EXPANDED ASSESSMENT OF FAST FOR POWER RAMP CASES WITH SHORT HOLD TIMES AND ADVANCED UO_2 FUEL WITH VARIOUS DOPANTS

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ABSTRACT

A critical part of the work performed by PNNL under their contract with NRC to maintain the NRC fuel performance codes is to continually assess the code predictions relative to new data. Of particular interest is assessment against fuel with new fuel materials and cladding material that are due to be deployed in the US nuclear fleet in the near term. Recent areas that have been identified for assessment are power ramps with very short hold time and UO_2 fuel with dopants including gadolinia, chromia, and silica. Results from a number of such tests have been identified and the data are compared to predictions of the fuel performance codes, FRAPCON and FAST. FAST is the current evolution of FRAPCON that contains transient capabilities that may be critical in evaluating the performance of power ramps with short hold times.

A number of power ramped rods have been identified in the SCIP-I, SCIP-II, and TRANS RAMP IV programs that had hold times between 5 and 108 seconds and measured gas release. This rods will be used to assess if the so-called "burst release" phenomena can be properly modeled by FRAPCON and FAST. The transient capabilities in FAST are necessary to correctly predict the temperature in the rods with hold times less than 10 seconds.

A number of Halden Instrumented fuel assemblies have been identified that include advanced UO_2 fuel with various dopants. These include IFA-681 that include UO_2 and UO_2-Gd_2O_3. The early power histories of these rods had been previously modeled, but the entire irradiation history has now been modeled. IFA-716 rods have been modeled that include UO_2 with standard grains, UO_2 with large grains, and UO_2 with Cr_2O_3 as manufactured by AREVA. IFA-677 rods have been modeled that include UO_2 manufactured by a number of different vendors and UO_2 with additives manufactured by Westinghouse Sweden. Comparisons will be shown of code predictions and data for fuel centerline temperature and for fission gas release.

Finally, several commercial rods have been modeled and results are compared against puncture data including, void volume, gas pressure, and fission gas release.

1. Introduction

The FRAPCON fuel performance code [1] has been used by the United Stated Nuclear Regulatory Commission (US NRC) for more than 20 years to perform independent analyses of vendor fuel codes and methods that are used to evaluate the performance of light water reactor (LWR) fuel relative to various safety analysis design limits. Because of its use in the review and approval of safety analysis codes and methods, it is important that FRAPCON be well validated over the entire range of applicability (e.g. burnup level and power level). The assessment of FRAPCON relative to relevant data is continually expanded as more data become available [2].

FAST (Fuel Analysis Steady-State & Transient) [3] is the next evolution of FRAPCON which includes steady-state and transient heat transfer models. The assessment of FAST [4] has been expanded beyond that of FRAPCON.

This paper will describe the expanded assessment of FAST that has been performed on fission gas release from power ramped rods with short hold times (5-120 seconds), fission gas release and centerline temperature from doped and large grain size fuels, and void volume and fission gas release from commercial fuel rods.

2. Power Ramped Rods

2.1. Modeling

Rods that did not fail from the Studsvik Cladding Integrity Programs (SCIP-1 and SCIP-2) were selected along with one rod from the Transramp IV program. Each of these tests consists of a father rod irradiated in a commercial power reactor. After the irradiation the rod is refabricated into a rodlet for power ramp testing in the Studsvik reactor. During this refabrication, fission gas from the base irradiation is replaced with helium fill gas. A brief description of each rod is below. FAST was used to model the base irradiation on the fill length rod. The refabrication option in FAST allowed a select length of the rod to continue with new fill gas conditions for the power ramp test.

SCIP-1: Three rods were modeled from the Studsvik Cladding integrity program SCIP-1 rods were ramped in the Studsvik R2 reactor. Rods were manufactured by Westinghouse Electric Sweden.

KKL-4: Rodlet KKL-4 [5] was taken form a father rod manufactured by a Westinghouse Electric Sweden rod irradiated to a rod average burnup of 35.9 MWd/kgU from 1994-1997 in Kernkraftwerk Leibstadt (KKL). The fuel was UO_2 and the cladding was Zircaloy-2. The refabricated segment KKL-4 had an average burnup measured at 40.1 MWd/kgU

M5-H1: Rodlet M5-H1 [6] was refabricated from a father rod manufactured by Framatome ANP and irradiated to a rod average burnup of 62.8 MWd/kgU from 1998-2003 through 5 cycles in Ringhals 4. The fuel was UO_2 and the cladding was M5. The rodlet had a mean burnup of 66.5 MWd/kgU measured by Gamma scanning

O2: Rodlet O2 [7] was refabricated from a rod irradiated in Oskarshamn 2 from 1995 to 2000 to a rod average burnup of 47.3 MWd/kgU. The fuel was UO_2 and the cladding was Zircaloy-2. The rodlet mean burnup was 55 MWd/kg/U as measured by gamma scanning

SCIP-II: Three rods were selected from the SCIP-II program. A5g, Aa1, Ed1.

A5g: The father rod for A5g [8] was an Areva 5% gadolinium doped UO_2 fuel rod with M5 cladding irradiated to a burnup of 37 MWd/kgU in Ringhals 4. The rodlet burnup was measured at 38 MWd/kgU, it was ramped to 42 kW/m with a 2 minute hold time.

Aa1: The father rod was irradiated in Oskarshamn 2 to a burnup of 25 MWd/kgU from 2006-2009 over 3 cycles. The fuel was UO_2 and the cladding was Zircaloy-2. The local burnup of the refabricated segment was 26 MWd/kgU. Aa1 [9] was ramped to 46.5 kW/m with a 1 minute hold time.

Ed1: The father rod was fabricated with sintered UO_2 and ZIRLO™cladding irradiated in Vandellos unit 2 from 2000-2007 over four cycles. The father rod average burnup was 64.2 MWd/kgU. The burnup of the rodlet was measured as 69 MWd/kgU. Ed1 [10] was ramped to 40.6 kW/m with a 10 second hold time.

TansRamp IV: One rod was selected from Trans-Ramp IV

Q11-3: The father rod was a typical 17x17 rod manufactured by FRAGEMA and irradiated in the Gravelines 3 over 4 cycles 28 MWd/tU. The fuel was UO_2 and the cladding was Zircaloy-4. Q11-3 [11] was ramped to 47 kW/m with a 40 second hold time.

2.2. Comparison to data

The predicted fission gas release for the power ramped rods with short hold times are shown in Table 1. This table shows predictions for the fission gas release during the power ramp (fission gas release from base irradiation is lost during refabrication) using the steady-state prediction of temperature as well as the transient prediction of temperature. For the steady-state run is was assumed that the power changed from the conditioning power to the ramp terminal level instantly. As seen in Figure 1, following an instant power increase, the transient prediction of fuel temperature converges with the steady-state prediction after about 30 seconds. Therefore, for power ramps with hold times of less than 40-60 seconds, it is important to model the transient response of the power ramp. For longer hold times this is not necessary. However, when using the transient option, the ramp rate should be considered. For the transient case the reported ramp rate was included which is significant (0.2 to 2 kW/m/s) for the short hold times modeled here.

Table 1: Predicted and measured fission gas release for ramped rodlets.

Rod	Average Rodlet Burnup	Ramp Terminal Level (kW/m)	Hold Time (s)	Steady-State Predicted FGR %	Transient Predicted FGR%	Measured FGR %
KKL4	40.1	46.8	5	4.82	4.15	1.2
M5-H1	66.5	39.4	5	13.45	6.00	5.9
O2	55	44.5	30	5.26	3.82	0.9
A5g†	38	42	120	0.0	0.0	1.2
Aa1†	26	46.5	60	0.0	0.0	0.023
Ed1†	69	40.6	10	0.0	0.0	7.4
Q11-3	28	47	40	9.38	5.86	0.5

† There was no power history given for these rods, so modeling is more uncertain

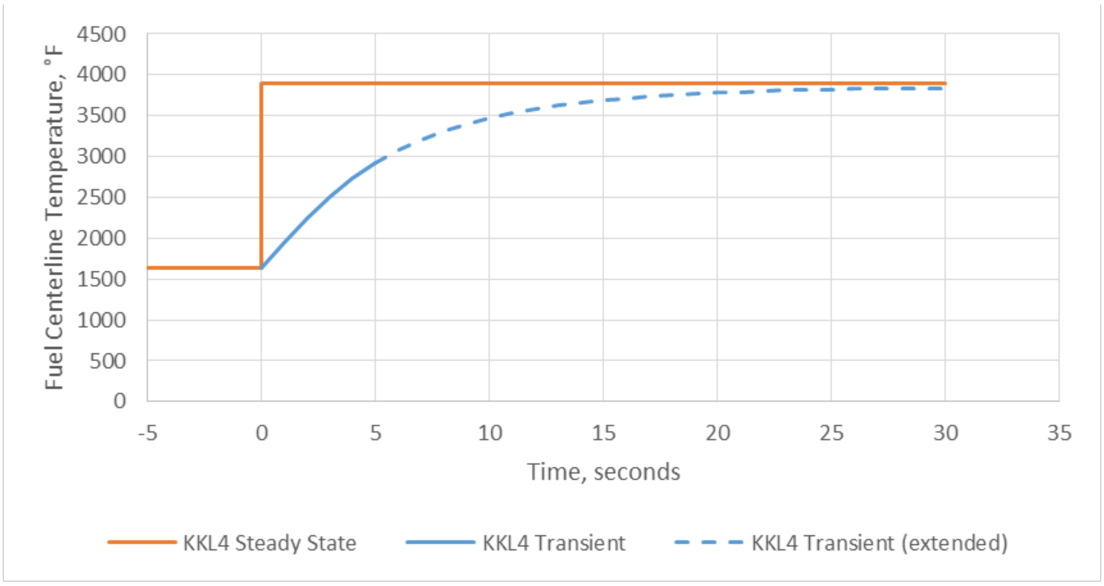

Figure 1: Steady-State and transient temperature solution for an instant change in power during KKL4.

It can be seen that for short hold times, the steady-state temperature solution provides an overestimate of the ramped fission gas release, while the transient temperature solution provides a better prediction of the fission gas release. It is noted that there is no information on the power history for A5g, Aa1, and Ed1 other than end of life burnup and approximate number of years in reactor. An average LHGR was calculated over the time in-reactor to use as a power history. However, this results in a very low LHGR. It is likely that one or more cycles were at higher LHGR which would lead to more gas on the grain boundaries available for transient release. Because of this lack of information on the base irradiation for these rods it is not recommended that they be included in the FAST assessment database. The standard error of the fission gas release from these seven rods using the steady state model is 7.5% absolute and 3.9% absolute using the transient model. This is similar to the uncertainty of 5.4% absolute for the large database of UO_2 power ramped rods in the FAST assessment database.

This demonstrates that FAST can adequately predict the so-called “burst release” phenomena and the steady-state temperature solution will over-predict the release while the transient temperature solution will provide a reasonable prediction of the release.

3. Halden Instrumented Fuel Assemblies

3.1. Modeling

Rods from three instrumented fuel assemblies (IFAs) irradiated in the Halden reactor were selected for this expanded assessment. Each IFA consists of 6 rods with an active length of about 400 mm. Some rods were instrumented with centerline thermocouples on the top and/or bottom of the stack. Other rods were instrumented with an expansion thermocouples through the full stack length. In each case annular pellets were modeled and centerline temperature is predicted to match the thermocouple data.

All rods consisted of Zircaloy-4 cladding and contained different types of advanced fuel pellet additives compared with standard UO_2 fuel pellets. IFA-677[12] was irradiated for 6 cycles over 500 days from 2005-2007. IFA-681[13] was irradiated for 15 cycles over 1300 days from 2005-20012. IFA-716 [14] was irradiated for 12 cycles over 700 Days from 2010-2013. The only pellet additives that FAST has an explicit model for is the Gd_2O_3 set as the addition of Gd_2O_3 has a significant impact on the radial power profile and the pellet thermal conductivity. All other fuel types were modeled with the standard UO_2 models included in the code.

The following is a brief description of each rod.

<u>IFA-677:</u> IFA-677 consisted of both standard fuel and fuel with additives. The rig average burnup was 26.3 MWd/kgOxide. Specific Burnup and fission gas release is available for rods 5 and 6.

IFA-677 Rod 1: Rod 1 was manufactured by Westinghouse Sw with Cr_2O_3 and Al_2O_3 doped UO_2 the rod was fitted with a centerline thermocouple in both the bottom and top of the fuel stack.

IFA-677 Rod 2: Rod 2 was a Framatome manufactured rod with standard UO_2 pellets and thermocouples fitted in the top and bottom.

IFA-677 Rod 3: Rod 3 is a rod with standard UO_2 pellets. The rod was manufactured by Global Nuclear Fuel (GNF) with top and bottom centerline thermocouples. The bottom thermocouple failed at about 475 days of irradiation. The top thermocouple failed at about 490 days.

IFA-677 Rod 4: Rod 4 is manufactured by GNF and using standard pellets. The rod has a bottom thermocouple which failed at about 225 days.

IFA-677 Rod 5: Rod 5 was manufactured by Westinghouse Sw. and irradiated to an average burnup of 25.7 MWd/kgOxide. The pellets were doped with Cr_2O_3 and Al_2O_3 and instrumented with a top and bottom thermocouple.

IFA-677 Rod 6: Rod 6 was manufactured by Westinghouse Sw. and irradiated to a burnup of 26.2 MWd/kgOxide. The pellets are fitted with a bottom thermocouple that failed about 450 days into the cycle.

IFA-681: IFA-681 consists of standard UO_2 and gadolinia (Gd_2O_3) doped fuel. The average rig burnup was 45 MWd/kgOxide. Fission gas release data is available for rods one, two and three.

IFA-681 Rod 1: Rod 1 consists of standard pellets. The rod is fitted with a thermocouple through the top of the stack and irradiated to a burnup of 50.1 MWd/kgOxide.

IFA-681 Rod 2: Rod 2 is a rod with 2% Gd doped fuel and a thermocouple through the top of the rod. The test rod achieved an average burnup of 49.4 MWd/kgOxide.

IFA-681 Rod 3: This rod has solid fuel with 8% Gd content by weight and irradiated to an average burnup of 35.9 MWd/kgOxide. The stack is fitted with a thermocouple though the top pellets to measure centerline temperature.

IFA-681 Rod 4: Rod 4 consists of hollow pellets with 2% by weight Gd. The rod was irradiated to an average burnup of 49 MWd/kgOxide and fitted with an expansion thermometer to measure average centerline temperature.

IFA-681 Rod 5: Test rod 5 had standard composition UO_2 pellets and irradiated to 49.5 MWd/kgOxide. The rod was fitted with an expansion thermometer.

IFA-681 Rod 6: Test rod 6 was irradiated to an average burnup of 36.2 MWd/kgOxide. It is fabricated with 8% Gd pellets. The pellets have an expansion thermometer through the center of the stack to measure average centerline temp.

IFA-716: IFA-716 consists of standard UO_2, Cr_2O_3 doped, and large grain UO_2. There is no FGR release data available

IFA-716 Rod 1: Rod 1 was manufactured by Areva (Framatome). The pellets consisted of 0.16% Cr_2O_3 and were fitted with a centerline thermocouple at the bottom of the stack.

IFA-716 Rod 2: Areva (Framatome) manufactured rod 2 with standard UO_2 pellets. The stack is fitted with a top thermocouple for centerline temperature. The rod leaked at about 640 days through the test.

IFA-716 Rod 3: This rod contained BeO additives that are not currently planned for use in any US reactor. Therefore, it was not modeled in FAST

IFA-716 Rod 4: ULBA manufactured rod 4 fitted with a bottom thermocouple for centerline temperature. The pellets are active sintered large grain UO_2.

IFA-716 Rod 5: Areva (Framatome) manufactured rod 5. The pellets are large grain UO_2, and fitted with a top thermocouple through the centerline.

IFA-716 Rod 6: Rod 6 has Cr_2O_3 doped pellets and is manufactured by Areva (Framatome). The stack is fitted with a bottom thermocouple that failed after 490 days.

3.2. Comparison to data

Measurements of fission gas release were only available for five of the fuel rods that were modeled. The predicted fission gas release for these rods are shown in Table 2. It can be seen that for these rods, FAST gives a reasonable prediction of fission gas release. The standard error of the fission gas release from these five rods is 4% absolute which is similar to the uncertainty of 2.6% absolute for the large database of UO_2 steady-state rods in the FAST assessment database.

Table 2: Predicted and measured fission gas release for Halden rods.

Rod	Burnup	Fuel Type	Predicted	Measured
IFA-677 rod 5	25.7	UO_2 + Add	22.45%	16%
IFA-677 rod 6	26.2	UO_2	22.46%	19%
IFA-681 rod 1	50.1	UO_2	4.61%	2.09%
IFA-681 rod 2	49.4	UO_2 +2% Gd_2O_3	5.60%	2.73%
IFA-681 rod 3	35.9	UO_2 +8% Gd_2O_3	0.45%	0.27%

Comparisons of centerline temperature were made for the time prior to when thermocouple signals became unreliable as noted by Halden. Figure 2 shows the predicted vs. measured temperature for the 6 rods in IFA-677. Figure 3 shows the predicted vs. measured temperature for the 6 rods in IFA-681. Figure 5 shows the predicted vs. measured temperature for the 5 rods that were modeled from IFA-716. Also shown in these figures is the upper and lower 2-sigma ranges that were calculated for UO_2 and UO_2-Gd_2O_3 fuel in the latest FRAPCON assessment [2]. It can be seen that the predicted temperatures generally fall within this same uncertainty, there is no particular bias is the temperature predictions, and these does not appear to be a biased prediction between the standard UO_2 rods and any of the large grain UO_2 or doped UO_2 rods. This shows that FAST will provide a reasonable prediction of large grain and doped UO_2 rods with approximately the same uncertainty as it does for standard UO_2 rods.

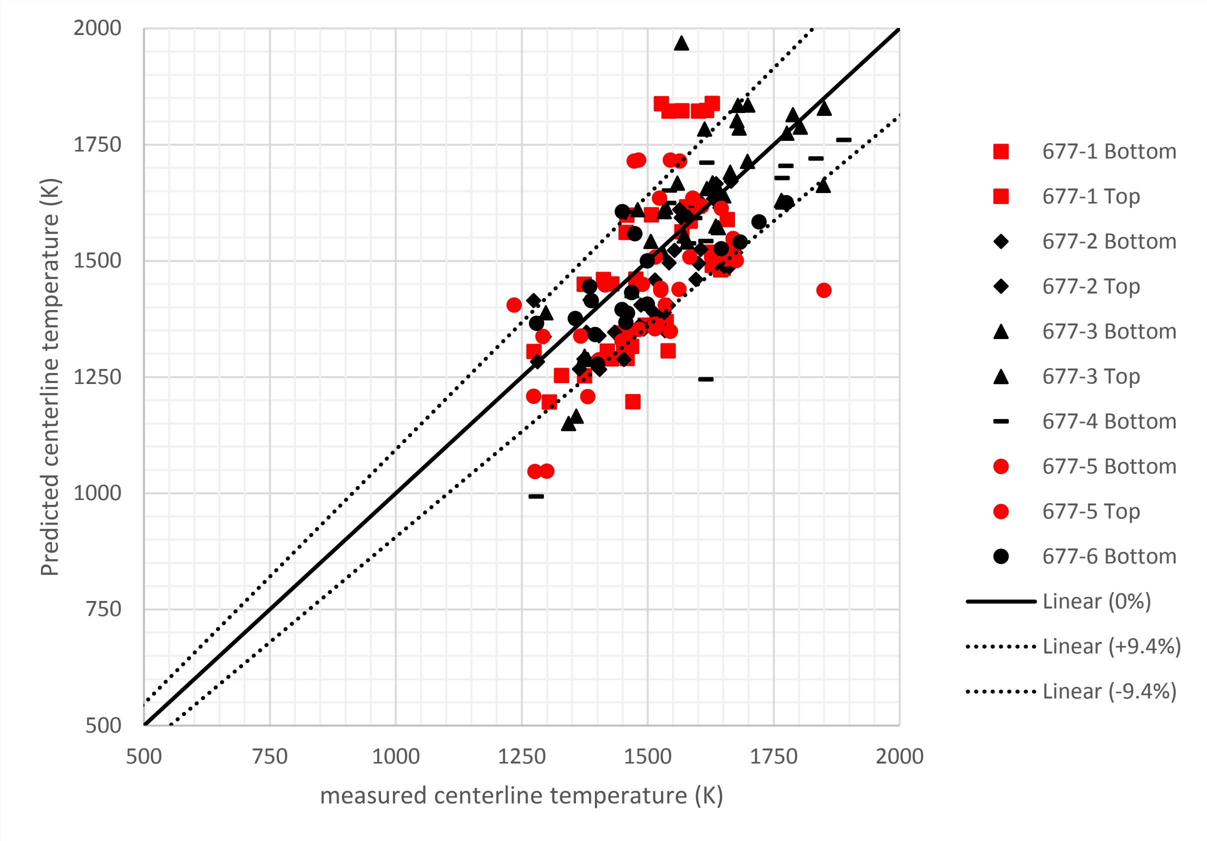

Figure 2: Predicted vs. measured centerline temperature IFA-677 rods 1 through 6. (UO_2 rods shown in black and UO_2+additives shown in red)

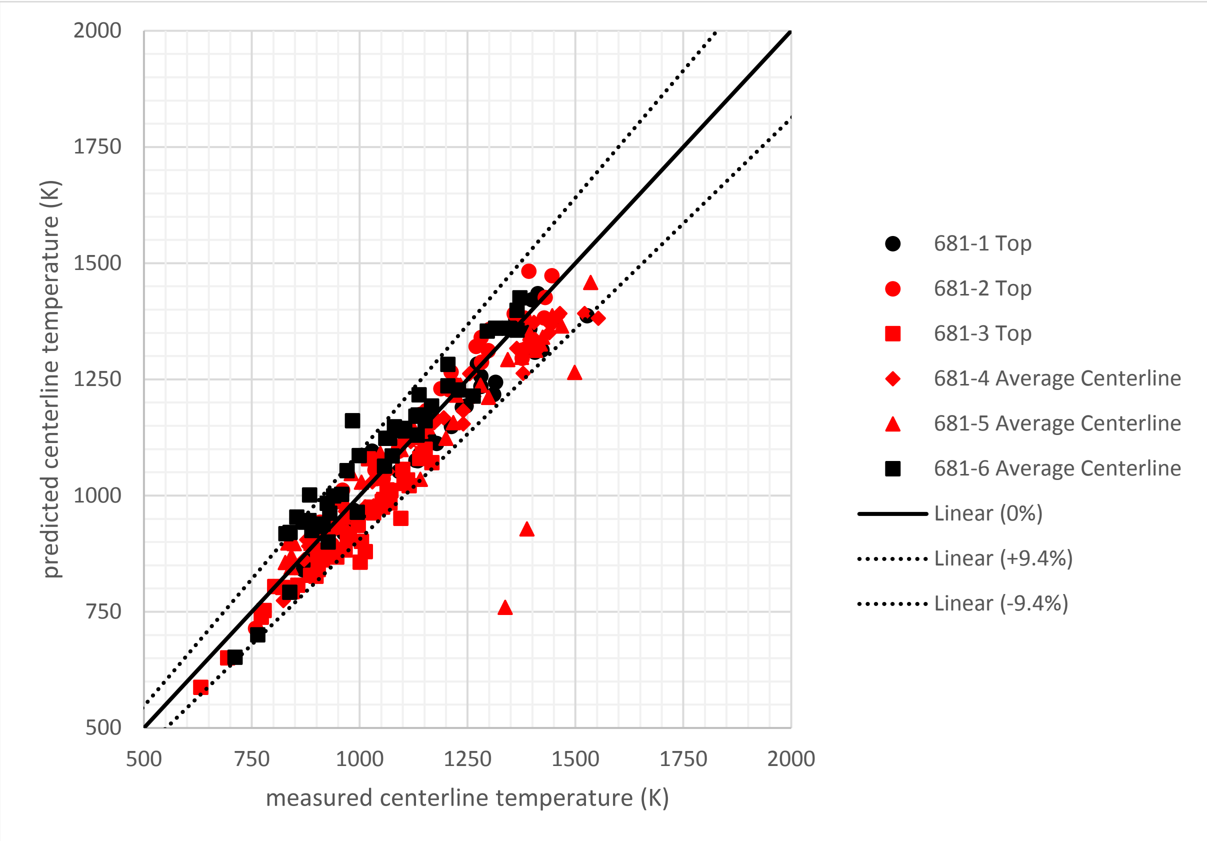

Figure 3: Predicted vs. measured centerline temperature IFA-681 rods 1 through 6. (UO_2 rods shown in black and UO_2-Gd_2O_3 shown in red)

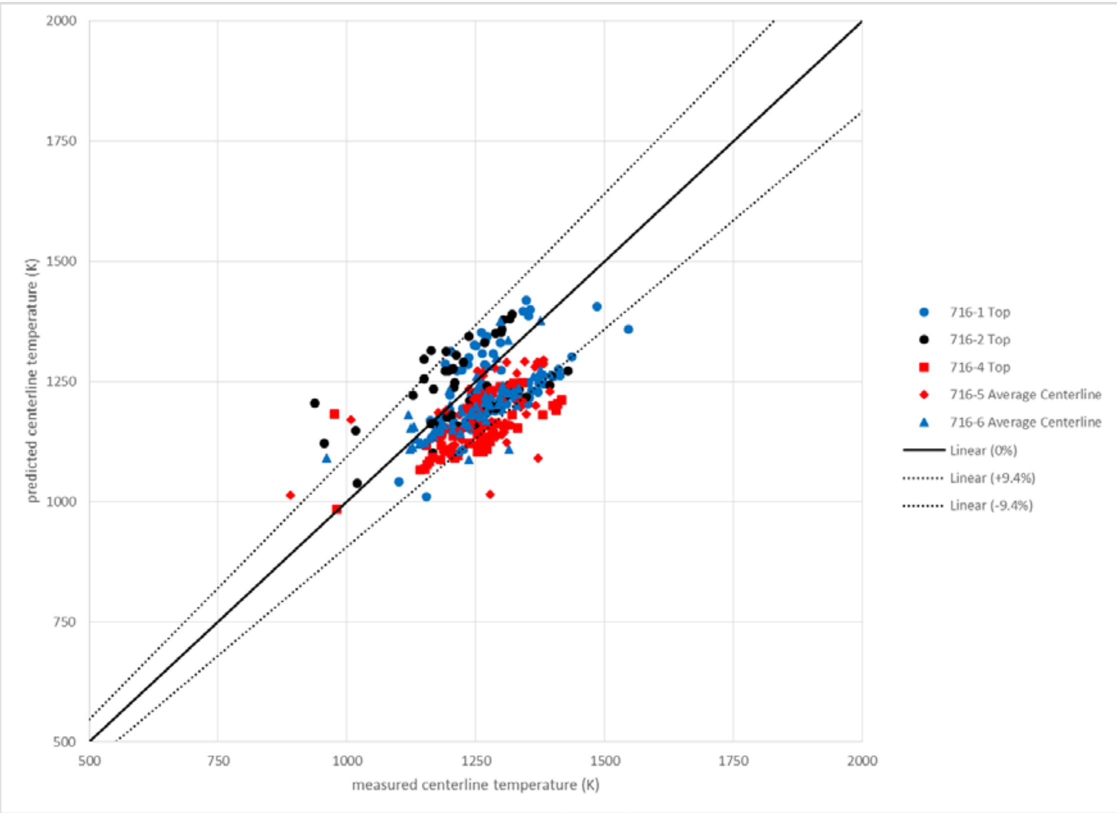

Figure 4: Predicted vs. measured centerline temperature IFA-716 rods 1 through 6. (Standard UO_2 rods shown in black, large grain UO_2 rods shown in red and UO_2 + Cr_2O_3 shown in blue)

4. Commercial PWR Rods

4.1. Modeling

Fabrication data, reactor operation data, and post-irradiation data have been obtained for two commercial PWR rods. These rods were modeled in FAST and predictions of end-of-life void volume, pressure, and fission gas release were compared to post-irradiation measurements.

The following is a brief description of each rod.

Fuel rod 2AH3-D12: This fuel rod was irradiated to 34.1 MWd/kgU in the Ringhals 3 reactor in Sweden. The fuel was standard UO_2 and the cladding was Optimized ZIRLO™.

Fuel rod 07-R2D5: This fuel rod was irradiated to 62 MWd/kgU in the Ringhals 2 reactor in Sweden. The fuel was standard UO_2 and the cladding was M5.

4.2. Comparison to data

Predictions and measurements for the end-of-life void volume, pressure, and fission gas release for these two commercial PWR rods are given in Table 3. To void volume is predicted well for one rod and about 12% under predicted for the other. This is within the uncertainty demonstrated for other commercial rods in the FAST assessment [2] and may be due to uncertainty in the as-fabricated void volume which is not measured for these rods. The uncertainty in void volume is up to ± 1 pellet volume. Fission gas release is reasonably predicted and is within the calculated 1-sigma uncertainty of 2.6% absolute for the large database of UO_2 steady-state rods in the FAST assessment database. Pressure is reasonably predicted based on over- or underpredictions of void volume and fission gas release.

Table 3: Predicted and measured end-of-life void volume, pressure, and fission gas release for commercial PWR rods.

Rod	Burnup	Void Volume (cm^3)		Pressure at 0°C (MPa)		FGR (%)	
		Predicted	Measured	Predicted	Measured	Predicted	Measured
2AH3-D12	34.1	15.2	15.5	2.4	2.7	0.6	3.6
07-R2D5	62	19.7	17.7	3.1	3.97	5.02	6.5

5. Conclusions

Using the database that was used to assess FRAPCON, FAST has been assessed to provide a best-estimate prediction of fuel temperature, fission gas release, corrosion, void volume, and cladding strain for UO_2, UO_2-Gd_2O_3, and MOX fuel with Zircaloy-2, Zircaloy-4, ZIRLO™, Optimized ZIRLO™ and M5 cladding up to a rod average burnup of 62 GWd/MTU.

Expanding this assessment, it has been demonstrated that FAST provide reasonable predictions of fission gas release during rapid power ramps (5-120 seconds) that are within previously established uncertainty ranges. FAST provides reasonable predictions of fission gas release and centerline temperatures for large grain UO_2 and doped UO_2 fuel rods that are within previously established uncertainty ranges. Based on the limited number of data, it appears that the default UO_2 fission gas release model can provide the same level of accuracy in prediction of UO_2-Gd_2O_3 and other doped fuel as it does for UO_2. Finally, two additional commercial rods were modeled in FAST and end-of-life void volume and fission gas release predictions were within previously established uncertainty ranges.

6. References

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