ESTIMATED MAXIMUM CLADDING STRESSES FOR BOUNDING PWR FUEL RODS DURING SHORT TERM OPERATIONS FOR DRY CASK STORAGE

D. D. Lanning and C.E. Beyer
Pacific Northwest National Laboratory
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1.0 INTRODUCTION

The Nuclear Regulatory Commission (NRC), Spent Fuel Project Office, has requested that the Pacific Northwest National Laboratory (PNNL) perform preliminary scoping calculations to estimate maximum cladding hoop stresses encountered by PWR spent fuel rods with low-to-moderate burnup (≤ 45 GWd/MTU) during transfer and short term operations (such as cask drying and backfilling). The motivation for making these estimates is that elevated cladding temperatures (above 400ºC) and the higher resulting stress during cooldown could result in hydride platelet re-solution and then reorientation upon reprecipitation during cooling in the irradiated cladding, if the hoop stresses exceed an established limit of 90 MPa. The platelet reorientation from predominantly circumferential (as-designed) to predominantly radial direction decreases cladding strength and toughness, and decreases the margin against cladding failure during subsequent fuel rod handling and storage. It is desirable to keep the cladding stresses during cooldown after drying, or other short term operations with elevated temperatures, below the level where such re-orientation has been determined to occur.

PNNL chose to use realistic bounding power histories for a selection of PWR rod designs (i.e., typical power histories for the peak power rods in the core). This was done to provide realistic fuel pellet fission gas release (FGR) and void volumes, and consequent end-of-life (EOL) rod internal pressures for the peak rods in the core. A best estimate modeling of the peak rods in the core will bound rod internal pressures and consequent cladding hoop stresses encountered by the majority of the fuel rods during cask drying operations. The NRC-sponsored FRAPCON-3 steady-state fuel performance computer code (Berna et al., 1997) was used to estimate the EOL FGR and rod internal pressures for the various selected rod design/power history combinations. The FRAPCON-3 code has been shown to calculate fuel temperatures, fission gas release, rod void volume, and rod internal pressures in a best estimate manner given best estimate design and rod power input. The use of close to best-estimate rod powers for a fuel batch will result in close to best-estimate rod pressures for the peak rods in a fuel batch.

The code ambient pressure/temperature history was extended beyond end-of-irradiation (with zero power) to simulate cask drying conditions and calculate rod pressure and cladding stress with isothermal heating up to a given maximum cladding temperature for dry cask storage operations.

EXCEL spreadsheet calculations were used to estimate the rod pressure cladding stress during cask cooling after the drying operation for the more realistic case of an axial temperature profile with the stated peak temperature taken to be the axial peak temperature. The axial temperature profiles were those determined from thermal-hydraulics code simulations of cask drying. Because the gas plenum at the upper end of the rod is not at the axial peak temperature, and this plenum constitutes the majority of the free internal volume, the rod pressures and cladding stresses are uniformly lower for the "axial-profile" cases than when the spent fuel is assumed to be at "isothermal" conditions.

Peak cladding temperatures up to 570ºC were considered. These temperatures are conservative; actual maximum temperatures measured from several loaded spend fuel casks subjected to vacuum conditions and decay-heating with approximately 1-week hold times were 400 to 424ºC (McKinnon,1993). Two levels of cladding thinning (wastage) due to corrosion were considered, corresponding with oxide layer thicknesses of 0 and 40 microns. Realistic oxide thicknesses for low burnup fuel are approximately 40 microns.

In this paper, the fuel rod design and power history inputs and the calculation methods are described, and resulting hoop stresses for the selected rod designs under the various assumptions are summarized. The results are discussed in Section 6.0.

2.0 FUEL ROD DESIGN AND POWER/TEMPERATURE HISTORY INPUTS AND CALCULATED EOL FUEL ROD CONDITIONS

Four PWR fuel rod designs were initially considered: B&W 15x15, Westinghouse 15x15, CE 14x14, and Westinghouse 14x14. The designs have variations in cladding radial dimensions and rod initial (He) fill gas pressures. Non-proprietary bounding values selected for these from O'Donnel et al. 2001 (NUREG-1754), are summarized in Table 1. Note that two levels of fill gas pressure are considered for the Westinghouse 15x15 design: the bounding value of 480 psia and a more nominal value of 360 psia (earlier designs had the higher initial fill gas pressure).

The Westinghouse 17x17 (non-IFBA) fuel designs were not considered in this analysis because in general these designs result in lower linear powers and fission gas release, and therefore lower rod pressures and stresses than the cases under consideration. Westinghouse fuel designs also include integral fuel burnable absorber (IFBA) rods (i.e., rods with a thin layer of ZrB_2 on the fuel pellets). These IFBA rods could potentially have higher rod pressures than the Westinghouse 15x15 non-IFBA designs considered in these analyses, because significant helium is produced by the reaction of B-10 with thermal neutrons. In order to assess this possibility, discussions were held in December 2003 with PG&E and Westinghouse (Columbia) staff, regarding reasonable assumptions for ZrB_2 layer thickness, coated pellet column length, rod component dimensions and internal void volumes, and rod fill pressure. These inputs were used to estimate the temperatures, rod pressures and stresses at rod average burnups ≤ 45 GWd/MTU, as described in Section 5.0

The power histories selected for the 14x14 and 15x15 rod designs are shown in Figure 1. These are intended to represent "peak-rod" power histories; it is estimated that only a few percent of the rods in the spent fuel population would have EOL FGR's commensurate with such power histories. These power histories result in rod-average burnups in the range of 40 to 45 GWd/MTU.

The resulting EOL conditions as-calculated by the FRAPCON code (version 3.2) are summarized in Table 2. The conditions of interest for pressure and stress calculations are rod internal void volume, rod contained gas inventory (total of fission gas and helium fill gas), and cladding wall thickness, i.e., as-fabricated thickness less any wastage connected with cladding corrosion. The axial peak corrosion layer thicknesses calculated by FRAPCON are listed in Table 2 for reference; they are similar to that recommended for estimating cladding wastage in Section 4.0 below.

Table 1. Design Parameters for non-IFBA PWR Rods

Rod Design	RT Fill Gas Pressure at BOL (psia) / RT void volume (cc)	As-Fabricated Cladding Outer Diameter, inches	As-Fabricated Cladding Wall thickness, inches
B&W 15x15	480 / 32.8	0.430	0.0265
Westinghouse 15x15 high fill	480 / 32.3	0.422	0.0243
Westinghouse 15x15 nominal fill	360 / 32.3	0.422	0.0243
CE 14x14	381 / 32.4	0.440	0.0280
Westinghouse 14x14	381 / 30.5	0.440	0.0260

[RT = room temperature]

Table 2. Calculated EOL Conditions for non-IFBA PWR Rods with Bounding Power Histories

Rod Design	EOL FGR, %	EOL Total Gas moles (fission gas moles)	EOL Void Volume, cc at 570ºC isothermal (fraction in plenum)	Peak EOL Oxide Layer Thickness, microns
B&W 15x15	4.4	0.050 (0.006)	24.7 (0.653)	44
Westinghouse 15x15 480 psia fill	4.5	0.050 (0.006)	24.2 (0.656)	44
Westinghouse 15x15 360 psia fill	5.4	0.040 (0.007)	24.0 (0.673)	44
CE 14x14	10.6	0.049 (0.014)	27.0 (0.689)	37
Westinghouse 14x14	9.7	0.045 (0.013)	26.6 (0.726)	37

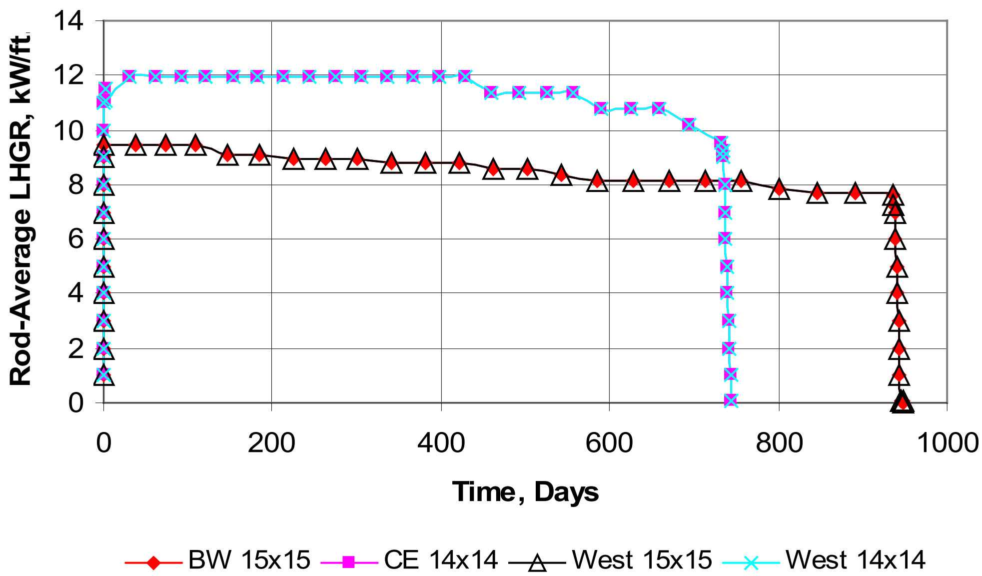

Figure 1. Power Histories for the Selected Cases

3.0 MAXIMUM STRESS ESTIMATES DURING CASK DRYING

At the end of each input power history, the case input was extended by reducing the power in steps to zero power, then reducing the coolant pressure and temperature in steps down to ambient conditions (~30ºC, 15 psia). In order to simulate (isothermal) heating in cask drying, the (axially-constant) coolant temperature and corresponding (equal) rod temperatures were then raised in steps, while keeping the pressure at 15 psia (i.e., ambient external back pressure). The heatup steps included the 570ºC peak drying temperatures. The hoop stresses are due solely to differential pressure across the cladding; the calculated pellet-cladding gap opened up in every case upon cooldown, and remained open during the isothermal heatup, precluding calculated pellet-cladding mechanical interaction in these cases.

Of course, during cask heatup there will be some axial profile to the rod temperatures, with a peak value somewhere near the axial center of the cask. This is significant to pressure calculations because the upper gas plenum will not be at the peak temperature, and the gas plenum constitutes the majority of the rod free internal volume, especially at EOL. An axial temperature profile has been previously estimated for the fuel cladding during cask heatup using a thermal hydraulics code, COBRA-SNF, and this axial profile was applied with axial peak cladding temperatures of 570ºC. The resulting temperature profiles are plotted in Figure 2. The calculated pressures and cladding stresses are shown in Table 3. These result from applying the axial profile, and the partition of rod internal volume between the plenum and balance of rod (see Table 2).

Note that the entries in Table 3 do not include effects of cladding wastage (i.e., cladding wall thinning) due to corrosion, because FRAPCON-3 currently does not make this correction when calculating hoop stress. These effects are assessed in Section 4.0 below. Note also that the stress values tabulated throughout this paper include the effect of zero psia backpressure (for vacuum drying), compared to ambient (15 psia) backpressure.

Table 3. Axial Temperature Profile Case Pressure and Hoop Stress Results based on FRAPCON-3.2 Calculations (no wastage from oxidation)

Rod Design	EOL Pressure, psia (Hoop Stress, MPa) at 570ºC Peak of Axial Temperature Profile
B&W 15x15	1823 (89.4)
Westinghouse 15x15 480 psia fill	1864 (98.6)
Westinghouse 15x15 360 psia fill	1502 (79.5)
CE 14x14	1634 (77.2)
Westinghouse 14x14	1491 (70.5)

Figure 2 Axial Temperature Profile Used to Calculate Fuel Rod Pressures and Stresses

4.0 EFFECTS OF CLADDING CORROSION AND WALL THINNING

The cladding hoop stresses at a given pressure are inversely proportional to wall thickness (using the thin-wall approximation for stress). The corrosion of the outer cladding surface during years of in-reactor exposure to the hot coolant results in substantial cladding oxidation and thus Zircaloy metal consumption and some reduction in the (effective) wall thickness. The wall reduction corresponding to a given oxide layer thickness can be estimated by the ratio of the metal density to the oxide density, and a ratio of 1.56 is commonly used for the ratio of oxide thickness to thickness of the consumed Zircaloy layer.

The rate of oxidation as a function of exposure is reduced in more recent advanced cladding types for use at higher burnups, but the low-to-moderate burnup rods will have cladding of the older standard or low-tin Zircaloy types. Corrosion data from G. R. Kilp et al. shows between 30 to 50 microns of corrosion between 40 to 45 GWd/MTU. Similar data from T. D. Pyecha et al. shows 20 to 40 microns of corrosion at 40 GWd/MTU. These ranges are fairly consistent with the peak oxide values calculated by FRAPCON-3 code and shown in Table 2.

Thus, a best estimate of cladding corrosion and corresponding wall thinning would be an oxide layer of ~40 microns and wall thinning of ~40/1.56 = ~25 microns = ~0.001 inch. The corresponding hydrogen content is about 300 ppm assuming the nascent hydrogen pickup fraction of 0.15 used in FRAPCON-3 for the $2H_2O + Zr \rightarrow ZrO_2 + 2H_2$ reaction. This amount of hydrogen is expected to be re-solved back into the Zr matrix at a temperature of 570ºC such that hydride reprecipitation is expected upon cooling to a temperature below 400ºC. Depending on the hoop stress and the precipitation temperature during the cooling the reprecipitated hydrides could reorient from the circumferential to the radial direction.

The impact upon the calculated hoop stresses at a temperature of 570ºC for the various cases of correcting for a 0.001 inch corrosion-related wall thickness reduction is shown in Table 4.

Table 4. EOL Hoop Stress Results for Isothermal and Axial Temperature Profile Cases
[with ~25 microns (0.001 inch) cladding wall reduction from 40 microns oxide layer thickness]

Rod Design	Factor increase In Hoop Stress	Hoop Stress, MPa at 570ºC Peak of Axial Temperature Profile
B&W 15x15	0.0265/0.0255 = 1.039	92.8
Westinghouse 15x15 480 psia fill	0.0243/0.0233 = 1.043	102.8
Westinghouse 15x15 360 psia fill	0.0243/0.0233 = 1.043	82.9
CE 14x14	0.0280/0.0270 = 1.037	80.0
Westinghouse 14x14	0.0260/0.0250 = 1.040	73.3

5.0 CALCULATED PRESSURES AND STRESSES FOR VANTAGE 5H (IFBA) 17X17 FUEL AT LOW BURNUP

There is a specific need to consider the Westinghouse 17x17 VANTAGE 5H (IFBA) design with natural and enriched boron in the IFBA coating, because low-burnup rods of that design may be stored in casks at the Diablo Canyon site. Discussions were held in December 2003 with PG&E and Westinghouse (Columbia) staff, regarding reasonable assumptions for ZrB_2 layer thickness, coated pellet column length, rod component dimensions, and rod fill pressure. These inputs were used to calculate the EOL total gas content and available void volume. From this, rod pressures and cladding stresses at conditions of interest could be calculated in the manner described above in Sections 2 thru 4. The results are shown in Table 5 below, which is a copy of Table 4 (results assuming 1 mil cladding wastage) with addition of the estimates for the VANTAGE 5H (natural and enriched boron) IFBA 17x17 rods. Note that the VANTAGE 5H stress results are higher than the Westinghouse 15x15 (480 psia fill pressure) case, which is the highest-stress case previously tabulated.

Table 5. EOL Hoop Stress Results for Isothermal and Axial Temperature Profile Cases
[with ~25 microns (0.001 inch) cladding wall reduction from 40 microns oxide layer thickness]

Rod Design	Hoop Stress, MPa at 570ºC Peak of Axial Temperature Profile
B&W 15x15	92.8
Westinghouse 15x15 480 psia fill	102.8
Westinghouse 15x15 360 psia fill	82.9
CE 14x14	80.0
Westinghouse 14x14	73.3
Westinghouse 17x17 IFBA (Natural boron)*	112
Westinghouse 17x17 IFBA (Enriched boron)*	< 126

*Based on a specific application from Diablo Canyon NPP, operated by PG&E. Results will vary, depending upon IFBA design specifics such as rod internal void volume and boron loading (grams per inch) and ZrB_2 column length.

6.0 DISCUSSION OF RESULTS

Utilizing the best-estimate corrosion of 40 microns (corresponding to 25 microns (0.001 inch) of cladding wall reduction), and an axial cladding temperature profile with a peak of 570ºC, the Westinghouse 15x15 (480 psia fill), B&W 15x15, and Westinghouse 17x17 Vantage 5H (IFBA) cases are the only ones that exceed the 90 MPa stress limit imposed by NRC SFPO in ISG 11 Rev. 3 for hydride reorientation (see Table 5). The purpose of these analyses is to determine whether or not hydride reorientation will take place during cask cooldown following drying and if so will a significant number of rods be effected such that there is a safety concern. It should be noted that these hoop stresses are for the peak rod in a fuel batch, such that the number of rods, which achieve these stresses, are relatively small.

It should be stressed that at 570ºC, all of the expected hydrogen (~300 ppm at 40 microns of oxide thickness) will be in solution, and will not precipitate until temperatures cool to ~ 400ºC, based on hydrogen solubility and solvus for precipitation during cooling in unirradiated Zircaloy see Kearns, 1967 and Sawatzky and Ells, 2000). The Westinghouse and B&W 15x15 design cases and the Westinghouse 17x17 (natural boron) IFBA case will have a hoop stress less than

90 MPa below 400ºC, such that hydride reorientation in the radial direction is not expected. There is data from Vizcaino et al., (2002) suggesting that the apparent hydrogen solubility of irradiated Zircaloy-4 is significantly greater than that of unirradiated Zircaloy, in which case the temperatures and stresses would have to fall even further (e.g., below 350ºC) at the point where hydride reprecipitation could begin. The calculated hoop stresses for each of the fuel designs at a peak cladding temperature of 350ºC (axial temperature profile) is provided in Table 6. This table shows a maximum hoop stress of < 80 MPa for the Westinghouse 15x15 design (fill gas pressure at 480 psig), and < 90 MPa is estimated for all the designs except the Westinghouse IFBA with enriched boron that is < 93 MPa. There is a small amount of conservatism in the helium release in this analysis because it is assumed that 100% of the helium is released, e.g., not 100% will be released but the conservatism is small, that would likely reduce the actual hoop stresses below 90 MPa. In addition, it is believed that the 90 MPa hoop stress for hydride reorientation may be conservative for coldworked and irradiated Zircaloy cladding (typical of PWR spent fuel).

Therefore, there is margin between the estimated stresses that may actually cause hydride reorientation and the maximum stresses that will actually be achieved at the temperatures of reprecipitation. It is judged to be unlikely that current low-burnup fuel rod cladding examined in this study will experience hydride reorientation during actual short-term operations as currently planned.

It should be noted that the cladding hoop stresses for the Westinghouse fuel designs with IFBA rods are strongly dependent on the specific design parameters assumed in this analysis. The design parameters that have a significant impact on the calculated hoop stresses are rod void volume, as-fabricated fill gas pressure; and the ZrB_2 parameters such as coating thickness and axial length, coating density, and boron-10 enrichment. Consequently, the application of the calculated hoop stresses in this analysis for the specific Vantage 5H fuel design considered may not be applicable to all IFBA designs unless they are similar to the PG&E application used in this analysis.

It should also be noted that if higher levels of corrosion and, therefore, hydrogen are present in some low burnup fuel rods than those assumed in this analysis this will result in higher hydride precipitation temperatures and stresses that could result in hydride reorientation. For example, 650 ppm of hydrogen in low burnup Zircaloy cladding will raise the precipitation temperature to 500ºC based on unirradiated Zircaloy hydrogen precipitation (and 450ºC based on Vizcaino et al.,) and raises the stress level at which precipitation begins during cooling.

Table 6. EOL Hoop Stress Results for Axial Temperature Profile Cases
at the Precipitation Temperature for 300 ppm Hydrogen (~350ºC)
[with ~25 microns (0.001 inch) cladding wall reduction from 40 microns oxide layer thickness]

Rod Design	Hoop Stress, MPa at 350ºC Peak of Axial Temperature Profile
B&W 15x15	68.7
Westinghouse 15x15 480 psia fill	76.1
Westinghouse 15x15 360 psia fill	61.4
CE 14x14	59.3
Westinghouse 14x14	54.3
Westinghouse 17x17 IFBA (Natural boron)*	83
Westinghouse 17x17 IFBA (Enriched boron)*	< 93

*Based on a specific application from Diablo Canyon NPP, operated by PG&E. Results will vary, depending upon IFBA design specifics such as rod internal void volume and boron loading (grams per inch) and ZrB_2 column length.

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