily explain the experimental observations on irradiated fuel rods.

Recent comparisons of cladding diameter predictions with experimental results [3] indicated a tendency for Bison to overpredict clad diameters especially with higher burnup. The addition of a relocation recovery model in Bison was proposed as a way to improve the cladding diameter comparisons. The recovery model implemented in Bison is modeled after the FRAPCON-4.0 method [21] which introduces a user-defined parameter specifying the fraction of relocation allowed to be recovered. Although this approach is not based on a mechanistic description of relocation recovery, it allows the user to have control over the contribution of recovery to the mechanical response of the fuel and cladding.

3. Bison Implementation

3.1. Relocation Model

The fuel relocation model implemented in Bison is based on the empirical ESCORE relocation model [17]. The model is described in detail elsewhere [22], however a brief overview will be provided here.

Since fuel relocation encompasses a number of physical processes which are not explicitly modeled in Bison, the aggregate effect is applied to the fuel through an additional radial strain. This radial relocation strain causes the pellet-cladding gap to close more rapidly than only considering thermal expansion effects and cladding creep down, which is consistent with experimental observations.

The radial relocation strain provided by the ESCORE model is given by the following:

$$\left(\frac{\Delta D}{D_o}\right)_{REL} = 0.8Q\left(\frac{G_o}{D_o}\right)(0.005BU^{0.3} - 0.20D_o + 0.3)$$

with

$$Q = \begin{cases} 0 & \text{for } q' \leq 6 \text{ kW/ft} \\ (q^{'} - 6)^{1/3} & \text{for } 6 \text{ kW/ft} < q' \leq \ 14 \text{ kW/ft} \\ (q^{'} - 10)/2 & \text{for } q' > \ 14 \text{ kW/ft} \end{cases}$$

where

$$\left(\frac{\Delta D}{D_o}\right)_{REL} = \text{Diametral strain due to relocation}$$

$$D_o = \text{As-fabricated cold pellet diameter (in)}$$

$$q' = \text{Pellet average linear heat rate (kW/ft)}$$

$$BU = \text{Pellet average burnup (MWd/MTU)}$$

$$G_o = \text{As-fabricated cold diametral gap (in)}$$

This radial relocation strain is applied incrementally by computing the relocation strain at the current time step and subtracting the relocation strain calculated for the previous time step. In the current Bison implementation, the addition of relocation strain is stopped when mechanical contact is detected between the pellet and cladding. In addition, the power level at which the relocation is activated was determined through a calibration of the ESCORE model as implemented in Bison using a set of Halden experiments with instrumented fuel rods [23]. In order to match the experimental fuel centerline temperature data from Halden, the relocation initiation power level was optimized to be 5 kW/m which is much lower than the default value in the ESCORE model (i.e., 19.7 kW/m).

3.2. Relocation Recovery Model

A straightforward approach has been used to implement a relocation recovery model in Bison. The model is activated once the pellet and cladding come into contact and simply recovers a fractional percentage of the relocation strain that has been applied to the fuel. The default value for the percentage of relocation strain recovered is 50% which is taken from FRAPCON-4.0 [21]. All of the updated validation cases run for this work used the default value for percent relocation strain recovered. The relocation strain is a function of burnup, which varies in both the axial and radial directions within the fuel. Once relocation recovery begins, 50% of the local maximum relocation strain in a given fuel element is the maximum allowed to be recovered. In order to explain the relocation recovery process as implemented in Bison, we refer to Figure 1, which shows a schematic of the typical relocation-recovery strain behavior plotted as a function of time.

The segment 'AB' represents the relocation phase of the relocation-recovery behavior. During this phase, the fuel and the cladding are not yet in contact. However, at point 'B', contact is established between the cladding and the fuel, thus ending relocation, and at this point relocation recovery is initiated. The recovery continues until the specified fractional amount of relocation strain has been recovered. Therefore, for the default value of 50%, recovery ends at point 'C' with the strain at point 'C' equal to half the value of the strain at point 'B'. The last segment 'CD' represents the phase when the recovery process is complete.

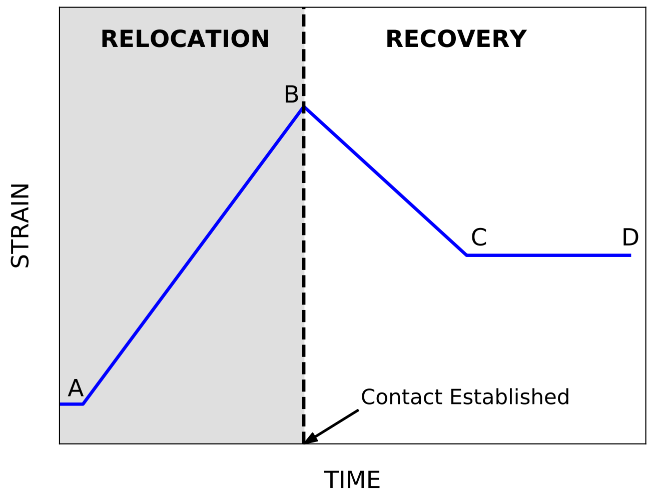


Figure 1: An ideal Relocation-Recovery curve: segment 'AB' is the relocation phase, segment 'BC' is the recovery phase and segment 'CD' represents the completion of relocation recovery process. The dashed line through point 'B' represents the time of contact between pellet and cladding.

There is, however, a scenario that needs to be considered. After initial contact between the fuel and cladding, if the gap reopens at a later time, the assumption is made in Bison that relocation is not re-initiated. However, the relocation recovery strain is cumulative and gets activated again after contact is re-established following gap reopening, with the limiting value of 50% of the maximum relocation strain as described above.

The contribution of relocation strain to the total fuel strain is given in the incremental form by Equation 1 as follows:

$$\Delta\varepsilon_{total}^{fuel} = \Delta\varepsilon_{thermal}^{fuel} + \Delta\varepsilon_{volumetric}^{fuel} + \Delta\varepsilon_{relocation}^{fuel} \tag{1}$$

After contact when relocation stops ($\Delta\varepsilon_{relocation}^{fuel} = 0$) and recovery strain is computed, Equation 1 takes the form:

$$\Delta\varepsilon_{total}^{fuel} = \Delta\varepsilon_{thermal}^{fuel} + \Delta\varepsilon_{volumetric}^{fuel} - \Delta\varepsilon_{recovery}^{fuel} \tag{2}$$

In order to make a choice for the computation of recovery strain, it is important to understand the physics of the whole system. The expanding fractured fuel is fragmented and has little to no rigidity to push the cladding out upon contact. However, numerically, fuel volumetric swelling may be larger than cladding creep strain and, therefore, would push the cladding out upon contact in the absence of a relocation-recovery model, which is non-physical. The fuel can only push the cladding out after its recovery is complete, at which time it would have gained enough rigidity. Based on the above discussion, the recovery strain is computed using Equation 3 below:

$$\Delta\varepsilon^{fuel}_{recovery} = \begin{cases} 0 & \text{for } \Delta\varepsilon^{fuel}_{volumetric} \leq 0 \\ \Delta\varepsilon^{fuel}_{volumetric} & \text{for } \Delta\varepsilon^{fuel}_{volumetric} > 0 \text{ and `A'} \\ 0 & \text{for } \Delta\varepsilon^{fuel}_{volumetric} > 0 \text{ and `B'} \end{cases} \tag{3}$$

where, 'A' = Pellet-Cladding are in contact and $\varepsilon^{fuel}_{recovery} < \left(0.5 \times \varepsilon^{fuel}_{relocation}\right)$ and 'B' = Pellet-Cladding not in contact or $\varepsilon^{fuel}_{recovery} = \left(0.5 \times \varepsilon^{fuel}_{relocation}\right)$

In Equation 3, the negative incremental volumetric swelling implies that the fuel is still undergoing densification. Fuel densification typically occurs in the initial stages of reactor operation and the fuel rarely comes into contact with the cladding so early in a reactor cycle. However, in order for Bison to treat the case, where the cladding and the fuel come into contact during fuel densification, the recovery strain is expressed as shown in Equation 3. Therefore, after the contact between the fuel and the cladding is established and incremental volumetric swelling is positive with recovery strain less than 50% of the maximum relocation strain, recovery begins and the total incremental fuel strain is determined by substituting Equation 3 in Equation 2:

$$\Delta\varepsilon^{fuel}_{total} = \Delta\varepsilon^{fuel}_{thermal} \tag{4}$$

Thermal strain of the fuel is usually much less than the creep strain of the cladding ($\Delta\varepsilon^{clad}_{creep} > \Delta\varepsilon^{fuel}_{thermal}$). This implies that upon contact, the cladding continues to push the fuel inward, in conformity with the physics of the problem, until the recovery is complete. Therefore, as a consequence of modeling the phenomenon of relocation-recovery, the calcuation of cladding creep is improved.

During the process of relocation recovery (segment BC in Figure 1), the pellet and cladding are in contact. The state of stress in the cladding is compressive as it is creeping inward and is the driver of recovery in the fuel. Once relocation recovery is completed (point C in Figure 1), the fuel is considered elastic again and can continue to swell. This will likely cause the stress in the cladding to become tensile with additional irradiation.

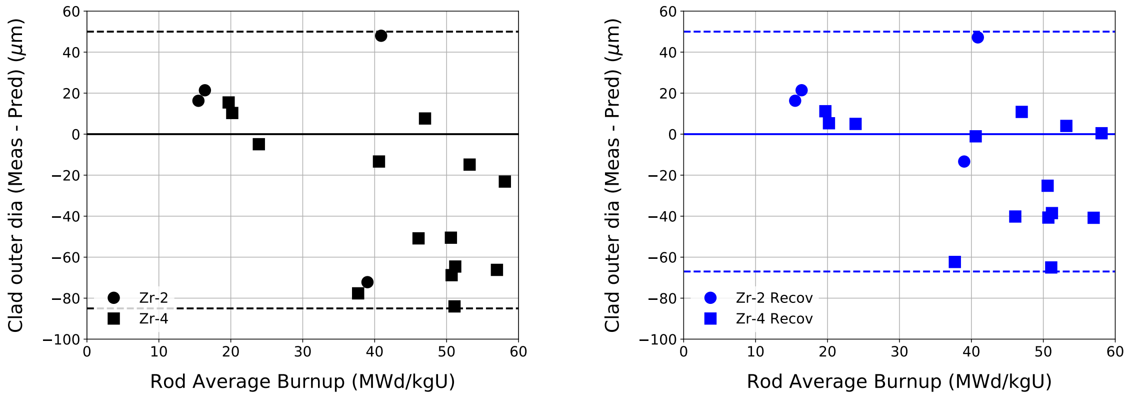
4. Results

One measure of the accuracy of a fuel performance code is the ability to predict the cladding diameter of a fuel rod over time. In the earlier Bison validation paper [3] a set of test cases simulating a variety of fuel rod experiments in which the rod diameter was measured were chosen to evaluate Bison in regards to PCMI. These test cases were re-run with the latest version of Bison and generated similar results for the diameter predictions including only relocation. Some small differences were observed, but these can be accounted for by other changes in Bison and did not significantly alter the results.

The improved fuel relocation model, now including the effect of recovery, was applied to the same set of Bison test cases, and the results are summarized in Table 1. The last two columns of the table show the difference between the measured and predicted rod diameters for the original study and the current work, respectively. As one can observe, the majority of the values have decreased or remained about the same in terms of the absolute value of the diameter difference. This indicates that the addition of a relocation recovery model has generally improved the Bison predictions. The most significant changes occured for the cases with the highest rod average burnup. This may be due to the fuel volumetric swelling in the previous simulations causing unrealistic tensile stresses in the cladding and an overprediction of the rod diameter. Figures 2–3 show different graphical representations of the data contained in Table 1. In Figure 2 the dashed lines represent the extent of the differences between the measured and predicted clad diameters while the solid line represents the position where the measured and predicted values exactly match. As mentioned above the majority of the validation case results have improved (i.e., moved closer to the solid line) and the overall range of differences between measured and predicted clad diameters has decreased. In Figure 3, letters 'A B ... R' are identifiers that correspond to each case listed in Table 1. Several individual cases will be discussed in more detail in the following sections.

Table 1: Rod diameter comparisons following base irradiation.

Case Description	Clad Type	Axial Comparison Location	Rod Average Burnup (MWd/kgU)	Diameter Change (No Recovery) [Meas. – Pred.] (μm)	Diameter Change (Recovery) [Meas. – Pred.] (μm)
Tribulation BN1/4 (A)	Zry-4	Midplane	19.7	15.5	11.2
Tribulation BN1/3 (B)	Zry-4	Midplane	20.2	10.3	5.3
OSIRIS J12 (C)	Zry-4	Average	23.9	-4.9	5.0
Tribulation BN3/15 (D)	Zry-4	Midplane	37.7	-77.7	-71.6
Risø-3 AN2 (E)	Zry-4	Average	40.6	-13.4	-1.1
OSIRIS H09 (F)	Zry-4	Average	46.1	-50.8	-40.2
REGATE (G)	Zry-4	Average	47.0	7.6	10.9
Tribulation BN1/4 (H)	Zry-4	Midplane	50.6	-50.5	-25.2
Tribulation BN1/3 (I)	Zry-4	Midplane	50.7	-68.8	-40.7
Tribulation BN3/15 (J)	Zry-4	Midplane	51.1	-84.0	-71.6
R. E. Ginna Rod 2 (K)	Zry-4	Average	51.2	-64.6	-38.5
USPWR TSQ002 (L)	Zry-4	Average	53.2	-14.9	4.0
R. E. Ginna Rod 4 (M)	Zry-4	Average	57.0	-66.2	-40.8
USPWR TSQ022 (N)	Zry-4	Average	58.1	-23.1	0.5
Risø-2 GE-m (O)	Zry-2	Average	15.5	16.3	16.3
Risø-3 II3 (P)	Zry-2	Average	16.4	21.4	21.4
Risø-3 II5 (Q)	Zry-2	Midplane	39.0	-72.2	-13.5
Risø-3 GE7 (R)	Zry-2	Average	40.9	48.0	47.2



(a) No recovery

(b) With recovery

Figure 2: The dfference between measured and predicted rod diameter as a function of burnup. The dashed horizontal lines in both (a) and (b) represent upper and lower bounds or the spread.

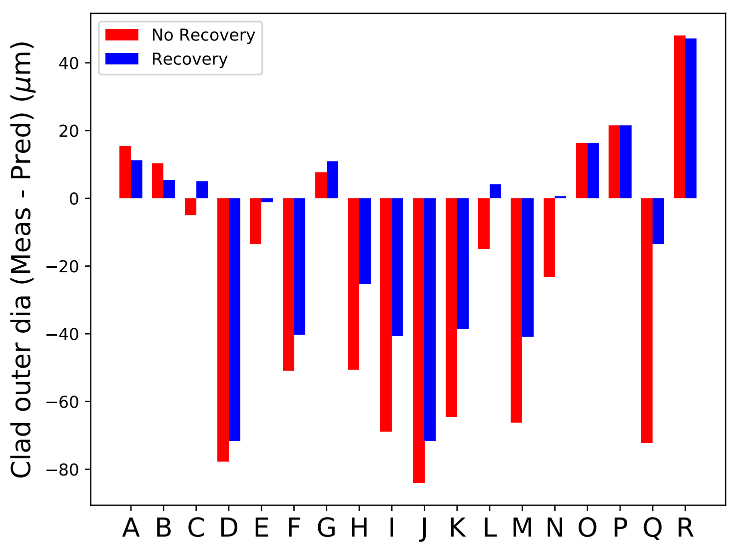


Figure 3: The difference between measured and predicted rod diameter for all validation cases. The letters 'A B ... R' are identifiers that correspond to each case listed in Table 1.

4.0.1. OSIRIS - H09

The OSIRIS H09 test rod is a standard full length PWR rod that was irradiated for 4 cycles in the Electricity of France (EDF) Cruas 2 PWR to a final discharge rod average burn-up of 46.06 MWd/kgU [24]. This experiment was chosen for analysis because of the availability of measured data for evaluation of several fuel rod performance characteristics including the fuel rod diameter at end of life (EOL). The fuel was modeled using a smeared fuel column for simplicity. A smeared fuel column is meshed using a single block of cylindrical elements to model the fuel (i.e., without dishes and chamfers) whereas a discrete pellet mesh includes those features.

Figure 4 shows the comparison of the Bison EOL diameter predictions and the experimental measurement along with the initial unirradiated diameter as a function of axial position of the rod. The current Bison relocation model without recovery results in a relatively small change in the diameter when compared with the initial value. However, the Bison diameter prediction including relocation recovery shows a significant improvement over the length of the rod and reduces the error between Bison and the measurement by a factor of 2.

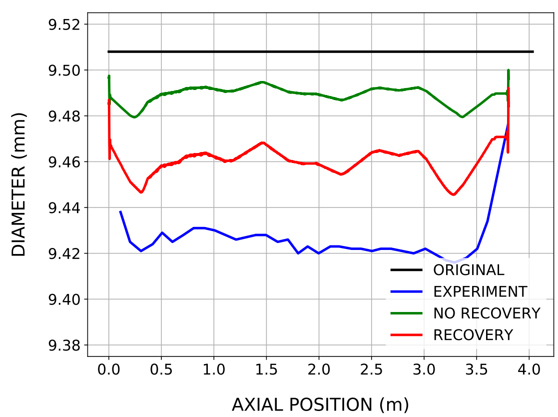


Figure 4: End of Life (EOL) diameter comparison for H-09 case

4.0.2. OSIRIS - J12

This test is of a segmented PWR rod with a base irradiation in the Electricity of France (EDF) Gravline 5 PWR [25]. The segment was then re-fabricated and ramp tested in the French Alternative Energies and Atomic Energy Commission (CEA) OSIRIS reactor to investigate PCMI resistance. This experiment was chosen because it allows for an evaluation of several aspects of the code, including fully coupled thermo-mechanics, contact, and several nonlinear material models in addition to rod diameter measurements. In this case, the test was modeled using a discrete pellet mesh for the fuel column.

Figure 5 shows the same comparison of clad diameter as a function of axial position as Figure 4. Once again the new relocation recovery model shows a significant improvement in the diameter predictions over the simulation without relocation recovery. In addition, one can clearly see the "bamboo" effect on the cladding deformation in both the Bison predictions and the experimental measurements. This is due to using a discrete pellet mesh for the fuel column and illustrates the ability of Bison to capture local PCMI behavior.

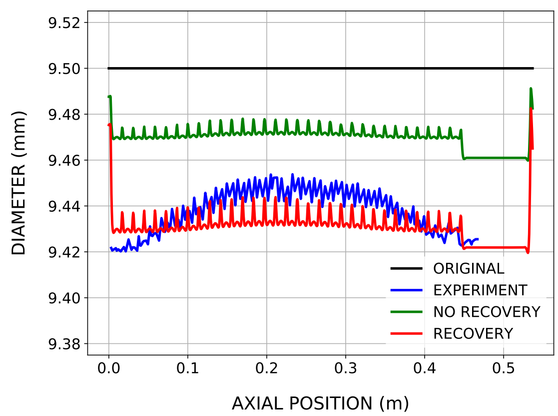


Figure 5: End of Life (EOL) diameter comparison for J-12 case

4.0.3. US PWR

The US PWR 16x16 lead test assembly (LTA) extended burnup demonstration (referred to as US PWR from here on) was conducted during the 1980's in a US commercial pressurized water reactor (PWR) [25]. The purpose of this series of experiments was to increase final discharge burnup and to demonstrate improved fuel utilization through more efficient fuel management. Two rods out of this series, TSQ002 and TSQ022, were discharged at a burnup of approximately 58 MWd/kgU. TSQ002 is a full length fuel rod with standard (solid) fuel pellets, whereas TSQ022 is a full length fuel rod with annular fuel pellets.

Figure 6 shows the comparison of EOL diameter for the TSQ002 rod and the EOL diameter comparison for the rod TSQ022 is shown in Figure 7. In both cases the addition of relocation recovery improves the predicted diameter results so that they are in excellent agreement with the experimental measurements. Some difference is seen at the plenum end of the rod which could be attributed to simplifications in the model at the end cap and potential difficulties in the measurements in that location.

5. Conclusions

A relocation recovery model was implemented in the fuel performance code Bison and used to re-evaluate a set of experimentally based test cases for fuel rod diameter measurements. The recovery

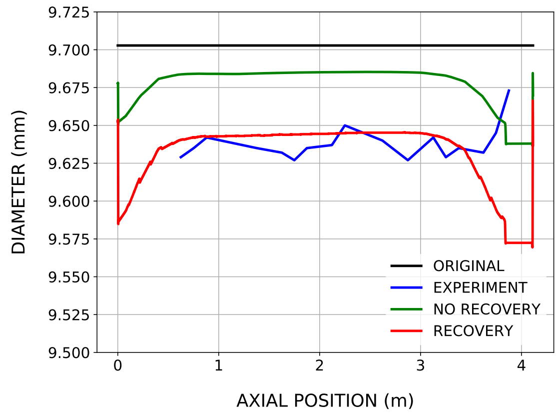


Figure 6: End of Life (EOL) diameter comparison for TSQ002 case

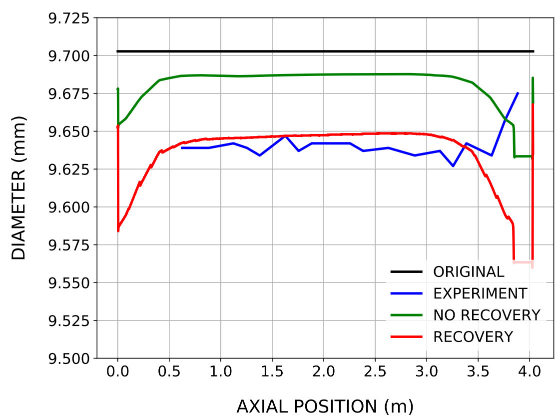


Figure 7: End of Life (EOL) diameter comparison for TSQ022 case

model chosen allows for a specified fraction (50% by default) of the relocation strain to be recovered. This simple approach eliminates much of the complexity of other mechanistic models while still capturing the major behavior of the recovery process. In Bison the fuel volumetric swelling rate was used to define the recovery rate once contact was established. This provided a realistic relocation recovery rate and minimized the possibility of non-physical behavior (i.e., stress reversal from compressive to tensile stress) in the cladding due to the relocation strain.

The relocation recovery model was added to a set of test cases previously used to evaluate Bison fuel rod diameter predictions. The model was applied to validation cases which included smeared and discrete pellet meshes as well as both solid and annular pellets. In almost all the cases, the Bison diameter predictions with recovery improved over the earlier predictions which did not include the effect of relocation recovery. In general, the cases with higher rod average burnup showed the most improvement since in the earlier simulations, without recovery, the volumetric swelling of the fuel results in significant overprediction of the cladding diameter. The comparisons between the predictions and measurements were made by computing an average diameter over the rod and also at the midplane of the rod depending on the experimental data available. In addition, the predicted and measured rod diameter as a function of axial position was compared when possible.

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References

[1] R. L. Williamson, J. D. Hales, S. R. Novascone, M. R. Tonks, D. R. Gaston, C. J. Permann, D. Andrs, R. C. Martineau, Multidimensional multiphysics simulation of nuclear fuel behavior, Journal of Nuclear Materials 423 (2012) 149–163.

[2] J. D. Hales, S. R. Novascone, B. W. Spencer, R. L. Williamson, G. Pastore, D. M. Perez, Verification of the BISON fuel performance code, Annals of Nuclear Energy 71 (2014) 81–90.

[3] R. L. Williamson, K. A. Gamble, D. M. Perez, S. R. Novascone, G. Pastore, R. J. Gardner, J. D. Hales, W. Liu, A. Mai, Validating the BISON fuel performance code to integral LWR experiments, Nuclear Engineering and Design 301 (2016) 232–244.

[4] D. Lanning, The Possible Impact of Fuel Pellet Cracking on Inferred Gap Conductance and Stored Energy, Nuclear Technology 56 (1982) 565–574.

[5] L. A. Walton, J. E. Matheson, FUMAC–A New Model for Light Water Reactor Fuel Relocation and Pellet-Cladding Interaction, Nuclear Technology 64 (2) (1984) 127–138.

[6] Y. Rashid, R. Dunham, R. Montgomery, Fuel Analysis and Licensing Code: FALCON MOD01. Volume 1: Theoretical and Numerical Bases, EPRI, Palo Alto, CA 1011307.

[7] K. Lassmann, H. Blank, Modelling of fuel rod behaviour and recent advances of the TRANSURANUS code, Nuclear Engineering and Design 106 (3) (1988) 291–313.

[8] 10 CFR Part 50.46, Acceptance Criteria for Emergency Cooling Systems for Light-Water-Cooled Nuclear Power Plants.

[9] A. Sesonske, Nuclear Power Plant Design Analysis, Technical Information Center, Office of Information Services, U.S. Atomic Energy Commission, 1973.

[10] C. R. Hann, J. L. Bates, D. W. Brite, J. L. Daniel, N. C. Davis, P. E. Hart, R. K. Marshall, G. B. Mellinger, R. E. Williford, Test Design, Precharacterization, and Fuel Assembly Fabrication for Instrumented Fuel Assemblies IFA-431 and IFA-432, Tech. Rep. NUREG/CR-0332, BNWL-1988, Pacific Northwest Laboratory (1977).

[11] R. E. Williford, C. L. Mohr, D. D. Lanning, M. E. Cunningham, W. N. Rausch, E. Bradley, The Analysis of Fuel Relocation for the NRC/PNL Halden Assemblies IFA-431, IFA-432, and IFA-513, Tech. Rep. NUREG/CR-0588, PNL-2709, Pacific Northwest Laboratory (1980).

[12] E. R. Bradley, M. E. Cunningham, D. D. Lanning, Final Data Report for the Instrumented Fuel Assembly (IFA)-432, Tech. Rep. NUREG/CR-2567, PNNL-4240, Pacific Northwest National Laboratory (1982).

[13] M. E. Cunningham, D. Lanning, Predicted and Observed Scatter in the Fuel Rod Temperature of Replicate Rods During Irradiation, Nuclear Technology 60 (1983) 420–429.

[14] D. D. Lanning, Experimental Support and Development of Single-Rod Fuel Codes Program, Tech. Rep. NUREG/CR-4718, PNL-5972, Pacific Northwest Laboratory (1987).

[15] C. Beyer, C. Hann, D. Lanning, F. Panisko, L. Parchen, GAPCON-THERMAL-2: A Computer Program for Calculating the Thermal Behavior of an Oxide Fuel Rod, Tech. Rep. BNWL-1898, Pacific Northwest National Laboratory (1975).

[16] M. E. Cunningham, C. R. Hann, O. A. R., Uncertainty Analysis and Thermal Stored Energy Calculations in Nuclear Fuel Rods, Nuclear Technology 47 (1980) 457–467.

[17] H. R. Freeburn, M. A. Krammen, ESCORE–the EPRI Steady-State Core Reload Evaluator Code: General Description, Tech. Rep. EPRI NP-5100, Electric Power Research Institute, Palo Alto, CA (USA) (February 1987).

[18] M. Oguma, Cracking and Relocation Behavior of Nuclear Fuel Pellets During Rise to Power, Nuclear Engineering and Design 76 (1) (1983) 35–45.

[19] L. J. Siefken et al., FRAP-T5: A Computer Code for the Transient Analysis of Oxide Fuel Rods, Tech. Rep. NUREG/CR-0840 (1979).

[20] G. Zhou et al, Westinghouse Advanced UO2 Fuel Behaviors during Power Transient, Paper 1059, in: 2005 Water Reactor Fuel Performance Meeting, Kyoto, 2005.

[21] K. J. Geelhood, W. G. Luscher, P. A. Raynaud, I. E. Porter, FRAPCON–4.0: A Computer Code for the Calculation of Steady-State, Thermal-Mechanical Behavior of Oxide Fuel Rods for High Burnup, Tech. Rep. PNNL-19418 Vol.1 Rev. 2, Pacific Northwest National Laboratory (2015).

[22] J. D. Hales, R. L. Williamson, S. R. Novascone, G. Pastore, B. W. Spencer, D. S. Stafford, K. A. Gamble, D. M. Perez, R. Gardner, W. Liu, J. Galloway, C. Matthews, C. Unal, N. Carlson, BISON Theory Manual: The Equations Behind Nuclear Fuel Analysis, Tech. Rep. INL/EXT-13-29930, Rev.3, Idaho National Laboratory (September 2016).

[23] L. P. Swiler, R. L. Williamson, D. M. Perez, Calibration of a fuel relocation model in BISON, in: Proceedings of the International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Sun Valley, Idaho, 2013.

[24] IFPE/OSIRIS R3 Database, Tech. rep., OECD Nuclear Energy Data Bank (May 2002).

[25] IAEA, Improvement of Computer Codes Used for Fuel Behaviour Simulation (FUMEX-III): Report of a Coordinated Research Project 2008-2012, Tech. Rep. IAEA-TECDOC-1697, International Atomic Energy Agency (2008-2012).