Development of Burnup Dependent Fuel Rod Model in CTF

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Abstract

The paper discusses an implementation of a burnup dependent fuel thermal conductivity model within the Pennsylvania State University (PSU), Reactor Dynamics and Fuel Management Group (RDFMG) version of the subchannel thermal-hydraulics code COBRA-TF (CTF). The model takes into account the degradation of fuel thermal conductivity with high burnups and the fuel thermal conductivity dependence on the Gadolinium content for both uranium dioxide (UO_2) and mixed oxide (MOX) nuclear fuel rods. The modified Nuclear Fuel Industries (NFI) model for UO_2 fuel rods and Duriez/Modified NFI model for MOX fuel rods were incorporated into CTF. To validate the burnup dependent fuel thermal conductivity model in CTF, the fuel centerline temperature predictions were compared against Halden experimental test data and FRAPCON-3.4 predictions. Experimental test cases from the Halden experiments for UO_2 fuel rods at Beginning of Life (BOL), through lifetime without Gd_2O_3 and through lifetime with Gd_2O_3 and for MOX fuel rod were simulated with CTF. Since experimental data and FRAPCON-3.4 results were based on single rod measurements, the same spatial discretization was adopted for the CTF calculations.

Comparison of the results showed that CTF with the burnup dependent fuel thermal conductivity model predicts the fuel centerline temperature within 5% error band. CTF predictions were performed using 58 data points having a mean of 1.0082 and a standard deviation of 0.0382.

Keywords: fuel thermal conductivity, fuel centerline temperature, COBRA-TF (CTF), FRAPCON-3.4

1. INTRODUCTION

The model for degradation of fuel thermal conductivity with high burnup already exists in one-dimensional (1D) fuel performance codes FRAPCON and FRAPTRAN [1, 2]. On the other side, subchannel thermal hydraulics codes such as COBRA-TF (COolant Boiling in Rod Arrays-Two Fluid) [8, 9] still use the old UO_2 material properties from 1979, which do not include the burnup effects on thermal conductivity. Inclusion of the high burnup degradation of thermal conductivity is important since it will affect the fuel centerline temperature predictions and thus it will introduce changes in the steady state and transient operation margins.

The paper discusses an implementation of a burnup dependent fuel thermal conductivity model within the Pennsylvania State University (PSU), Reactor Dynamics and Fuel Management Group (RDFMG) version of the subchannel thermal-hydraulics code COBRA-TF (CTF). The model takes into account the degradation of fuel thermal conductivity with high burnups and the fuel thermal conductivity dependence on Gadolinium content for both uranium dioxide (UO_2) and mixed oxide (MOX) nuclear fuel rods. The modified Nuclear Fuel Industries (NFI) model [3] for UO_2 fuel rods and Duriez/Modified NFI model for MOX fuel rods [3] were incorporated into CTF. To validate the burnup dependent fuel thermal conductivity model in CTF, the fuel centerline temperature predictions were compared against Halden experimental test data [4, 5, 6, and 7] and FRAPCON-3.4 predictions. Experimental test cases from the Halden reactor for UO_2 fuel rods at Beginning of Life (BOL) [4,5] through lifetime without Gd_2O_3 and through lifetime with Gd_2O_3 [4,6], and a MOX fuel rod [4,7] were simulated with CTF. Since experimental data and FRAPCON-3.4 results were based on single rod measurements, the same spatial discretization was adopted into CTF calculations.

2. METHODOLOGY

2.1 Comparisons of Fuel Thermal Conductivity Models

Four fuel thermal conductivity models - MATPRO-11 from 1979 [10], CTF MATPRO-11 [8], FRAPCON-3.4 MATPRO-11 Rev.2 [11], and modified NFI model [3] - were compared across the applicable temperature range. It is seen from Figure 1 that CTF currently has MATPRO-11 model from 1979. When the CTF MATPRO-11 model is compared against the modified NFI model at 0 GWD/MTU, it is observed that both models give the same thermal conductivity values up to 2000°K. Above 2000°K, CTF starts to overpredict the thermal conductivities. On the other hand, MATPRO-11 Rev.2 model always underpredicts the thermal conductivities when compared to the modified NFI model. As temperature increases from 300°K to 2000°K, the thermal conductivity decreases showing the phonon contributions and after 2000°K thermal conductivity starts to increase due to the electronic contributions.

Figure 2 shows the comparison of the thermal conductivity models between MATPRO-11 from 1979, CTF MATPRO-11, FRAPCON-3.4 MATPRO-11 Rev.2 and Duriez/modified NFI model [3] for MOX fuel rods across the applicable temperature range. When the CTF MATPRO-11 model is compared against the Duriez/modified NFI model at 0 GWD/MTU, it is observed that CTF MATPRO-11 model overpredicts the thermal conductivities since it doesn't take into account the stoichiometry and the fact that the MOX fuel thermal conductivity is strongly influenced by the oxygen to metal ratio.

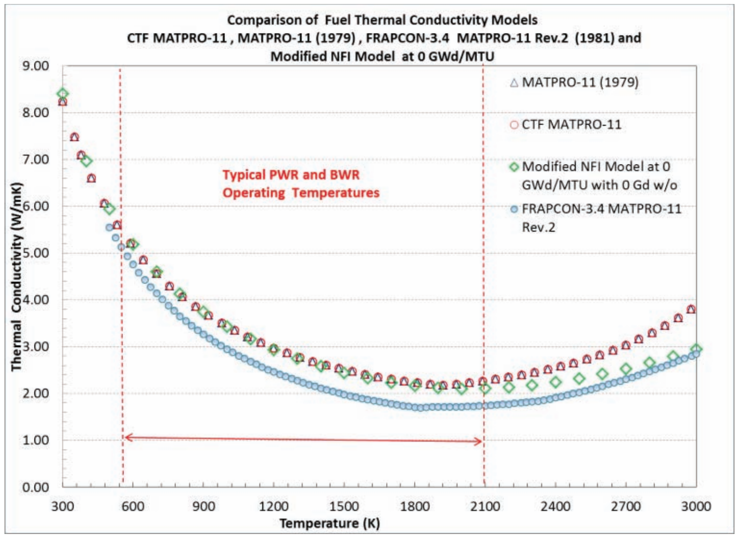

Figure 1 Comparison of CTF, MATPRO-11, and the Modified NFI Fuel Thermal Conductivity Models

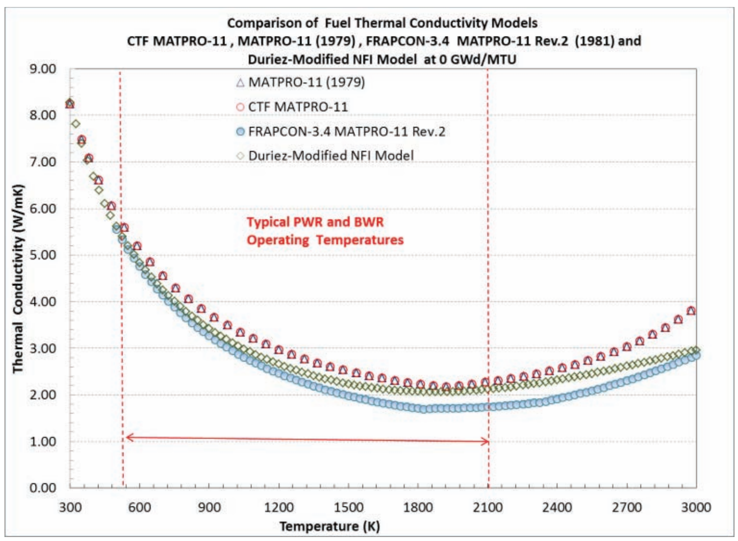

Figure 2 Comparison of CTF, MATPRO-11, and the Duriez/Modified NFI Fuel Thermal Conductivity Models

2.2 Verification of the Burnup Dependent Fuel Rod Model in CTF

This section discusses first the impact of burnup and gadolinium concentration on fuel thermal conductivity and then demonstrates the verification of the new fuel thermal conductivity model in CTF. The modified NFI fuel thermal conductivity model was successfully implemented into CTF. After implementing the new model into CTF, CTF predicted thermal conductivity values were compared against the FRAPCON-3.4 predictions to validate the CTF updated model results (Figure 4 and Figure 5).

A new input option called IFRAP is created to invoke the new model as an option. In order to keep backwards compatibility, CTF MATPRO-11 model is kept available to the users. When IFRAP=1, CTF will use the modified NFI model; and when IFRAP=0, CTF will use the MATPRO-11 model. In order to use IFRAP=1 option, new inputs are required in the input deck for the fuel type (MOX or UO_2), axial fuel rod exposure (GWD/MTU) and axial gadolinium concentration. If the users do not specify these new inputs, default values which are 0 GWD/MTU and 0 w/o Gd will be used.

One example test case, REP-Na3 in CABRI reactor tests was selected from FRAPTRAN 1.4 Integral Assessment [12] as a benchmark case. Fuel thermal conductivity values predicted by current CTF using MATPRO-11 model and improved CTF using the modified NFI model were compared. Steady-state thermal conductivities were retrieved from both cases and tabulated as a function of temperature.

Figure 3 shows that CTF with MATPRO-11 model (IFRAP=0) and CTF with modified NFI model (IFRAP=1) predicts very similar thermal conductivities at 0 GWd/MTU exposure and 0 w/o Gd concentration (blue and red curves on the top in Figure 3). When exposure increases from 0 GWD/MTU to 30 GWD/MTU and gadolinium concentration goes from 0 w/o to 6 w/o in the fuel, the difference between the two models increases due to the degradation of the fuel thermal conductivity as it can be seen clearly in Figure 3.

To verify that the new thermal conductivity model in CTF is implemented correctly into the code, CTF predicted fuel thermal conductivities were compared against the same points predicted by FRAPCON-3.4. Figure 4 and Figure 5 show the comparison of the FRAPCON-3.4 and CTF predicted fuel thermal conductivities at different exposure levels and gadolinium concentrations. FRAPCON-3.4 modified NFI model is solved numerically across the correlation temperature range between 300°K to 3000°K. CTF steady-state thermal conductivity predictions for a typical PWR fuel rod is in the range of 600°K to 2400°K as shown in Figure 4 and 5. It is confirmed from these figures that the modified NFI model implemented in CTF works properly and predicts the correct thermal conductivities.

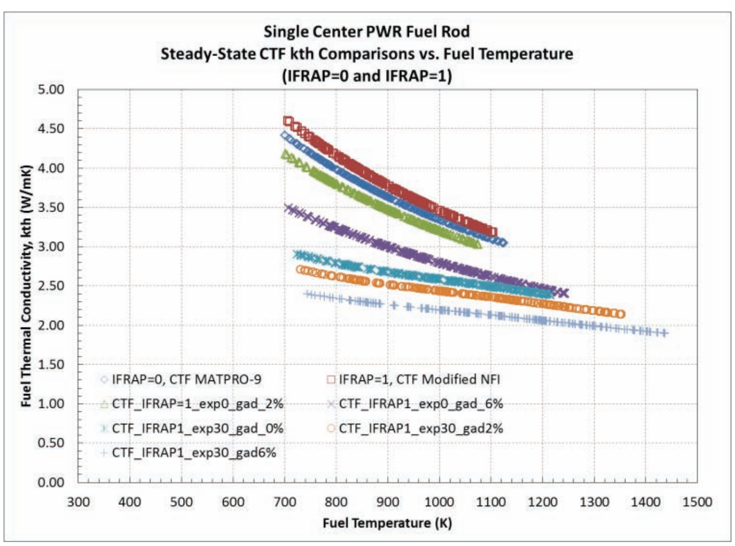

Figure 3 Comparisons of CTF predicted Fuel Thermal Conductivities vs. Fuel Temperature for a PWR Fuel Rod at Different Gd Concentration and Exposure Levels

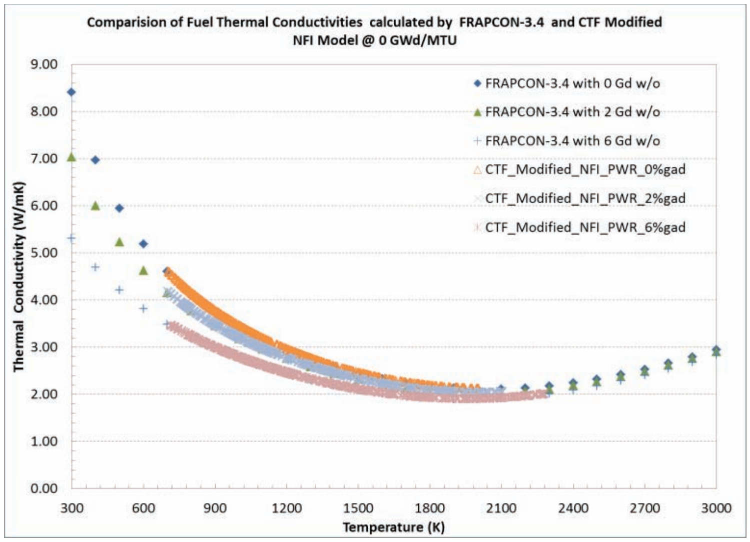

Figure 4 Comparisons of CTF predicted Fuel Thermal Conductivities vs. Fuel Temperature for a PWR Fuel Rod at Different Gd Concentration and at 0 GWd/MTU

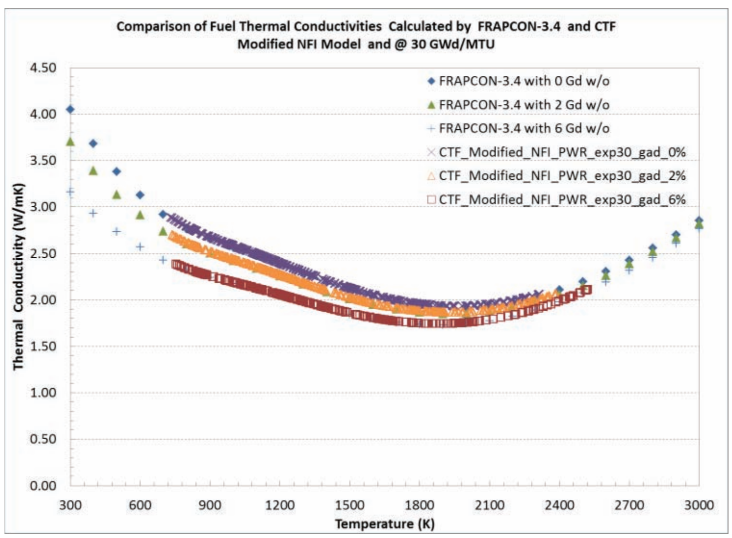

Figure 5 Comparisons of CTF predicted Fuel Thermal Conductivities to FRAPCON-3.4 Predictions for a PWR Fuel Rod at Different Gd Concentration and at 30 GWd/MTU

3. RESULTS

This section discusses the validation of fuel centerline temperature predictions in CTF. Five test cases were selected from the FRAPCON Integral Assessment Report [4] for comparisons to Halden Reactor experiments: (1) During first ramp to power (BOL, UO_2); (2) throughout life (burnup, UO_2); (3) Burnup with 2% Gd_2O_3; (4) Burnup with 8% Gd_2O_3; and (5) MOX case with burnup. Fuel centerline temperature predictions from the current and the updated fuel thermal conductivity models in CTF were compared against the Halden experimental test data and FRAPCON-3.4 predictions. The reason why these rods are selected for comparison to experimental data is that they are representatives for all different conditions including BOL and burnup conditions as well as different Gd concentrations and different fuel rods, UO_2 and MOX rods. In addition to that the rods selected for comparison are solid rods so that a good comparison can be made for the fuel centerline temperatures. Note that when comparisons are performed with the experimental data, CTF coolant temperature, cladding thickness, cladding conductivity and gap conductance are set equal to the experimental data so that the focus of this paper is to only investigate the impact of fuel thermal conductivity degradation on the uncertainty of the fuel centerline temperature prediction.

3.1 Assessment of Fuel Centerline Temperature Predictions at BOL

The BOL fuel centerline temperature predictions are compared against the measurements taken during first ramp to power for IFA-432r1 from Halden experiments [4, 5]. First ramp to power takes place during the first 1 or 2 days of operation. Since this is a short time period, initial fuel rod dimensions will still be valid because there will be no time for change in dimensions due to fission gas release, fuel densification, swelling, cladding creeps, or corrosion [4]. There will be only thermal expansion due to temperature increase. IFA-432r1 is selected from FRAPCON-3.4 Integral Assessment study for comparison of the fuel centerline temperatures. Fuel centerline temperatures predicted by CTF are compared against FRAPCON-3.4 predictions and the experimental data. Figure 6 shows the comparison of fuel centerline temperature predicted by CTF with IFRAP=0 (current model); CTF with IFRAP=1 (updated model); FRAPCON-3.4; and the measured data for IFA-432r1 at BOL. It is seen from Figure 6 that both CTF and FRAPCON-3.4 give excellent predictions which are within 5% error band.

A 5% error band is selected for comparison, because it is the representative of experimental uncertainty in the fuel centerline temperature. Current MATPRO-11 model in CTF (IFRAP=0) also predicts the fuel centerline temperature at BOL as good as CTF with the updated model (IFRAP=1) and FRAPCON-3.4. Both of the codes predict the fuel centerline temperature within 5% error band as compared to the measured data.

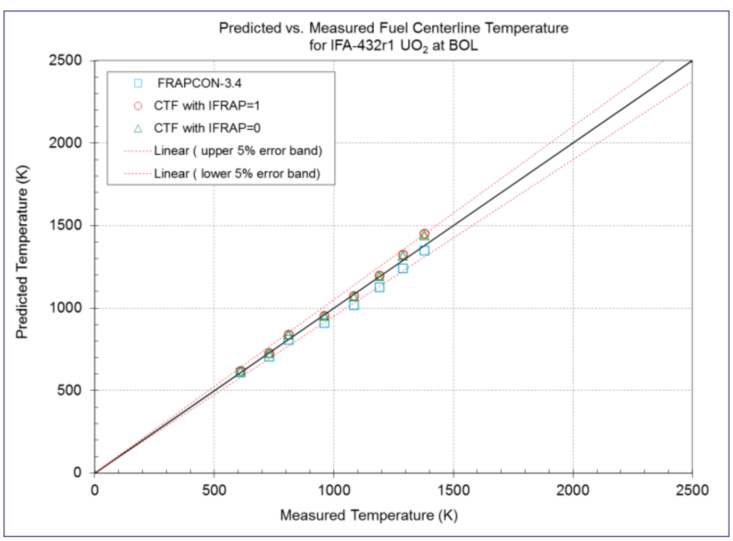

Figure 6 IFA-432r1 BOL UO_2 Fuel Centerline Temperature Predictions

3.2 Assessment of Fuel Centerline Temperature Predictions for Burnup Case

The assessment of fuel centerline temperature predictions by CTF is performed using IFA-432r1 exposed UO_2 with burnup of 45 GWD/MTU from Halden reactor test assemblies [4, 5] to evaluate CTF's ability to account for the fuel thermal conductivity degradation with burnup. Figure 7 shows predicted vs. measured fuel centerline temperature for IFA-432 rod 1. It is seen from Figure 7 that CTF with IFRAP=1 predicted fuel centerline temperatures are within 5% error band_and agrees well with the experimental data. On the other hand, CTF with IFRAP=0 option underpredicts the fuel centerline temperatures and predicted fuel centerline temperatures are outside of the 5% error band.

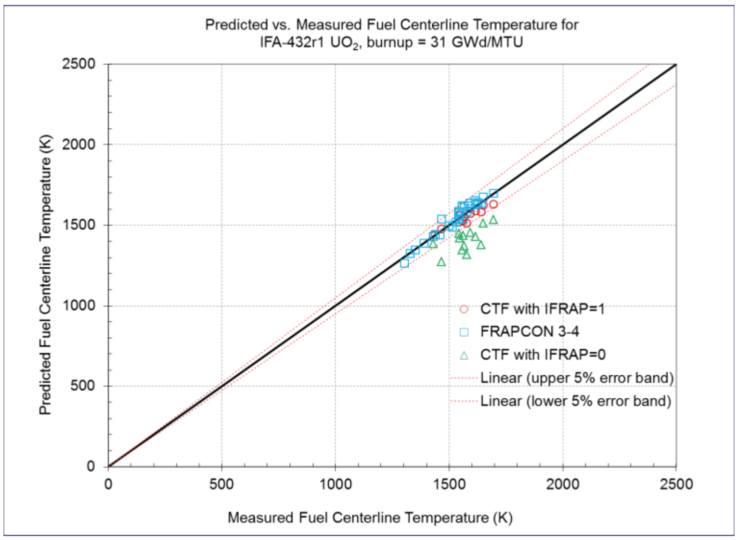

Figure 7 Predicted vs. Measured Fuel Centerline Temperature for IFA-432r1 UO_2 at 45 GWD/MTU

3.3 Assessment of Temperature Predictions for UO_2 + 2%Gd_2O_3 Fuel Rod

The assessment of fuel centerline temperature predictions by CTF is performed using IFA-681 rod 2 UO_2 + 2%Gd_2O_3 fuel rod from Halden reactor test assemblies [4, 6] to evaluate CTF's ability to account for the fuel thermal conductivity degradation with burnup and gadolinium concentration.

IFA-681r2 is selected for comparison of the analysis because it is a solid rod and has 2% Gd concentration, which consists of natural Gd (contains ^{155}Gd or ^{157}Gd). This allows investigating the degradation of fuel thermal conductivity due to Gd and also the effect of neutron absorption by Gd atoms on the radial power profile.

Figure 8 shows predicted vs. measured fuel centerline temperature for IFA-681r2. It is seen from Figure 8 that CTF with IFRAP=1 option gives excellent predictions and almost identical temperature values as FRAPCON-3.4. On the other hand CTF IFRAP=0 underpredicts the fuel centerline temperature since it doesn't take into account the burnup and Gd effects on the fuel thermal conductivity.

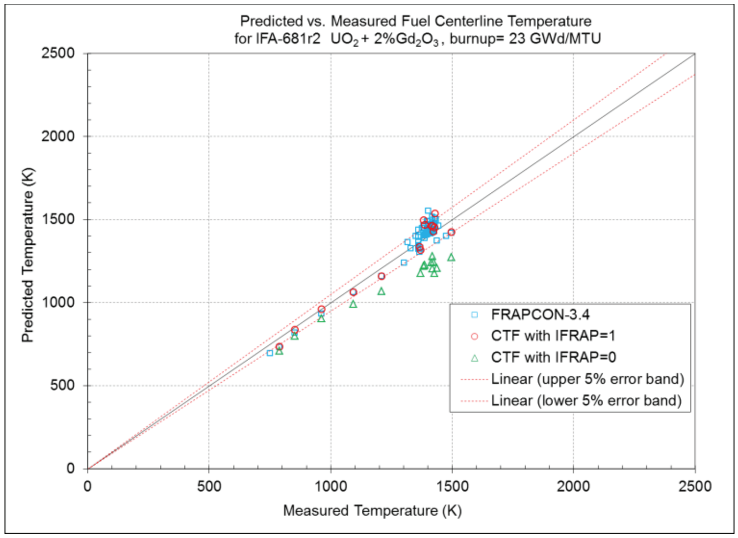

Figure 8 Predicted vs. Measured Fuel Centerline Temperature for IFA-681r2 UO_2+2% Gd_2O_3

3.4 Assessment of Temperature Predictions for UO_2+ 8% Gd_2O_3 Fuel Rod

This section summarizes the assessment of fuel centerline temperature predictions for IFA-681 rod 3 with UO_2+8%Gd_2O_3 fuel rod from Halden reactor test assemblies [4, 6]. CTF's ability to account for the fuel thermal conductivity degradation with burnup and gadolinium concentration is investigated. Rod 3 is selected for comparisons, because it is a solid rod and has 8% Gd concentration, which is higher than Rod 2 described in section 3.3 and also it contains natural Gd (contains ^{155}Gd or ^{157}Gd).

It is shown in the FRAPCON-3.4 Integral Assessment Report [4] that FRAPCON-3.4 predictions shows excellent agreement when it is compared to experimental data until 200 days. After 200 days FRAPCON-3.4 overpredicts the temperatures by up to 100ºK and the reason for this overprediction is not clear.

Since there are some uncertainties in the reported temperature data, CTF temperature prediction comparisons and statistical calculations are performed until 200 days. After 200 days, a couple of test points are run with CTF to demonstrate that CTF also overpredicts after 200 days and predictions are in line with FRAPCON-3.4.

Figure 9 shows the comparison of fuel centerline temperature predicted by FRAPCON-3.4, CTF with IFRAP=1, and CTF with IFRAP=0 options against the measured data as a function of measurement time. It is seen from Figure 9 that CTF with IFRAP=1 option gives good agreement with the data within 0.983 mean and 3.5 % standard deviation.

Figure 10 shows predicted versus measured fuel centerline temperature for IFA-681r3. It is seen from Figure 10 that CTF with IFRAP=1 option gives excellent agreement and predicts almost the same temperatures as FRAPCON-3.4. On the other hand, CTF IFRAP=0 underpredicts the fuel centerline temperature.

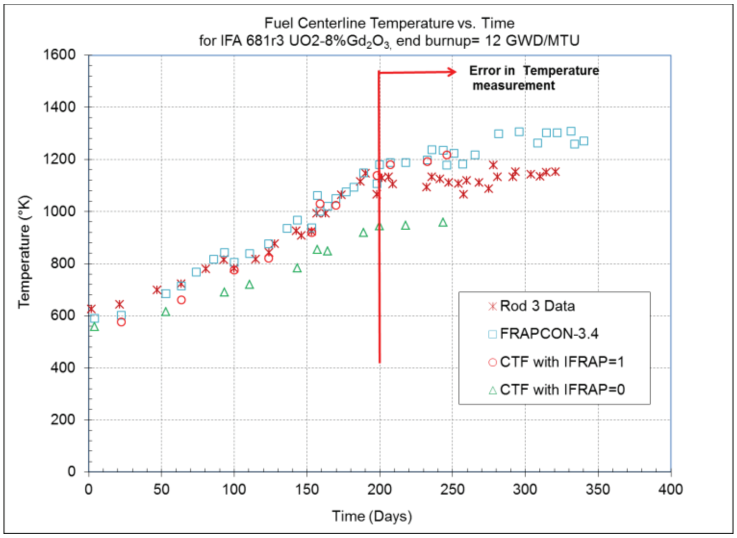

Figure 9 Fuel Centerline Temperatures vs. Rod Average Burnup for IFA-681r3 UO_2+8%Gd_2O_3

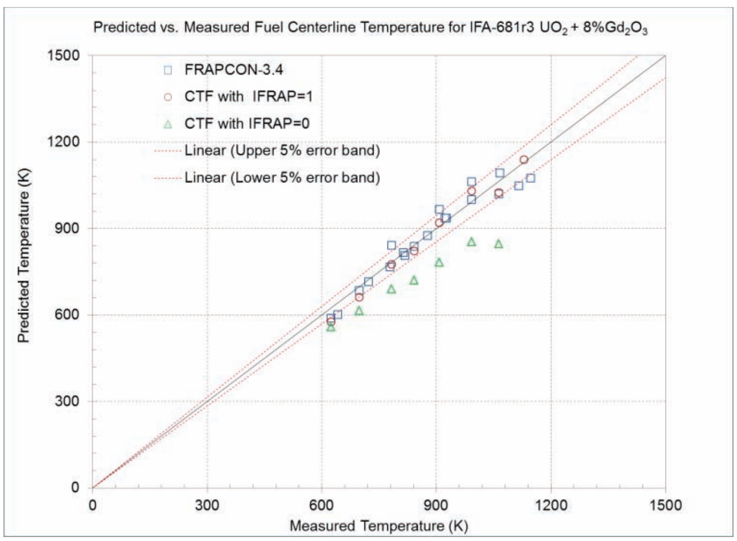

Figure 10 Predicted vs. Measured Fuel Centerline Temperature for IFA-681r3 UO_2+8%Gd_2O_3

3.5 Assessment of Fuel Centerline Temperature for a MOX Fuel Rod

The assessment of fuel centerline temperature predictions by CTF for a MOX fuel rod is performed using IFA-610 rod 2 from the Halden reactor test assemblies [4, 7]. Fuel centerline predictions from CTF with IFRAP=1 is compared against the predictions from CTF with IFRAP=0, FRAPCON-3.4, and the experimental data.

IFA-610 rod 2 is base irradiated for four cycles in the French Gravelines-4 reactors to burnup level of 55 MWD/kgM and then it is refabricated and instrumented with a centerline thermocouple to be used for cladding liftoff experiments in Halden reactor [7].

Figure 11 shows the linear heat generation rate versus rod average burnup starting from the fresh fuel. The period rod stayed in the Halden reactor starts from burnup level of 54

GWD/MTU. The LHGRs used from Figure 11 for the fuel centerline temperature comparisons are between burnup levels of approximately 54 GWD/MTU to 57 GWD/MTU.

Figure 12 shows predicted versus measured fuel centerline temperature for IFA-610 rod 2. It is seen from Figure 12 that CTF with IFRAP=1 predicted fuel centerline temperatures are within 5% error band and agrees well with the experimental data. On the other hand, CTF with IFRAP=0 option underpredicts the fuel centerline temperature and the predicted fuel centerline temperatures are outside of the 5% error band.

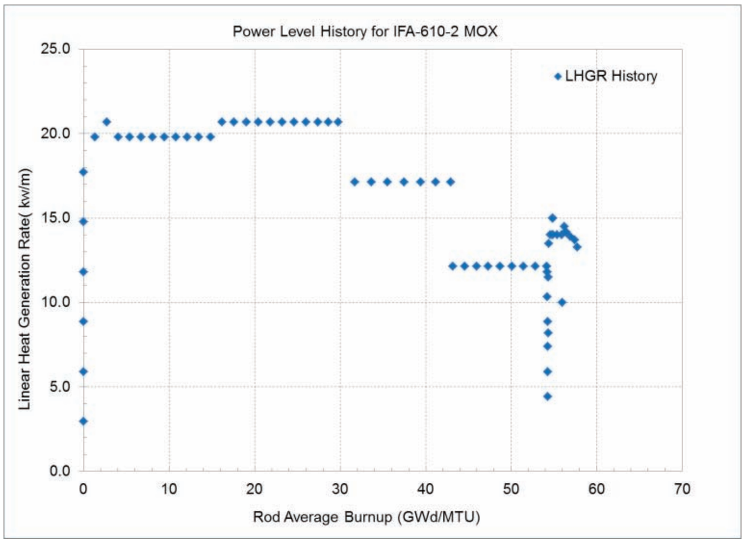

Figure 11 Linear Heat Generation Rate vs. Rod Average Burnup for IFA-610r2 MOX Fuel Rod

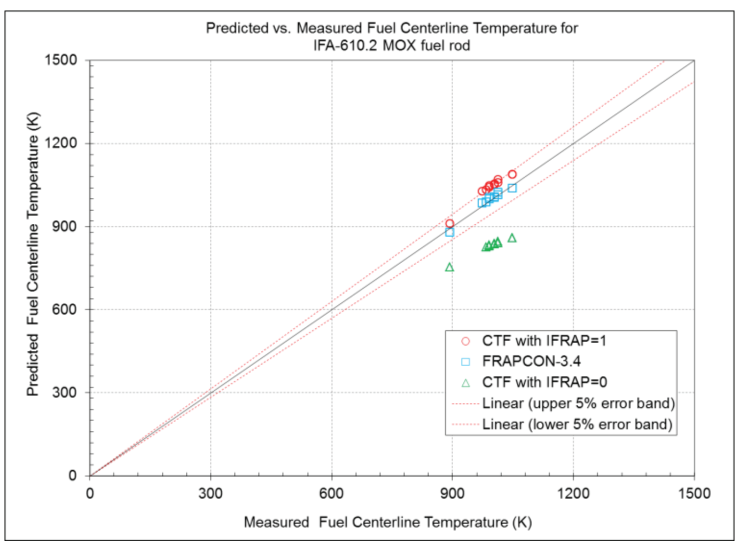

Figure 12 Predicted vs. Measured Fuel Centerline Temperature for IFA-610r2 MOX Fuel Rod

3.6 Statistical Analysis of CTF Fuel Centerline Temperature Predictions

All data points used in CTF predictions are combined together to see the overall picture. Predicted versus measured fuel centerline temperatures, normalized fuel centerline temperatures versus rod average burnup and descriptive statistics analysis are performed and shown in Figure 13 and 14. Figure 13 shows the comparison of the predicted fuel centerline temperature against the measured data for all data points. It is demonstrated in Figure 13 that CTF predictions with IFRAP=1 option are within 5% error band. Figure 14 shows normalized fuel centerline temperature versus rod average burnup for all data points predicted by CTF using IFRAP=1 option.

Table 1 summarizes the mean and standard deviation of each case analyzed. In summary, CTF with IFRAP=1 option predictions are performed using fifty-eight (58) data points and have a mean of 1.0082 and a standard deviation of 0.0382. On the other hand, FRAPCON-3.4 predictions are performed using one hundred and twenty-eight (128) data points and have a mean of 1.0038 and a standard deviation of 0.0340. When statistical analysis are performed for FRAPCON-3.4 using the same data cases as CTF (58 data points), mean becomes 0.9981 and standard deviation decreases to 0.0329.

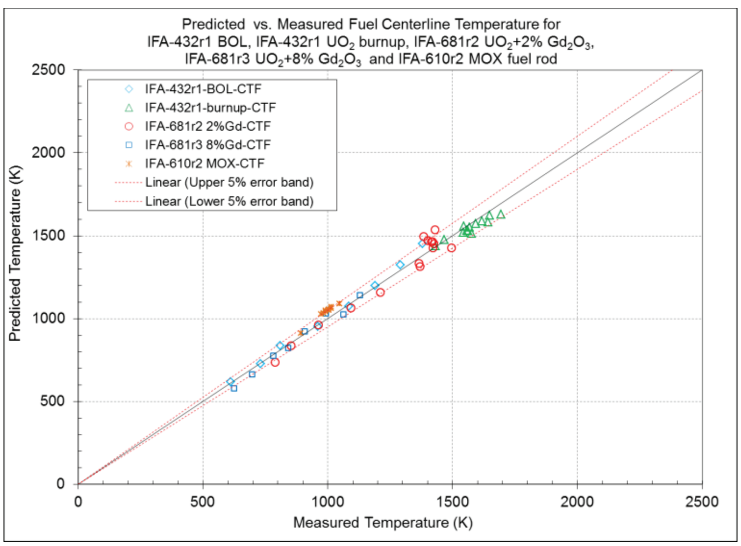

Figure 13 Predicted vs. Measured Fuel Centerline Temperature for IFA-432r1 BOL, IFA-432r1 burnup, IFA-681r2 UO_2+2%Gd_2O_3, 681r3 UO_2+8%$Gd_2O_3$and IFA-610r2 MOX

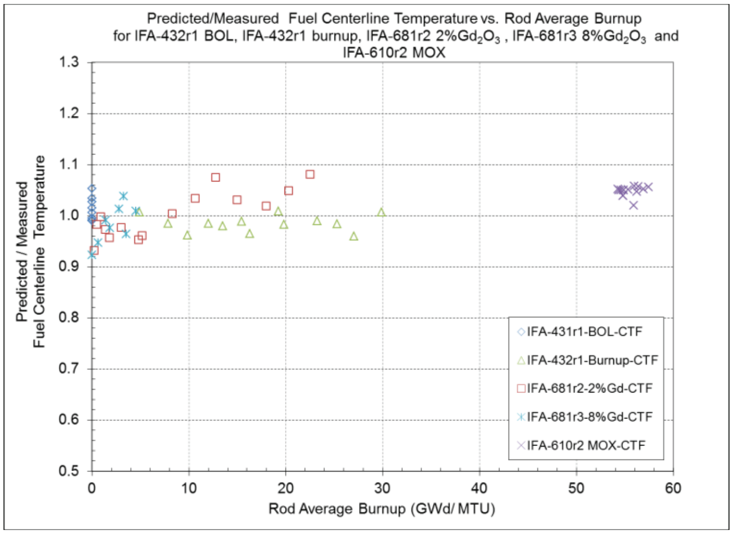

Figure 14 Normalized Fuel Centerline Temperature vs. Rod Average Burnup for IFA-432r1 BOL, IFA-432r1 burnup, IFA- 681r2 UO_2+2%Gd_2O_3, IFA-681r3 UO_2+8%Gd_2O_3 and IFA-610r2 MOX

Table 1 Statistical Summary of P/M Ratios for All Calculations

Case Rod #	CTF IFRAP=0 (P/M)			CTF IFRAP=1 (P/M)			FRAPCON-3.4 (P/M)		
	# of data points	Mean	Standard Deviation	# of data points	Mean	Standard Deviation	# of data points	Mean	Standard Deviation
BOL UO_2 IFA-432r1	8	1.0115	0.0209	8	1.0138	0.0227	8	0.9664	0.0226
Burnup UO_2 IFA-432r1	13	0.9105	0.0750	13	0.9848	0.0157	13	1.012	0.0185
UO_2+2%Gd_2O_3 IFA-681r2	15	0.8817	0.0319	15	1.002	0.0454	15	0.9931	0.0416
UO_2+8%Gd_2O_3 IFA-681r3	8	0.856	0.032	8	0.983	0.0352	8	1.013	0.048
MOX IFA-610r2	14	0.8350	0.0069	14	1.047	0.0094	14	1.0031	0.0082
All data points	58	0.8920	0.0693	58	1.0082	0.0382	58	0.9981	0.0329

4. CONCLUSIONS

Modified NFI fuel thermal conductivity model was implemented into CTF as an input option called IFRAP=1 and predicted fuel thermal conductivities were benchmarked against FRAPCON-3.4 predictions. It was demonstrated that the new model in CTF predicts the same thermal conductivities as FRAPCON-3.4. In addition to that, the fuel centerline temperatures predicted by CTF with the new model were validated against the Halden experimental test data and the FRAPCON-3.4 predictions. Experimental test cases from Halden reactor for UO_2 fuel rods at BOL, through lifetime without Gd_2O_3, through lifetime with Gd_2O_3 and a MOX fuel rod were simulated with CTF. It was demonstrated that the new thermal conductivity model in CTF predicts the fuel centerline temperature within 5% error band as compared to experimental data. CTF predictions were performed using fifty-eight (58) data points and have a mean of 1.0082 and a standard deviation of 0.0382.

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