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Original Article

FRAPCON analysis of cladding performance during dry storage operations

David J. Richmond*, Kenneth J. Geelhood

PNNL, 902 Battelle Blvd, Richland, WA 99352, USA

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ABSTRACT

There is an increasing need in the United States and around the world to move used nuclear fuel from wet storage in fuel pools to dry storage in casks stored at independent spent fuel storage installations or interim storage sites. Under normal conditions, the Nuclear Regulatory Commission limits cladding temperature to 400°C for high-burnup (>45 GWd/mtU) fuel, with higher temperatures allowed for low-burnup fuel. An analysis was conducted with FRAPCON-4.0 on three modern fuel designs with three representative used nuclear fuel storage temperature profiles that peaked at 400°C. Results were representative of the majority of US light water reactor fuel. They conservatively showed that hoop stress remains below 90 MPa at the licensing temperature limit. Results also show that the limiting case for hoop stress may not be at the highest rod internal pressure in all cases but will be related to the axial temperature and oxidation profiles of the rods at the end of life and in storage.

1. Introduction

Currently, there is a focus on moving fuel out of spent fuel pools into dry storage systems in the United States and around the world. Increasingly, this fuel will be high-burnup fuel, greater than 45 GWd/MTU. The current rod average fuel burnup limit in the United States is 62 GWd/MTU which corresponds to an assembly average burnup of about 55 GWd/MTU. Previous work has been carried out to analyze conditions of dry storage Ref. [1] in low-burnup fuel with older designs. With this in mind, it is useful to investigate whether the current regulatory limits on fuel in dry storage still have a valid basis for modern, high-burnup fuel. Three different fuel designs were analyzed with three different axial temperature profiles to simulate steady state, bounding, dry storage conditions. These conditions also encompass bounding temperatures for drying and loading operations. The varied analysis characterizes the effects of fuel design and storage system design on the cladding conditions. Temperatures were imposed so that the peak cladding temperature is at the current licensing limit to bound hoop stress and rod internal pressure (RIP) results.

1.1. *Current regulations*

The Nuclear Regulatory Commission has limited the maximum peak cladding temperature during normal conditions of dry storage to 400°C (752°F) for fuel with a burnup greater than 45 GWd/MTU. This limit is set to protect the fuel rod cladding and the storage system components from damage mechanisms related to high temperature Ref. [2]. The principle mechanism for cladding damage at these temperatures is embrittlement due to radial hydride reorientation. This occurs at high temperatures and stresses where hydrogen in the cladding will orient itself into a radial direction due to the hoop stress in the cladding. This makes the cladding more susceptible to crack growth and fracture during long-term storage. With this knowledge, the 400°C thermal limit is meant to keep cladding hoop stress below 90 MPa Ref. [2]. Previous research Ref. [2] has determined these temperature and hoop stress limits to be a reasonable bound for avoiding reorientation.

There is a higher 570°C limit during short-term operations. The 570°C limit may only be applied provided that applicants for a certificate of compliance under section 10 Code of Federal Regulations 72.3 can show hoop stress remains below 90 MPa Ref. [2]. Applicants do not need to analyze hoop stress if clad temperature remains below 400°C. Most cask licenses are based on maintaining the 400°C limit and do not attempt to characterize hoop stress. However, because of the methodology laid out in Interim Staff Guidance-11 Ref. [2], it is important to analyze hoop stress at

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* *Corresponding author.*
E-mail addresses: david.richmond@pnnl.gov (D.J. Richmond), kenneth.geelhood@pnnl.gov (K.J. Geelhood).

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400°C and determine if it remains below the 90 MPa limit for hydride reorientation in high-burnup fuel.

1.2. Dry storage system background

Dry storage systems fall into two broad classes, canistered and noncanistered. An example of a noncanistered system is the TN-32, shown in Fig. 1. Noncanistered systems consist of grid structures to support the fuel, with a thick metal wall and support structures for shielding, heat removal, and structural integrity. The cask interior is filled with helium which is chosen for its lack of reactivity and its heat transfer properties.

Canistered systems are more common in the United States than the noncanistered systems due to their versatility and generally lower cost. Similar to the noncanistered system, there is a metal grid to hold the fuel assemblies; however, this grid sits in a relatively thin canister (Fig. 2) instead of the thick walled cask. This canister may have different industry names, such as multipurpose canister, dry shielded canister, or transportable storage canister. This design allows the canister to be placed in a vertical ventilated storage system such as the HI-STORM 100 (Fig. 2) or a variety of other systems. For example, a single canister could be placed in vertical storage modules, horizontal modules, underground storage modules, onsite transfer casks, and offsite transportation casks.

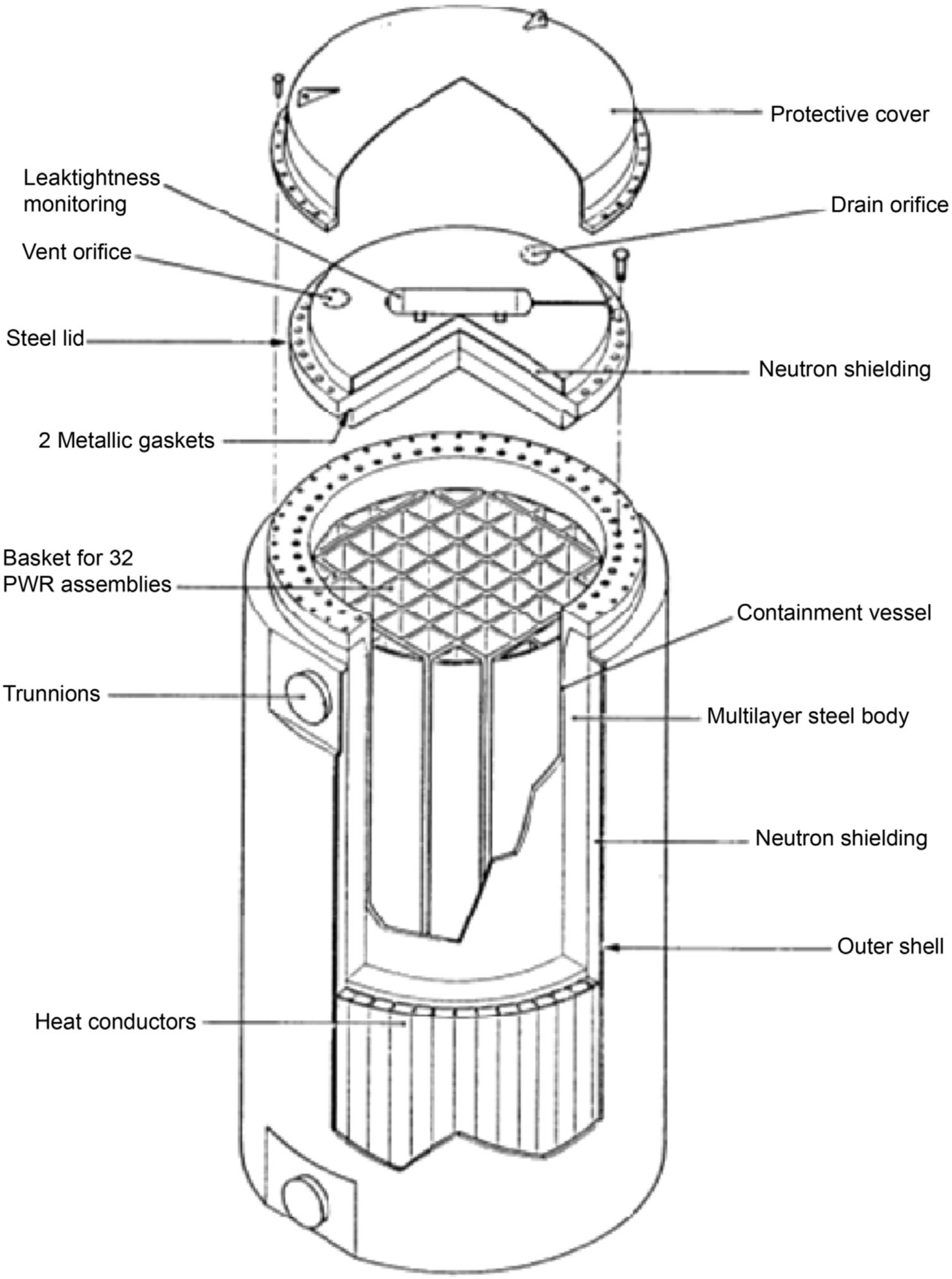

Fig. 1. TN-32 used fuel storage cask Ref. [3].
PWR, pressurized water reactor.

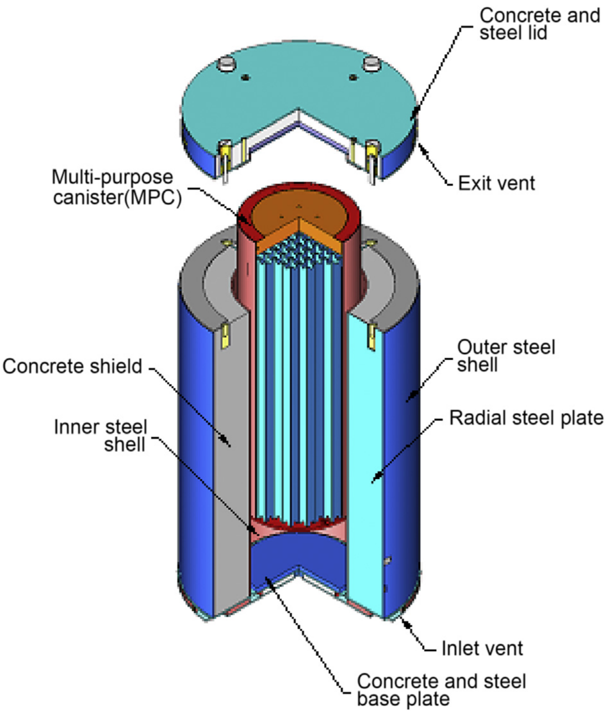

Fig. 2. HI-STORM 100 cutaway view Ref. [3].

2. Model description

2.1. Application of FRAPCON

For this analysis, the primary goal was to obtain bounding estimates for cladding hoop stress and RIP at loading and during drying operations. To accomplish this, a FRAPCON Ref. [4] base-irradiation case was extended with an additional time step at zero power after a typical irradiation history. Temperature profiles typical of dry storage are imposed on the cladding surface with coolant pressures that reflect realistic canister fill gas pressures for this time step. This approach neglects time spent in the fuel pool (typically a minimum of 5–10 years). This has been neglected because there is no reason to believe that the pool conditions would have a large effect on the cladding condition at loading. Rods in the cooling pool only have decay heat generation, and ≈100°F water provides heat removal to maintain low clad temperatures. These conditions are much less severe than those found in reactor or those in dry storage. For example, it can be assumed that there will be no waterside cladding corrosion, no cladding creep, and no fission product release from the pellets.

2.2. Fuel designs

This analysis focuses on modern designs that are currently in use and will be placed into dry storage in the future. For boiling water reactor (BWR) fuel, a generalized 10 × 10 fuel design was used. For pressurized water reactor (PWR) fuel, two designs were studied. A 17 × 17 design with UO_2 pellets and a 17 × 17 design with an integral fuel burnable absorber (IFBA) blanket. Other burnable absorbers are used such as UO_2-Gd_2O_3, but the IFBA design was chosen because it will result in the highest RIP due to the production of helium from the B-10 + neutron reaction. For the IFBA model, FRAPCON assumes that all B-10 that absorbs neutron produces helium that is released to the void volume. The PWR designs used ZIRLO cladding, and the BWR used Zircaloy-2. These three designs were chosen because they are expected to be representative of most light water reactor fuel in use in the United States.

2.3. Power histories

The power histories and axial profiles used in the base irradiation are realistic limiting cases meant to give maximum RIP. Power history for both PWR fuels was nearly the same and is shown in Fig. 3. The rod average burnup was 45.17 GWd/MTU for the BWR case. The PWR rod average burnup was 55.02 GWd/MTU for the 17 × 17 and 57.30 GWd/MTU for the 17 × 17 IFBA case.

2.4. Temperature profiles

Dry storage conditions result in nonuniform temperature profiles at the cladding surface. This is due to the axial decay heat generation profile of spent fuel and the flow conditions which vary by storage system design and loading pattern. The typical heat generation profile is nearly symmetric with steady heat generation along the active length of the fuel tapering to zero heat generation at each end. Often, a flat heat generation profile will be used in the center of the active length as a bounding profile.

For this analysis, three different temperature profiles designated "vacuum", "mid flow," and "high flow" (Fig. 4) were generated based on thermal modeling experience and generalized models of storage systems for a range of conditions.

The shape of each temperature profile is driven primarily by the amount of internal recirculation in the canister and the resulting heat transfer due to convection. The "vacuum" profile closely follows the heat generation profile of a spent fuel rod indicating that there is no significant heat transfer due to convection. The only significant mechanisms are thermal radiation and conduction through the backfill gas and fuel basket because during vacuum drying, the low density of the fill gas does not allow it to effectively transport energy by convection. The profile for the vacuum case is also characteristic of a horizontal module. In the horizontal case, there is no significant driving force for recirculation even though the fill gas density is higher than the "vacuum" case.

The "mid flow" and "high flow" cases represent a vertical ventilated storage module with low fill gas density (around 1–2 atm) and high fill gas density (around 5–6 atm). In the "mid flow" case, the peak of the temperature profile sits in the top third of the active length of the fuel. This is typical across a wide array of vertical storage systems, where they are moderately loaded (≈60%

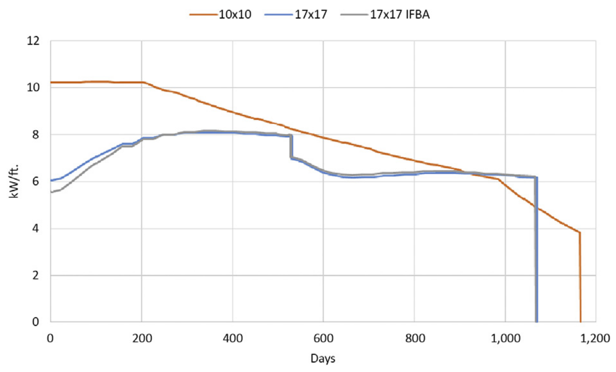

Fig. 3. Power histories of selected cases.
IFBA, integral fuel burnable absorber.

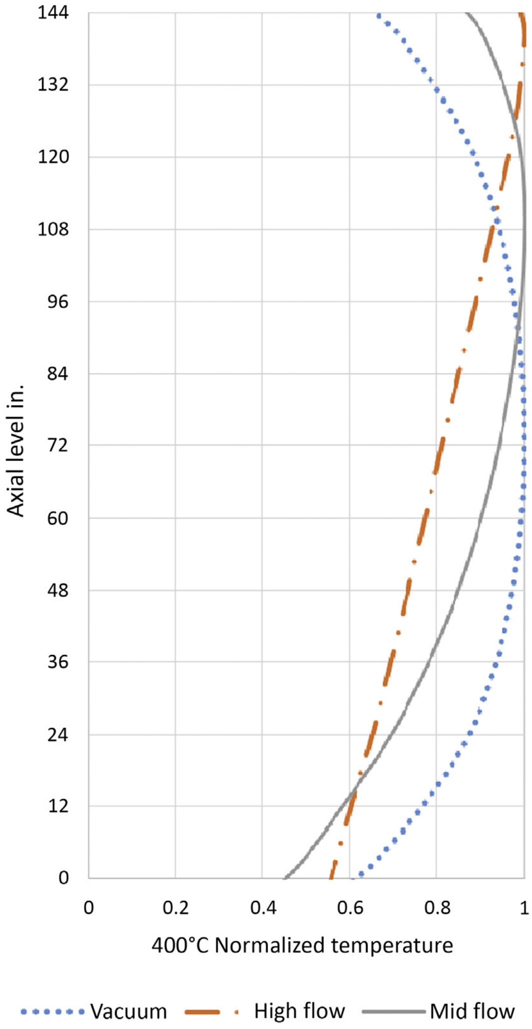

Fig. 4. Peak normalized temperature profiles used.

design basis) and allow for moderate flow. The "high flow" case represents analysis carried out on a system with particularly favorable convection conditions loaded at 100% design basis. It is unusual for the peak to be this close to the top of the active length during actual operation; however, it is useful to investigate a case where the temperature peak is near the plenum of the rod. This will result in a high plenum temperature and, coupled with the typically 60–70% of the free void volume being in the plenum at the end of life, will result in high RIP.

2.5. Oxide formation

During irradiation in the reactor, the zirconium in fuel cladding reacts with the water according to Eq. (1) to form zirconium dioxide and hydrogen.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 \tag{1}$$

Throughout the operation, the zirconium dioxide generated in this reaction is deposited on the outside of the fuel cladding. In addition, under irradiation, oxygen is released from the fuel pellet, and once fuel–clad bonding occurs (typically around 20–30 GWd/MTU), it can form a ZrO_2 layer on the cladding inner surface. The inner and outer layers of oxide have two major effects. The first is the deposited oxide acts as an insulator for the fuel, causing it to operate at higher temperatures. The second effect is more important in this analysis. The oxide layer has no appreciable structural strength and, therefore, effectively thins the cladding according to Eq. (2). This is based on the Pilling–Bedworth ratio (1.56) of cladding to oxide density Ref. [5]. Hoop stress results are reported in Section 3 with this effect adjusted for.

$$t_{eff} = t_{nom} - \frac{\delta}{1.56} \tag{2}$$

where,

t_{eff} = effective cladding thickness (m)
t_{nom} = nominal cladding thickness (m)
δ = oxide layer thickness (m)

2.6. Calculation of hoop stress

In FRAPCON, hoop stress is calculated according to Eq. (3) Ref. [4].

$$\sigma = \frac{r_i P_i - r_o P_o}{t} \tag{3}$$

where,

σ = hoop stress (MPa)
P_i = internal pressure (MPa)
P_o = coolant pressure (MPa)
r_i = inside radius (m)
r_o = outer radius (m)
t = cladding thickness ($r_o - r_i$) (m)

The application of this equation in FRAPCON uses the fabricated values for r_i and r_o. This does not account for clad thinning discussed in Section 2. To account for this, the hoop stress is adjusted by multiplying a stress factor given by Eq. (4). This adjustment has a significant impact in the results presented in Section 3.

$$K = \frac{t_{nom}}{t_{nom} - t_{eff}} \tag{4}$$

where,

K = Stress Factor
t_{nom} = nominal cladding thickness (m)
t_{eff} = effective cladding thickness (m)

2.7. Conservatism

The results of this work are meant to be realistic and bounding for fuel in dry storage and during loading and drying operations. Although they do not constitute a complete set of fuel designs, they are representative of the light water reactor fuel currently in use. Much of the conservatism this analysis can take credit for is inherent in the design and operation of dry storage systems. Casks are licensed for a design basis heat load to ensure peak clad temperature remains below 400°C (752°F). For licensing purposes, the supporting analysis for these license submittals must be carried out in a conservative fashion Ref. [6]. At loading, there are additional factors that add margin to the peak temperatures. These include the methods for calculating decay heat and operational considerations for selecting fuel. Because of these factors, there is no reason to believe that during normal operations, the clad temperature will reach the 400°C limit.

From a thermal standpoint, drying operations are best thought of as a special condition for spent fuel storage analysis. Vacuum drying procedures typically do not last long enough for the cask to reach a steady-state temperature Ref. [7]. This means a transient temperature solution must be used for accurate clad temperature predictions during the process. Therefore, it is important to note that in the field vacuum drying may not always be the limiting condition for spent fuel. Often, peak temperatures are reached during operations performed after drying is completed. This may be in transit from the fuel-handling building to the independent spent fuel storage installations or directly after being stored at the independent spent fuel storage installations. This means that the 400°C peak "vacuum" profile can be expected to give a conservative estimate of hoop stress and RIP for drying operations.

For a licensing calculation, a justification of the limiting fuel design and power history would need to be undertaken by an applicant. In this case, the analysis is meant to give a realistic bound for the fuel being loaded into dry storage in the United States. By analyzing the fuel with the licensing limit as the peak temperature, a bounding estimate of hoop stress and RIP will be achieved. Because of the margin to 90 MPa shown in Section 3 and the favorable comparison with the previous work discussed in Section 3.3, this approach is acceptable for the present analysis.

3. Results and discussion

This section presents results and discussion from the FRAPCON analysis. Tables 1 and 2 show the maximum hoop stress and RIP calculated by FRAPCON. The hoop stress results are adjusted for clad thinning according to Eq. (4). External oxide distribution is calculated in FRAPCON. For the inner oxide layer, a constant 15 microns is assumed as a bounding value Refs. [8,9]. Pressures listed are absolute pressure. The effect of different canister fill gas pressure on hoop stress has been factored in. Table 3 lists the plenum temperature experienced by the rods for each temperature profile. All hoop stresses remained below the 90 MPa limit for hydride reorientation. Cladding-irradiated yield stress is 540 MPa. Ref. [5] Based on the results below, there is no reason to consider rod burst for undamaged fuel rods at the bounding 400°C limit. The variations of hoop stress and RIP are discussed in detail below.

3.1. Effect of fuel Design

Comparing the rod designs in all cases, the IFBA fuel shows the highest internal pressure and hoop stress. This is expected because of the increased gas generation caused by the burnable absorber during irradiation. Previous work by Lanning and Beyer Ref. [1] shows that initial fill gas pressure and fuel design have a large impact on the hoop stress calculated for dry storage. This is confirmed by the results shown here. Generally, the hoop stress experienced in drying is directly related to RIP. RIP is driven by the initial fill gas pressure and the amount of gas produced and released from the fuel pellets during irradiation. These results indicate that fuel design parameters may be a more limiting consideration than dry storage conditions. Further study would be warranted, but in this analysis, the BWR fuel is far from the limiting 90 MPa hoop stress even at the licensing temperature limit. This could mitigate the long-term storage and transportation concerns of hydride reorientation in BWR fuel.

Table 1
Maximum hoop stress (MPa) 400°C peak temperature.

Profile	Vacuum (0.004 atm)	Medium flow (1 atm)	High flow (6.8 atm)
Fuel			
10 × 10	39.4	43.2	39.7
17 × 17	49.3	52.7	49.2
17 × 17 IFBA	77.5	80.6	78.2

IFBA, integral fuel burnable absorber.

Table 2
End of life rod internal pressure (MPa) 400C peak temperature.

Profile	Vacuum (0.004 atm)	Medium flow (1 atm)	High flow (6.8 atm)
Fuel			
10 × 10	5.4	6.0	6.3
17 × 17	6.2	6.7	7.0
17 × 17 IFBA	9.7	10.2	10.6

IFBA, integral fuel burnable absorber.

Table 3
Maximum plenum temperature (all fuel types) (°C).

Profile	Temperature (°C)
Vacuum (0.004 atm)	264
Medium (1 atm)	348
High (6.8 atm)	397

3.2. Effect of varied temperature profile

The methodology in this analysis characterizes the effects different temperature profiles have on clad hoop stress and RIP during storage. The maximum RIP occurs in the high-flow case. This is a predictable result because the high-flow profile places the peak clad temperature very near the top of the active length of the fuel and, therefore, shows the highest plenum temperature. Similarly, the lowest RIP is experienced in the vacuum case where the peak is furthest from the plenum. A cursory look at the pressure results might lead one to believe that the highest hoop stress would be experienced in the high-flow case because of the RIP. Table 1 shows that this is not the case and that the highest hoop stress is seen in the mid-flow case for all fuel designs analyzed. This result can be explained by examining the axial distribution of cladding hoop stress and oxide deposition along the axial length of the rod shown in Figs. 5 and 6.

A qualitative comparison of the distribution of the stresses and oxide layer shows them having a similar profile. This is expected due to the adjustment for clad thinning taken into account by Eq. (4). In effect, the weakest point in the cladding will be where the oxide layer is the thickest. Further examination shows that the axial hoop stress profile and oxide layer profile closely match the shape of the mid-flow temperature profile in Fig. 4. In Fig. 5, the mid-flow hoop stress is noticeably offset from both the high and vacuum cases. In the mid-flow case, high temperature is being applied at what is already the weakest point in the cladding which causes a higher predicted hoop stress even though the RIP is lower than in the high-flow case. This indicates that even if a 400°C temperature were reached, the limiting case for hydride reorientation would be a vertical cask with a medium amount of internal recirculation, not a vacuum drying scenario.

3.3. Standard conditions and comparison with other work

For purposes of comparison, end of life RIP and void volume have been analyzed at atmospheric conditions. Results for this analysis are presented in Tables 4 and 5.

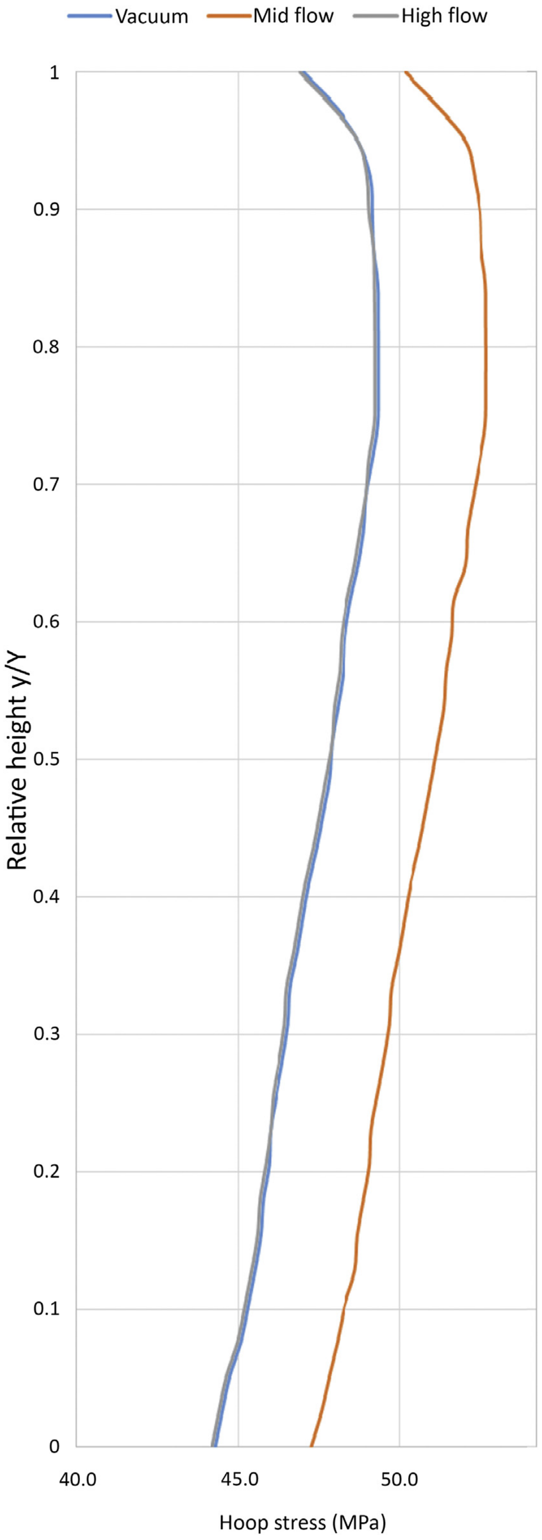

Fig. 5. Hoop stress 17 × 17 design.

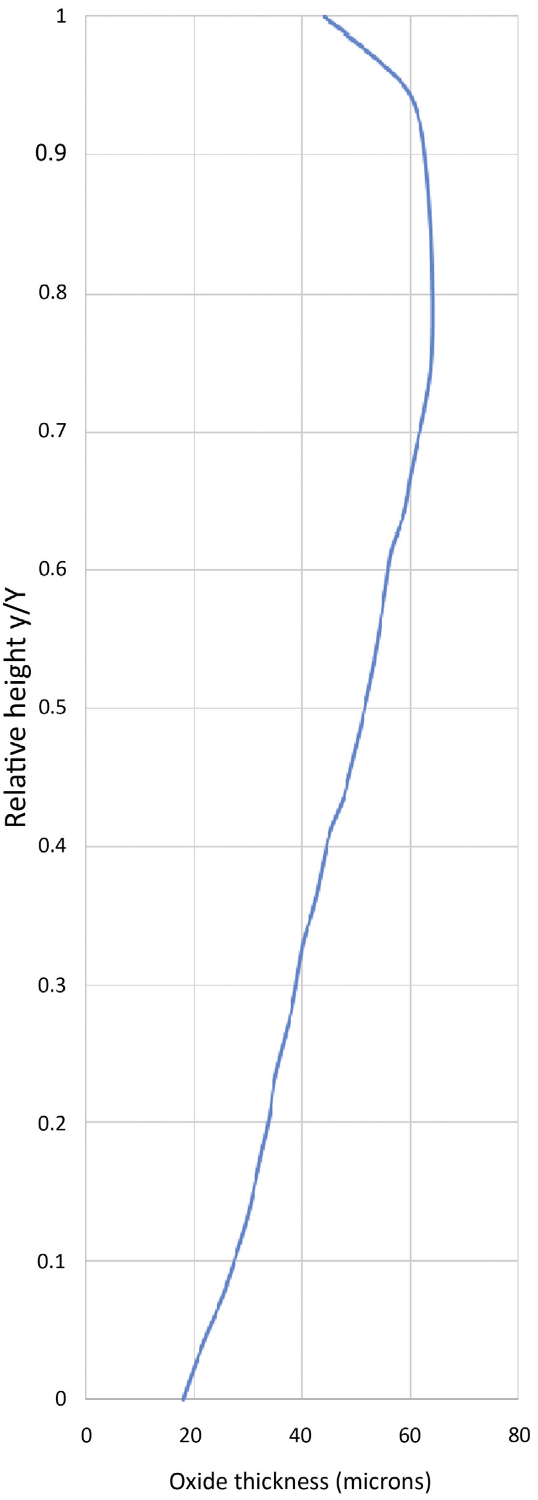

Fig. 6. End of life oxide thickness 17 × 17 design.

The RIP at room temperature draws a useful comparison with the previous work carried out analyzing spent fuel, by Oak Ridge National Laboratory (ORNL) Ref. [10] and the Electric Power Research Institute (EPRI) Ref. [11]. The EPRI conducted a literature search of RIP data correlated with burnup. The RIPs found in Table 4 acceptably bound the dataset, with the 17 × 17 results near the bottom and 17 × 17 IFBA rods near the top. The void volume also lies within the EPRI dataset. The ORNL report analyzes rods with an isothermal temperature profile. As discussed in Section 2, an isothermal temperature profile is not a realistic scenario and as such is of limited use in comparing internal

Table 4
Rod internal pressure at atmospheric conditions (25°C, 1 atm).

Fuel	RIP (MPa)
10 × 10	2.8
17 × 17	3.2
17 × 17 IFBA	5.0

IFBA, integral fuel burnable absorber; RIP, rod internal pressure.

Table 5
Total rod void volume at atmospheric conditions (25°C, 1 atm).

Fuel	Void volume (cm^3)
10 × 10	24.1
17 × 17	14.5
17 × 17 IFBA	19.5

IFBA, integral fuel burnable absorber.

pressure and hoop stress results. In addition, the ORNL report did not use FRAPCON's validated IFBA He-release model and, therefore, did not capture the interrelated effects of RIP on fuel rod deformation. However, the void volume predictions in Table 5 fall within the highest frequency of the ORNL data and can be compared reasonably because void volume shows minimal change with temperature and pressure. These comparisons give confidence that although this analysis studies a relatively small amount of cases, the results are still representative and conservative for current fuel designs.

4. Conclusions

The results presented in this article show that the cladding hoop stress in modern fuel designs will likely remain below 90 MPa at the 400°C limit during normal conditions of storage and transfer operations, such as vacuum drying. Fuel design was found to have a large impact on RIP and cladding hoop stress. The limiting temperature profile was found to be one where medium internal recirculation is present, rather than the vacuum drying or high-flow condition. This is due to the axial oxide distribution and associated clad thinning. Claddings that have higher waterside corrosion will be more limiting than modern alloys with relatively low oxide formation. More study may be warranted to characterize a bounding oxide thickness. All analyses were reasonably representative of modern high-burnup fuel and conservative for conditions of dry storage operations.

Conflict of interest

There is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2018.01.003.

References

[1] D. Lanning, C. Beyer, Estimated Maximum Cladding Stresses for Bounding PWR Fuel Rods during Short Term Operations for Dry Cask Storage, Pacific Northwest National Laboratory, Richland, WA, 2004.
[2] "Interim Staff Guidance – 11, Cladding Considerations for the Transportation and Storage of Spent Fuel, Revision 3" Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, Spent Fuel Project Office, 2003.
[3] S.R. Greene, J.S. Medford, S.A. Macy, Storage and Transport Cask Data for Used Commercial Nuclear Fuel, 2013. ATI-TR-13047.
[4] 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, Pacific Northwest National Laboratory, Richland, WA, 2015. PNNL-19417, Vol. 1 Rev. 2.
[5] K.J. Geelhood, C. Beyer, Used Nuclear Fuel Loading and Structural Performance under Normal Conditions of Transport – Supporting Material Properties and Modeling Inputs, U.S. Department of Energy, Used Fuel Disposition Campaign, 2013. FCRD-UFD-2013–20000123.
[6] "Standard Review Plan for Spent Fuel Storage Systems at a General License Facility," Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, 2010. NUREG-1536 Rev. 1.
[7] J.A. Fort, T.E. Michener, S.R. Suffield, D.J. Richmond, Thermal Modeling of a Loaded MAGNASTOR Storage System at Catawba Nuclear Station, U.S. Department of Energy, Used Fuel Disposition Campaign, 2016. FCRD-UFD-2016–20000068, PNNL-25871.
[8] J.B. Minne, et al. Specific Aspects of Internal Corrosion of Nuclear Cladding Made of Zircaloy, EDF R&D, France
[9] L. Desgranges, Internal corrosion layer in PWR fuel, in: OECD/NEA Seminar Proceedings, Thermal Performance of High Burn-up LWR Fuel. Cadarache, France, 1988.
[10] R.N. Bratton, M.A. Jessee, W.A. Wieselquist, Rod Internal Pressure Quantification and Distribution Analysis Using FRAPCON, U.S. Department of Energy, Used Fuel Disposition Campaign, 2015. ORNL/TM-2015/557, FCRD-UFD-2015–20000636.
[11] "End-of-Life Rod Internal Pressures in Spent Pressurized Water Reactor Fuel", EPRI, Palo Alto, CA, 2013, 3002001949.