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Rim Structure Effects on Fuel Rod Performance with Burn up Extension Using FRAPCON

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Abstract

Extending the authorized fuel burn up limit of Light Water Reactor (LWR) is one of the most promising methods to enhance the commercial competitiveness of nuclear power plants. The benefits with high burn up include reduced maintenance and fuel cycle costs, less refueling operations thus leading to higher capacity factors, and reduction of the volume of spent fuel discharged normalized to the energy produced. However, to ensure the integrity of fuel rods with high burn up fuel, there are still a number of issues that need to be remedied. For example, the formation of High Burn up Structure (HBS) or rim structure is possibly the most significant restructuring processes at the rim of pellets in-pile with burn up extension in LWR and the effect of HBS on fuel thermo-physical or mechanical properties is a key requirement to ensure successful implementation of extended burn up. There is independently experimental evidence to support that HBS concomitantly affects thermal and mechanical properties of fuel. But it is still not well understood how such HBS affects fuel thermo-physical or mechanical properties. In this work, the impact of the HBS formation on the fission gas behavior of fuel rods was evaluated under normal operating conditions. The fuel performance code FRAPCON-4.0 was used to simulate fission gas related properties of full-length fuel rods with the HBS formation via the FRAPFGR model and without rim structure via the Massih model under normal operating conditions. It is found that as the burn up extends from the current limit of 62 to proposed new limit of 75 GWd/MTU, the plenum pressure and fission gas release have only modest increase with flat power history profiles and without the HBS effects considered. However the increase is more pronounced when the power history profiles have higher peaking factors and when the contribution of HBS formation is taken account. It is recommended to keep the power history profiles as flat as possible, both radially and axially, in NPP operations to ensure the integrity of fuel rods such that the benefits of burn up extension can be realized.

Keywords: High burn up structure; LWR fuel; Thermo-mechanical properties; Fission gas release

Introduction

Extending the authorized fuel burn up limit of Light Water Reactor (LWR) is one of the most promising methods to enhance the commercial competitiveness of nuclear power plants. The benefits with high burn up include increased availability, reduced maintenance and fuel cycle costs, less refueling operations thus leading to higher capacity factors, and reduction of the volume of spent fuel discharged normalized to the energy produced. To ensure the integrity of fuel rods operating with high burn up fuel, it has become important to determine and assess the practical limitations that may arise from the physical evolution of the fuel. For example, Uranium Dioxide (UO_2) and other nuclear fuels (*i.e.*, Mixed Oxide (MOX, (U, Pu) O_2)) develop a unique microstructure that occurs at the pellet periphery under irradiation usually known as the High Burn-Up Structure (HBS) or rim structure. It is characterized by the microstructural restructuring including the loss of original grain structure by restructuring into fine grains, large bubbles with high density, and relocation of fission gas in the matrix (*i.e.*, dissolved or as fine, nanometer size, bubbles) into large bubbles. As the self-reorganization of the nuclear fuel pellet in responding to the radiation damage and harsh thermo-mechanical conditions established in-pile, the formation of such HBS is possibly the most significant restructuring processes at the rim of pellets in-pile and the primary postulated limitation for the reactor performance and safety with burn up extension in LWRs [1,2].

Since it was observed for the first time in very high burn up fuel in the late 1950s by Belle [3], observations on restructuring of UO_2 fuel and characteristics of this HBS formation have been a topic for decades [2,4-9]. Many thermo-mechanical, physical and chemical properties of this structure have also been investigated, including fission gas release and fission product depletion, porosity, thermal conductivity, oxidation state and stoichiometry of UO_2, and lattice parameter [10-16]. It was clear from these studies that the HBS formation concomitantly affects thermal and mechanical properties of fuel, supported by independently experimental evidence. For example, it was shown that the HBS formation alters thermo-mechanical [17,18] and fission gas retention properties [19] of the high burn up fuel that is significantly different from the fuel within the current burn up limit of 62 GWD/MT with respect to the original UO_2 under normal operation. In addition, HBS plays an important role in fuel fragmentation and pulverization during Reactivity Initiated Accidents (RIAs) [20] as well as Loss Of Coolant Accidents (LOCAs) [21].

The effect of HBS on fuel thermo-physical or mechanical properties is a key requirement to ensure successful implementation of extended burn up, e.g., from the current rod averaged burn up limit of 62 GWD/MT to proposed new limit of 75 GWD/MT. However, it is still not well understood how such HBS affects fuel thermo-physical or mechanical properties. The application of the latest generation of characterization tools and techniques to probe the properties of high burn up fuel is still limited due to multiple challenges need to be remedied, though the challenges on instrumentation access and sample handling have been recently overcome [16]. Complementally, modeling and simulation may provide new information on the mechanical properties of high burn up structure in UO_2 fuel and deliver guidance on how and why HBS might be a primary postulated limitation for the reactor performance and safety with burn up extension.

With burn up extension, fission gas will be released extensively from the fuel pellet, causing excessive internal pressurization of the fuel rod, leading to the reduction of the thermal contact between fuel and cladding, thus increasing the fuel temperature. This may ultimately lead to fuel rod failure during accidents such as Loss-Of-Coolant Accident (LOCA) with which the differential pressure difference between fuel rod internal and external might challenge the fuel rod integrity. In order to provide a more detailed description of fuel performance with increased burn up, an important step is to assess explicitly the impact of HBS formation on the fuel rod performance. For this purpose, in this study, the impact of rim structure on the fission gas behavior of full-length fuel rods under normal operating conditions with burn up extension was evaluated by carrying out modeling and simulation via fuel performance code FRAPCON-4.0 [22]. The fission gas release and the rod internal pressure behavior was investigated under burn up of 62 GWd/MTU and burn up extension to 75 GWd/MTU with and without directly accounting for the rim structure or HBS formation.

HBS Effect on Rod Internal Pressure

The fuel performance code FRAPCON-4.0. was used to simulate fission gas related properties of a full-length fuel rod with and without rim structure under normal operating conditions. The FRAPCON-4.0 code is a steady-state fuel performance code, developed by PNNL to be applied to in-reactor operational conditions [22]. The code architecture is based on the coupling of thermal, mechanical and Fission Gas Release (FGR) modules. In order to investigate the effect of rim structure on fission gas behavior of fuel rods in this study, the FRAPFGR model has been chosen for the FGR module. The FRAPFGR model has been developed at PNNL to initialize the transient release model in FRAPTRAN that is used to calculate fission gas release during fast transients such as an RIA. Because of this, the FRAPFGR model predicts not only the steady state gas release, but also the amount of gas remaining within the grains and residing on the grain boundaries for each axial and radial node. During a fast transient due to cracking along the grain boundaries, the grain boundary gas is released. The FRAPFGR model has been validated against the gas release data as well as Electron Probe Micro Analysis (EPMA) and X-Ray Fluorescence (XRF) data. The high burn up rim structure observed in the outer edge of high burn up pellets is characterized in terms of sub-micron grains and high porosity. Both items are modeled in the FRAPFGR model for explicitly accounting for the rim structure formation. Meanwhile, the Massih model [23] implemented in the FRAPCON-4.0 code has also been chosen to predict fission gas release without directly accounting for the HBS formation.

To illustrate the effect of the HBS, FRAPCON-4.0 calculations were performed using both the Massih and FRAPFGR models for all the fuel rods in an assembly with burn up extension. The power histories for the FRAPCON-4.0 calculations were obtained from an equilibrium cycle core design with 24 months fuel cycle length for a typical Pressurized Water Reactor (PWR). The core design work was performed with CASL's VERA-CS code [24,25].

The calculated Rod Internal Pressures (RIP) using Massih and FRAPFGR are compared in Figure 1 for a twice-burnt assembly on the periphery with burn up extension. It can be seen from Figure 1 that when the fuel rod discharge burn up stays within the current burn up limit of 62 GWD/MT, the RIPs are about the same with and without HBS considered. However when the rod averaged discharge burn up is extended up to about 75 GWD/MT range, the RIPs are much higher when the HBS is considered in FRAPCON-4.0 calculations. That indicates that HBS could have adverse effect on the integrity of fuel rods and warrant investigations on means to reduce the impact of HBS when the fuel burn up is extended.

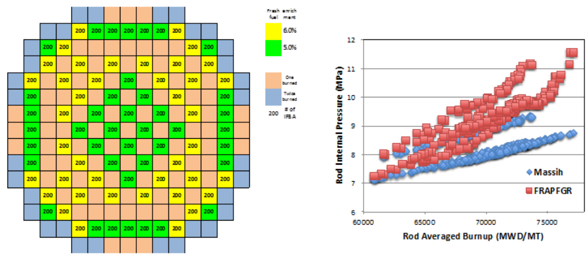

Figure 1: The left Figure on shows the loading map for a 24 months cycle design for a typical PWR and the Figure on the right show the comparison of calculated rod internal pressure with Massih and FRAPFGR models for all the fuel rods in a twice-burnt assembly with burn up extension.

Investigation of Methods to Reduce the HBS Effects

In this section, the methods to reduce the effect of HBS on burn up extension are investigated. In subsection 3.1, FRAPCON-4.0 simulations of a single fuel rod with idealized power profile (uniform axial power profile) is used to investigate the HBS effects on fuel behaviors. In subsection 3.2, sensitivity studies of HBS effects on axial peaking factors and radial peaking factors are performed with more realistic power profiles.

FRAPCON-4.0 simulations with idealized conditions

The investigation started with FRAPCON-4.0 simulations of a single fuel rod under idealized conditions, e.g. uniform axial power history. The main parameters to simulate a full-length fuel rod performance used in FRAPCON-4.0 simulations are listed in Table 1. Four sets of linear heat rate (average power) profile for three cycles selected for the simulations are shown in Figure 1. BU62/BU62-2 and BU75/BU75-2 are depicting 4.5-year normal and 6-year with burn up extension operation, respectively. For the first normal operation of BU62, the average power is about 24.2, 17.9 and 11.7 kW/m for the 1st, 2nd and 3rd cycle. By normalizing to the average power of first cycle, the correspondingly normalized rates are 1, 0.74 and 0.48 for three cycles. For the second normal operation of BU62-2, the average powers are about 21.3, 19.1 and 13.8 kW/m for the 1-st, 2-nd and 3-rd cycle, which corresponds to the normalized rate 1, 0.9 and 0.65.

Table 1: Fuel rod parameters used in FRAPCON.

Parameter	Value
Rod outer diameter (mm)	9.5
Cladding thickness (mm)	0.57
Gap thickness (mm)	0.084
Total (active) fuel column length (m)	3.657
Cold plenum length (mm)	160
Dish radius (mm)	1
Dish depth (mm)	0.275
Chamfer width (mm)	0
Enrichment (%)	3.5
Pellet density (%TD)	94.8
Cladding type	Zry-4

For the first burn up extension of BU75, the average power is about 21.9, 16.2 and 10.6 kW/m for the 1-st, 2-nd and 3-rd cycle, remaining the same normalized rates as BU62. For the second burn up extension of BU75-2, the average power is about 19.3, 17.3 and 12.5 kW/m for the 1-st, 2-nd and 3-rd cycle, corresponding to the same normalized rates as BU62-2. The power axial profile is assumed as uniform.

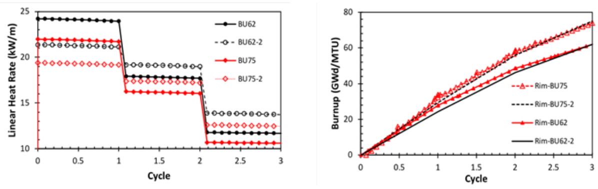

Figure 2: The left Figure shows the linear average power profile for three cycles. BU62/BU62-2 and BU75/BU75-2 are corresponding to 4.5-year normal and 6-year with burn up extension operation, respectively. The Figure on the right shows the burn up as a function of cycle number.

Noted that the FRAPCON-4.0 code is a 1.5 D code, meaning that the equations are simplified to radial form at multiple axial locations. The equations are fully solved radially, while axially effects are only partially modeled. While the model used here is less accurate due to the neglecting of all azimuthal gradients and many axial effects, it is advantageous in its computational performance, which is rendered substantially less cumbersome by case runtimes. Also noted that the FRAPFGR model may not predict stable fission gas release as well as the Massih model does. Based on our extensive simulations with the FRAPFGR model and with comparison with the Massih model, no issue regarding the stability of the FRAPFGR model occurs by explicitly accounting for the HBS formation.

During irradiation, the thermal, mechanical and chemical properties of fuel rod vary with power, exposure or time and operating history. Nearly all of these properties are expected to change in responding to burn up established in-pile, especially with burn up extension, leading to the degradation of the fuel integrity and performance. Figure 2 shows burn up evolution as a function of cycles with/out considering rim structure. It is unlikely that the rim structure has any impact on the fuel burn up based on the model implemented in FRAPCON-4.0. It is observed that the burn up profiles for the case without rim structure with the Massih model are identical to those with the rim structure formation within the FRAPFGR model (not shown here). By the End of Life (EOL), the burn up reaches about 62 and 75 GWd/MTU with the average power profile of BU62/BU62-2 and BU75/BU75-2 as shown in Figure 2. By the End of First Cycle (1st-EOC), burn ups are 27.88, 24.32, 33.69, and 29.39 GWd/MTU, corresponding to BU62, BU62-2, BU75 and BU75-2 average power, respectively. By the 2nd EOC, burn ups are 48.51, 46.17, 58.68, and 55.85 GWd/MTU. By the 3rd-EOC, burn ups are 61.99, 61.97, 75, and 74.97 GWd/MTU. It is apparent that burn up is relative higher in the 1st and 2nd cycle, as well as the early stage of 3rd cycle with the average power profile of BU62 and BU75. This is due to the fact the linear heat rate is higher in the 1st cycle. Meanwhile, the slopes of burn up are reduced for the 2nd and 3rd cycle to project the corresponding lower powers.

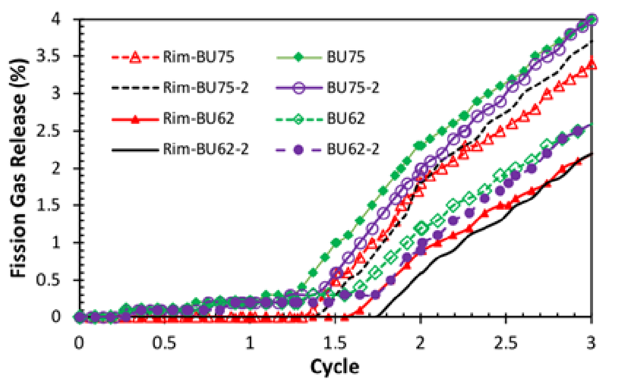

Figure 3: Fission gas release evolution as a function of cycle.

The increase in fission products concentration with increasing burn up will affect a number of fuel properties during operation and post-irradiation. To ensure successfully implement extended burn up, good fission gas retention is desired, since the release of fission products with the potential for contributing to cladding failure. Figure 3 shows the evolution of fission gas release as a function of cycles with/out considering the impact of rim structure. As is seem from the Figure, it can be observed that the fission gas release is reduced by the rim structure. In particular, by EOL, the fission gas release is about 2.2% and 2.6% under the normal operation (about the same for the average power profile of BU62 and BU62-2 shown in Figure 2) with and without considering rim structure, respectively. Thus, with rim structure, the relative reduction of the fission gas release is about 15% under the normal operation.

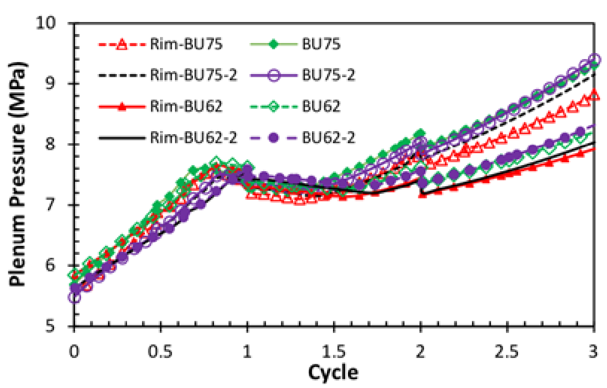

Figure 4: Plenum pressure evolution as a function of cycle.

With burn up extension, it is expected that extensive fission gas will release from the fuel pellet. As shown in Figure 3, by the EOL with burn up extension, the fission gas release is about 3.5% and 4.0%, corresponding to the average power profile of BU75 shown in Figure 2, with and without considering rim structure, respectively. However, corresponding to the average power profile of BU75-2, the fission gas release is about 3.7 and 4.0 with and without considering rim structure. Thus, with rim structure, fission gas release is relatively reduced by about 12.5% and 7.5%. However, the absolute amount of the reduction of fission gas release by the EOL is in the range of 0.3% to 0.5% under normal operation and with burn up extension and the benefit might not be too significant with considering HBS.

During irradiation, the internal pressurization of the fuel rod is excessive as extensive fission gas is released from fuel pellets to the free volume within a fuel rod. Figure 4 shows the rod internal pressure evolution as a function of cycles with/out considering the rim structure. It is observed that the plenum pressure is reduced by the rim structure. In particular, by the EOL, the plenum pressure is about 7.9 (8.0) and 8.2 (8.3) MPa under the normal operation for the average power profile of BU62 (BU62-2) with and without considering rim structure, correspondingly. Thus, by considering the effect of rim structure, there is a slight reduction of the rod internal pressure by about 0.28 MPa under the normal operation.

With increased burn up, it is anticipated the fuel rod has a higher internal pressure due to the decreasing free volume of gap and plenum by pellet swelling and elongating, inward cladding creep and differential thermal expansion between pellets and cladding. As shown in Figure 4, by the EOL with burn up extension, the plenum pressure is about 8.9 (9.14) and 9.3 (9.4) MPa with and without considering rim structure, driven by the average power profile of BU75 (BU75-2). Thus, compared with normal operation, it is observed from the simulations that the rod internal pressure increases by ~12% as the burn up is extended from 62 to 75 GWd/MTU, no matter whether or not the contribution of HBS is taken into account. Meanwhile, with considering rim structure, the benefit for decreasing plenum pressure is only about 0.4 (0.26) MPa for the average power profile of BU75 (BU75-2).

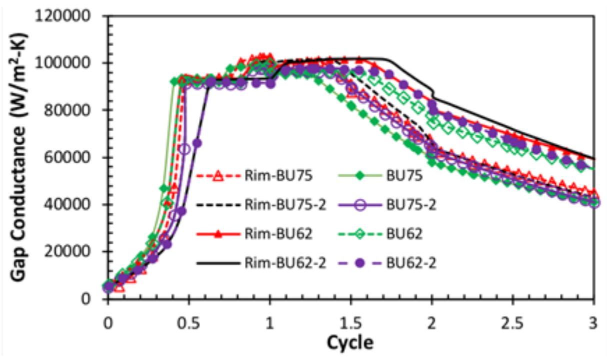

Figure 5: Gap conductance evolution as a function of cycle.

It is unlikely that the rim structure has larger positive impact on the plenum pressure for the 1st and 2nd cycle than that of EOL. Under normal operation, the plenum pressure is about 7.56 (7.62) and 7.53 (7.58) MPa for with and without rim structure for the average power profile of BU62 (BU62-2) by the end of 1st cycle. By the end of 2nd cycle, the plenum pressure is about 7.43 (7.61) and 7.39 (7.55) MPa for with and without rim structure for the average power profile of BU62 (BU62-2).

With burn up extension, the plenum pressure is about 7.4 (7.49) and 7.38 (7.44) MPa for with and without rim structure for the average power profile of BU75 (BU75-2) by the end of 1st cycle. By the end of 2nd cycle, the plenum pressure is about 7.92 (8.18) and 7.95 (8.03) MPa for with and without rim structure for the average power profile of BU75 (BU75-2). It is noted by the end of 1st cycle, the rod internal pressure under normal operation is higher than that of with burn up extension. This may seem surprising at first however, the relative lower linear heat rate with burn up extension in the 1st cycle may induce less fuel pellet thermal expansion and lead to lower rod internal pressure.

The increase in fission products concentration with increasing burn up will also affect thermal conductance of the pellet-to-cladding gap. Figure 5 shows the evolution of gap conductance as a function of cycles with/out considering the rim structure. As is seem from the Figure 5, the gap conductance is enhanced by the rim structure. In particular, by the EOL, the gap conductance is about 59189 (54914) and 59478 (55189) W/m2-K under the normal operation for the average power profile of BU62 (BU62-2) with and without considering rim structure, correspondingly. Thus, with rim structure, the enhancement of the gap conductance is about 4275 (4288) W/m2-K under the normal operation. The relative enhancement of the gap conductance with rim structure is about 7.8% for both average powers (BU62 and BU62-2 shown in Figure 2).

With increasing burn up, it is expected the gap conductance will increase due to the decreasing gap of pellet-cladding by pellet swelling, inward cladding creep, differential thermal expansion between pellets and cladding, and gap closure by radial relocation. However, as shown in Figure 5, by the EOL with high burn up, the gap conductance is about 44018 (40864) and 43009 (41042) W/m2-K with and without considering rim structure, driven by the average power profile of BU75 (BU75-2). Thus, a considerable decrease of gap conductance (~ 26%) is observed the burn up extended from 62 to 75 GWd/MTU, no matter whether or not the contribution of HBS is taken into account. One possible explanation for this apparent contradiction lies in the fact that the decrease rate of gas thermal conductivity is much faster than that of pellet-cladding gap as burn up increasing.

In addition, as burn up increasing, the gap conductance is increased about 3153 (1966) W/m2-K for the average power profile of BU75 (BU75-2) with considering rim structure. The relative enhancement of the gap conductance with rim structure is about 7.7% and 4.8% for the average power profile of BU75 and BU75-2. Thus, rim structure will induce the enhancement of the gap conductance no matter whether or not with burn up extension. It is likely that the rim structure has some positive impact on the gap conductance.

Sensitivity studies on peaking factors

The results from subsection 3.1 indicated that HBS effects are minimal if the axial power profiles are uniform. However this idealized power profile does not happen in real NPP operations. In this subsection, sensitivity studies are performed to find out the HBS effects on fuel behaviors, especially fission gas release and fuel rod internal pressure, when different axial and radial peaking factors are used in the calculations. The power history of BU75-2 is used as the reference case. The sensitivity studies on axial peaking factors are performed by keeping the linear heat generation rate the same as that shown in Figure 2 for BU75-2. Instead of using uniform axial power profile, chopped cosine power profiles are used in the calculations with the peak-to-average ratios of 1.1, 1.2, 1.3 and 1.4 respectively. The rod averaged burn up is kept at about 75 GWD/MT for these different axial power profiles. It is recognized that the axial power profile changes throughout the lifetime the fuel in a reactor core. For simplicity of calculations only the chopped cosine shapes are used in the calculations. The calculated fission gas release and rod plenum pressure are shown in Figure 6 for both the Massih and FRAPFGR models. It can be seen from Figure 7 that, when HBS effects are considered, both the fission gas release and rod plenum pressure increase significantly when the axial power peaking factors are increased.

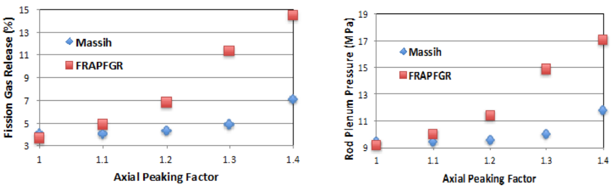

Figure 6: The left Figure shows the comparison of fission gas release for Massih and FRAPFGR models with different axial peaking factors. The Figure on the right shows the comparison of rod internal pressure for Massih and FRAPFGR models with different axial peaking factors.

The sensitivity studies on radial peaking factors are performed by keeping the linear heat generation rate for the 1st cycle the same as that of the reference value. However the linear heat generation rate for the 2nd cycle is increased by 10%, 20%, 30% and 40% respectively while the linear heat generation rate for the 3rd cycle is decreased by the same amount as that increased for the 2nd cycle operations. The axial power profile is kept uniform. In this way, the rod averaged burn up is also kept at 75 GWD/MT. The calculated fission gas release and rod plenum pressure are shown in Figure 7 for both the Massih and FRAPFGR models. It can be seen from Figure 7 that the both the fission gas release and rod plenum pressure increase significantly when the axial power peaking factors are increased and when the HBS effects are considered.

Discussion

With a view to extend the authorized fuel burn up limit of LWR to enhance the commercial competitiveness of nuclear energy, a number of key issues relative to fuel behavior at high burn up are needed to demonstrate with increasing confidence that fuel can operate safely at extended exposures under a wide range of conditions to achieve high burn up without deterioration of the fuel rod integrity. Having initially investigated of the impact of rim structure on the fission gas behavior of fuel rod, it is observed that HBS formation could have adverse effect on fuel behaviors as the burn up extended from 62 to 75 GWD/MT. The plenum pressure and fission gas release increase, and gap conductance decreases at the burn up extended from 62 to 75 GWD/MT. Without the consideration of HBS effects, the changes are modest and may not compromise the integrity of nuclear fuel rods during normal operations and with burn up extension. However, when HBS effects are considered, the fission gas release and rod internal pressure increase significantly when the power history profiles have higher peaking factors, both radially and axially. It can be concluded that the high burn up itself, such as 75 GWD/MT, might not be the limiting factor with respect to achieving burn up extension. The power histories, especially the peaking factors, have more impact on the HBS effects and fission gas release. The increased pressurization of fuel rods with highly peaked power histories could challenge the fuel rods integrity with burn up extension. Therefore, it is important to keep the power profiles as flat as possible in NPP operations in order to reduce the effects of HBS and to ensure the integrity of fuel rods such that the benefits of burn up extension can be fully realized.

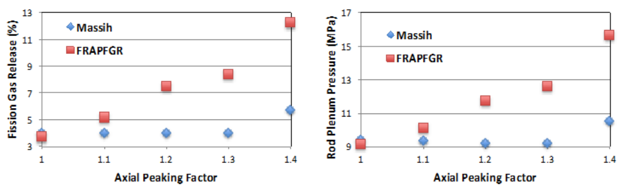

Figure 7: The left Figure shows the linear average power profile for three cycles. BU62/BU62-2 and BU75/BU75-2 are corresponding to 4.5-year normal and 6-year with burn up extension operation, respectively. The Figure on the right shows the burn up as a function of cycle number.

Conclusion

Rim structure is the self-reorganization of the nuclear fuel pellet in responding to the radiation damage and harsh thermo-mechanical conditions established in-pile, especially with burn up extension. We speculate that rim structure may impact significant fuel performance under accidents, since the internal gas pressure, especially after a reactivity insertion accident, is remarkably enhanced by the burst release of fission gas, which may ultimately lead to fuel rod failure during accidental transients. Action is needed to demonstrate with increasing confidence that fuel can operate safely at extended exposures under a wide range of conditions under normal operation and rods from very high burn up. In conjunction with the enhancement of the safety margins associated with burn up extension, future simulation will be focused on the impact of rim structure on the fission gas behavior of fuel rod under design-basis accidents. However, the FRAPFGR model is a relatively simple mode based purely empirically. Apparently, it is needed to develop realistic high burn up models that are based more on theory than on empirical observations to minimize the amount of data needed to assure safe operation. Meanwhile, expanding and acquiring experimental databases specifically targeted at assessing key properties and behavior of the HBS formation are crucial for the fuel performance within the safety margins associated with burn up extension, as well as to valid and verify the analytic method development. Although the amount of data is limited, data for UO2 fuel with a local burn up in the range 160–250 GWd/MTU have already been collected experimentally.

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