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OREGON STATE TRIGA® REACTOR CONVERSION ANALYSIS HIGHLIGHTS

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ABSTRACT

Analyses were performed in support of the conversion of the Oregon State University TRIGA® Reactor (OSTR) from the use of Highly Enriched Uranium (HEU) fuel to Low Enriched Uranium (LEU) fuel. The analyses predicted neutronic and thermal-hydraulic behavior for the original OSTR HEU core and the LEU 30/20 core. The only facility change required for conversion from HEU to LEU fuel was replacement of all fuel and graphite reflector elements. The reflector elements, previously aluminum clad, were replaced with new stainless steel clad graphite reflector elements. Results of the analysis compare very well with measured data taken of the LEU core. Future work includes elimination of the bias observed in the MCNP5 model, publishing the neutronic analysis results and publishing results for the transient (pulse) operational condition.

Introduction

Analyses were performed in support of the conversion of the Oregon State University TRIGA® Reactor (OSTR) from the use of Highly Enriched Uranium (HEU) fuel to Low Enriched Uranium (LEU) fuel[1]. This paper presents a brief summary of the significant findings pertaining to the steady state operation of the reactor.

The analyses predicted neutronic and thermal-hydraulic behavior for the original OSTR HEU core and the LEU 30/20 core. The only facility change required for conversion from HEU to LEU fuel was replacement of all fuel and graphite reflector elements. The reflector elements, previously aluminum clad, were replaced with new stainless steel clad graphite reflector elements.

Fuel Differences

The LEU 30/20 fuel has been approved by the Nuclear Regulatory Commission (NRC) for use in non-power reactors.[2] The LEU 30/20 fuel installed in the OSTR was manufactured to the same dimensions as those of the HEU fuel. Fuel element dimensions, upper and lower end fittings and clad are identical to HEU fuel elements. The only changes to the fuel exist in the fuel alloy compacts themselves. Table 1 compares the design features of the HEU fuel and the LEU 30/20 fuel.

The LEU 30/20 fuel previously approved for use in TRIGA® reactors by NUREG-1282 contained 0.9 mass percent natural erbium, while the LEU 30/20 fuel for the OSTR contains 1.1 mass percent natural erbium. The HEU fuel contained 1.6 mass percent erbium. Table 1 of NUREG-1282 bounds the erbium content from 0.0 to 1.8 mass percent for nominal 20% enriched fuels under varying wt% uranium content. The conclusion of NUREG-1282 was that fuel performance is substantially independent of uranium content up to 45 wt%. While the analysis concentrated on uranium loading, erbium loading was also varied. A reasonable conclusion can be drawn that if no performance issues were observed, fuel performance is independent of erbium content in this range as well. Additionally, in the Simnad[3] paper referenced in NUREG-1282 it was concluded that, "All available evidence indicates that the addition of erbium to the U-ZrH introduces no deleterious effects to the fuel." The only anticipated effect of the increased erbium content is to decrease reactivity, the purpose of which is to reduce the power per element in order to increase the number of fuel elements in the core.

Table 1, Fuel Characteristics for HEU and LEU 30/20 Cores

Fuel Type	HEU	LEU
Uranium content [mass %]	8.5	30
U-235 enrichment [mass % U]	70	19.75
Erbium content [mass %]	1.6	1.1
Fuel alloy inner diameter [mm]	6.35	6.35
Fuel alloy outer diameter [mm]	36.449	36.449
Fuel alloy length [mm]	381	381
Cladding material	Type 304 SS	Type 304 SS
Cladding thickness [mm]	0.508	0.508
Cladding outer diameter [mm]	37.465	37.465

Neutronics Analysis

To assess the impact of the conversion from HEU fuel to LEU 30/20 fuel, detailed neutronic analyses were undertaken utilizing MCNP5.[4] MCNP5 is a general purpose stochastic transport code which permits detailed neutronics calculations of complex 3-dimensional systems, and it is well suited to explicitly handle the material and geometric heterogeneities present in the OSTR core. In the model developed to describe the OSTR, facility drawings, provided by the manufacturer at the time of construction of the facility were used to define the geometry of the core and surrounding structures. A cross-sectional view of the MCNP5 model is shown in Figure 1.

Extensive start-up testing data was available for the original HEU core. To demonstrate the capability of MCNP5 to accurately predict core neutronic parameters, the MCNP5 model was modified to simulate core conditions present during start-up testing (the initial critical core and the initial operational core were simulated), and the calculational results of the model were compared to the experimentally determined values. Comparison of measured and predicted reactivity values indicates that on average, the model exhibits a bias of … %Δk/k, etc.

LEU 30/20 CORE

The analysis of the LEU 30/20 core was performed by modifying the HEU MCNP5 model to mimic the arrangement of LEU core components. Fuel compact properties were updated to reflect LEU number densities. The initial operational LEU core configuration is shown in Figure 2.

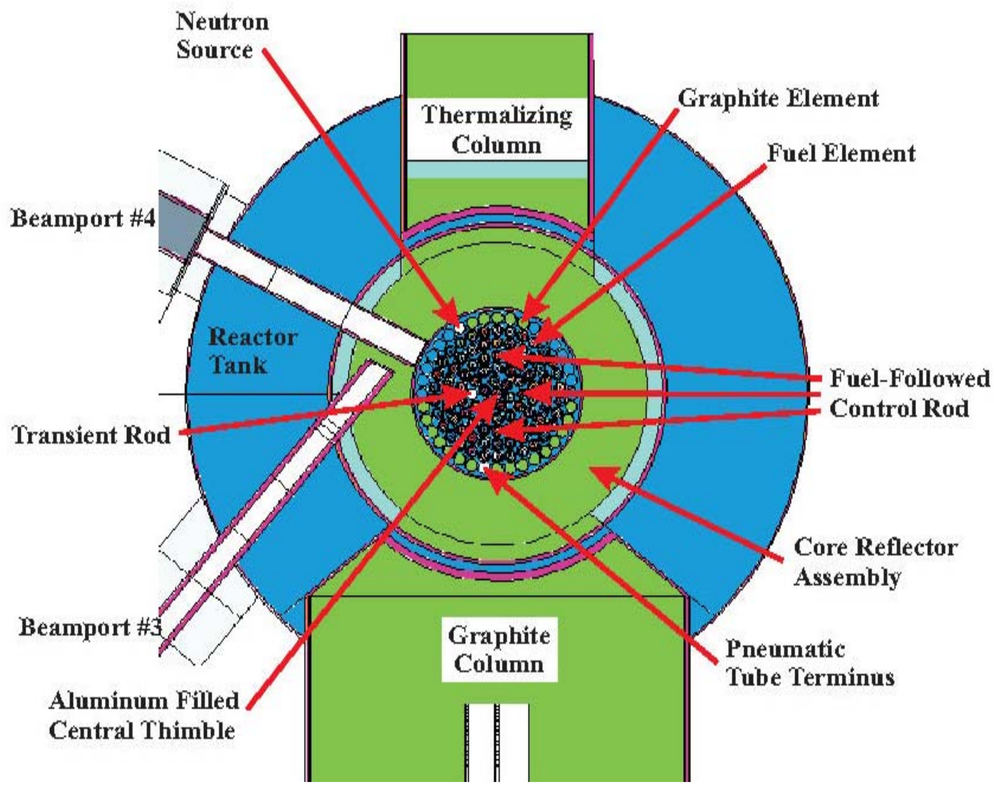

Figure 1, Vertical Cross-section of the MCNP5 Model used to Perform Neutronic Analyses of the OSTR HEU Core (taken at the core mid-plane)

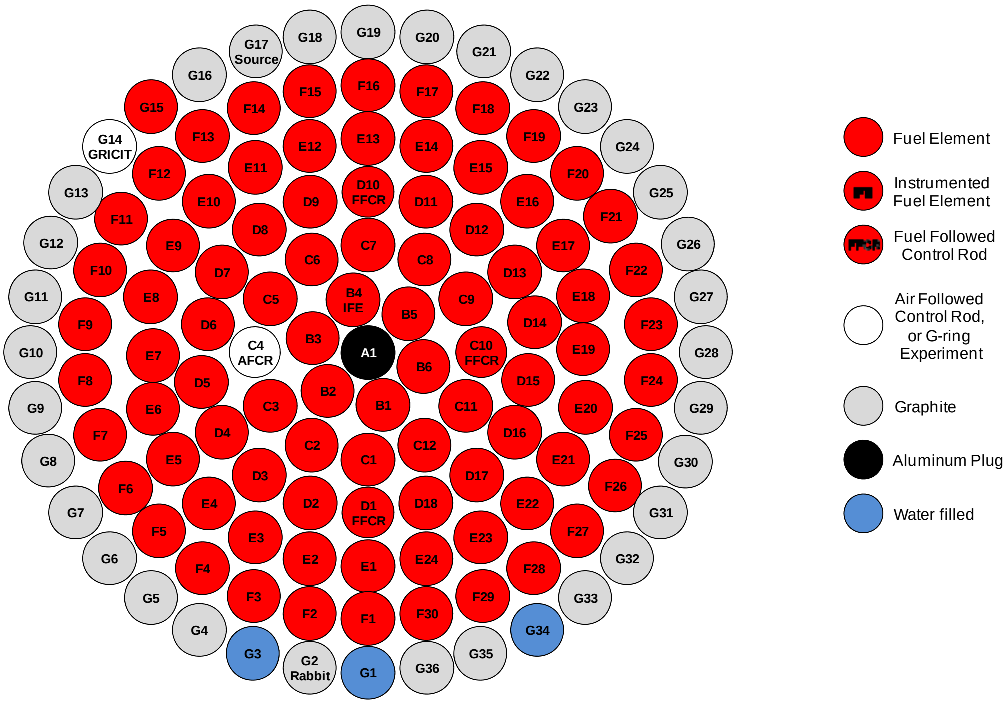

Figure 1, Initial LEU Full Power Core Configuration

REBUS-MCNP5 was utilized to perform a depletion analysis of the HEU and LEU 30/20 cores[5Error! Bookmark not defined.]. The depletion analysis was performed by dividing the fuel into five equal-height axial segments, with each axial segment further subdivided into three equal-volume radial rings. The depletion analysis was conducted at a core power of 1.1 MW_{th}, a fuel temperature of 327°C, and a moderator temperature of 50°C. The results of the depletion analysis are shown in Figure 2, 3. Based upon the depletion analysis, middle-of-life (MOL) and end-of-life (EOL) for the LEU 30/20 core were determined to be 1600 MWd and 3600 MWd, respectively. From Figure 2, , it can be seen that the lifetime of the LEU 30/20 core is nearly as long as the HEU core, while the reactivity swing which occurs during the operation of the core due to depletion of the erbium is not nearly as pronounced for the LEU 30/20 core.

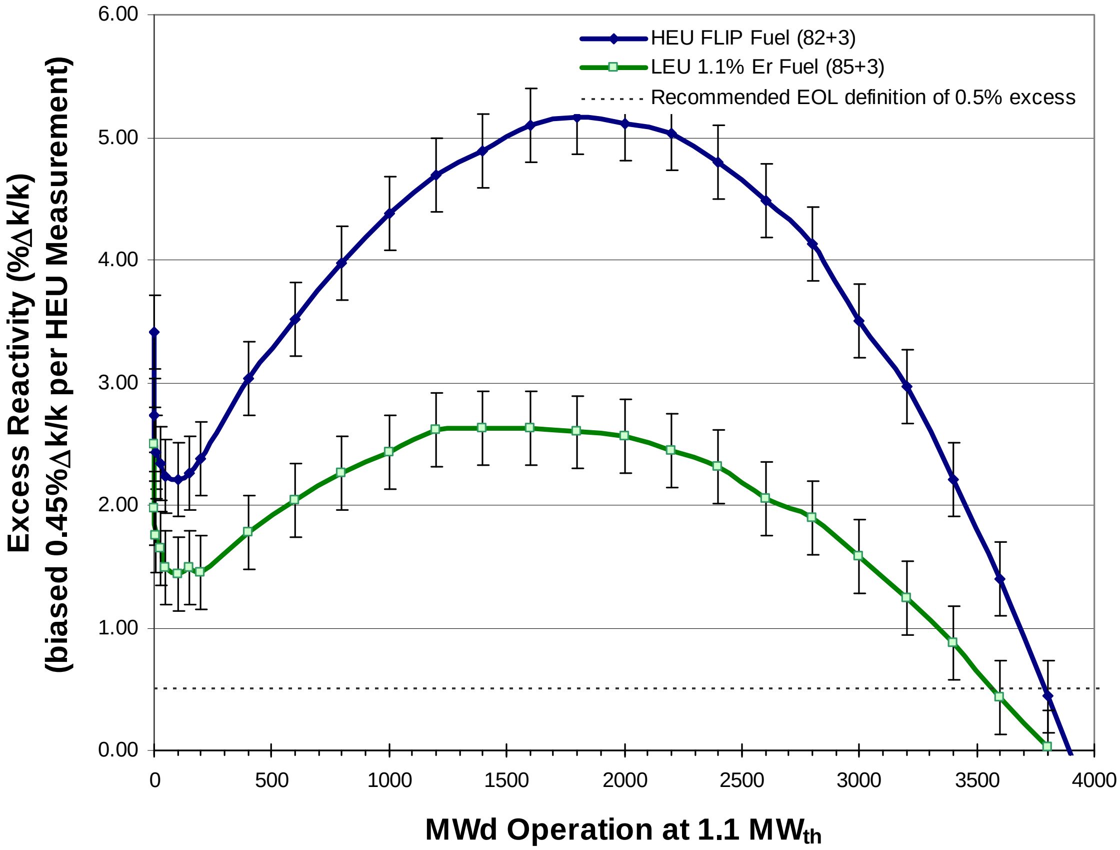

Figure 2, REBUS-MCNP5 Depletion Analysis Results for the LEU 30/20 Core and the HEU Core.

Control Rod Worths

Results for the calculated and measured control rod worths are summarized in Table 2. Predicted and measured values of total rod worth agree reasonably well, except for the HEU transient rod where the predicted value is 26.6% greater than the measured value.

The predicted rod worth curve for the safety control rod in the LEU core is shown in Figure 4. Control rod worth in the LEU core was measured as soon as the operational core configuration was established. Measured and predicted values of integrated control rod worth are summarized in Table . The results of both the HEU and LEU comparisons of predicted and measured data provided a high degree of confidence in the fidelity of the MCNP5 model.

Table 2, Summary of LEU BOL Total Integrated Rod Worth

Control Rod	HEU Measured Rod Worth [$]	HEU MCNP5 Predicted Rod Worth [$]	LEU Measured Rod Worth [$]	LEU MCNP5 Predicted Rod Worth [$]
Shim Rod	2.75 ± 0.39	2.54 ± 0.17	2.76 ± 0.39	2.55 ± 0.16
Safety Rod	2.94 ± 0.41	3.01 ± 0.17	2.66 ± 0.37	2.60 ± 0.16
Regulating Rod	3.71 ± 0.52	3.72 ± 0.20	3.71 ± 0.52	3.36 ± 0.19
Transient Rod	2.33 ± 0.33	2.95 ± 0.16	2.86 ± 0.40	2.86 ± 0.15
Sum of all Rods	11.73 ± 0.84	12.22 ± 0.35	11.99 ± 0.85	11.37 ± 0.33

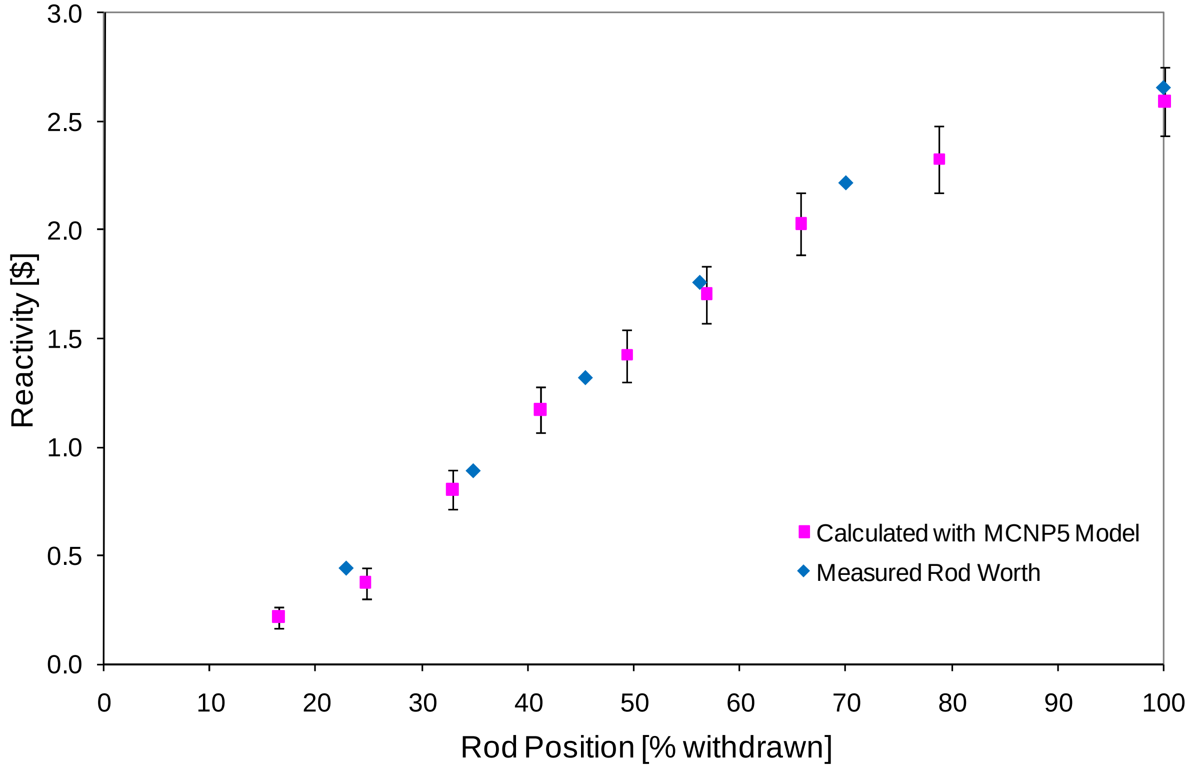

Figure 4, Safety Control Rod Calibration Curve

LEU Power Summary

The LEU Core power distributions, as well as the intra-fuel relative power distribution (radial and axial distribution in the highest power, or "hot rod") are shown in

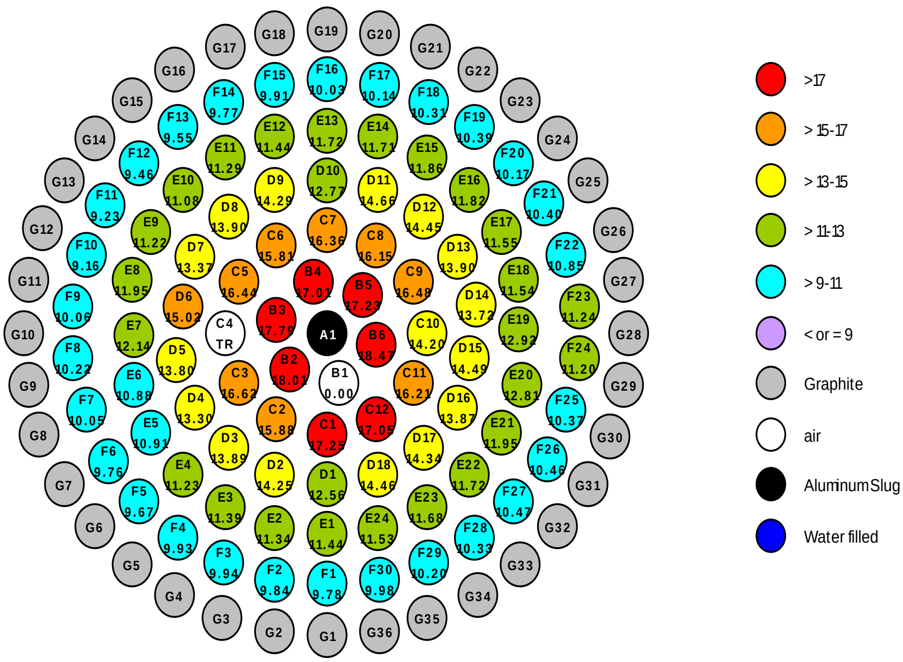

Figure 5, 5 and 6, respectively. Power distribution diagrams were used to derive Hot Channel Peak Factors. The hot channel peak factor, axial power distribution and radial power distribution were used as input for the thermal hydraulic analysis.

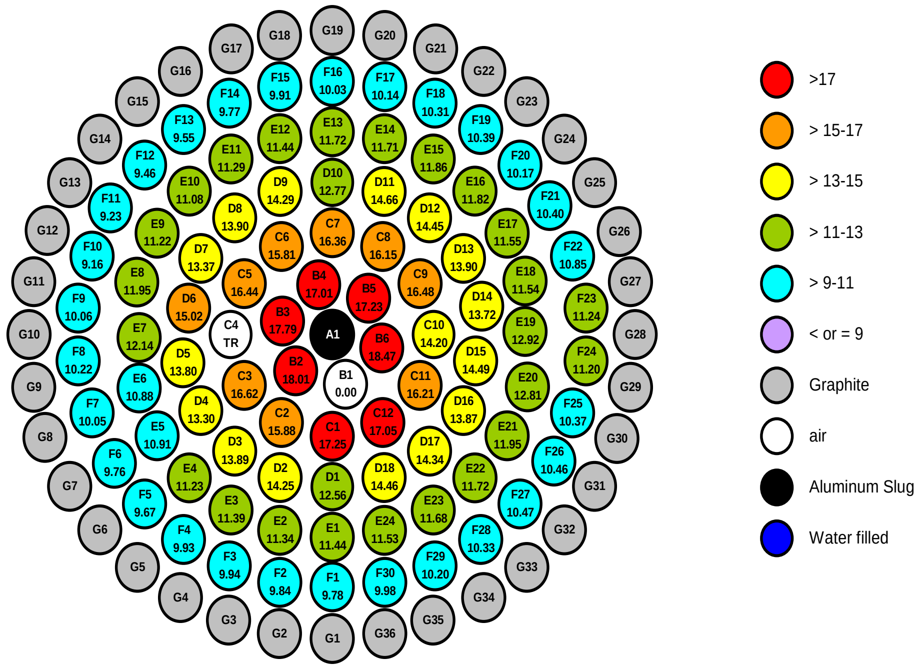

Figure 5, Core Power Distribution (LEU BOL Core).

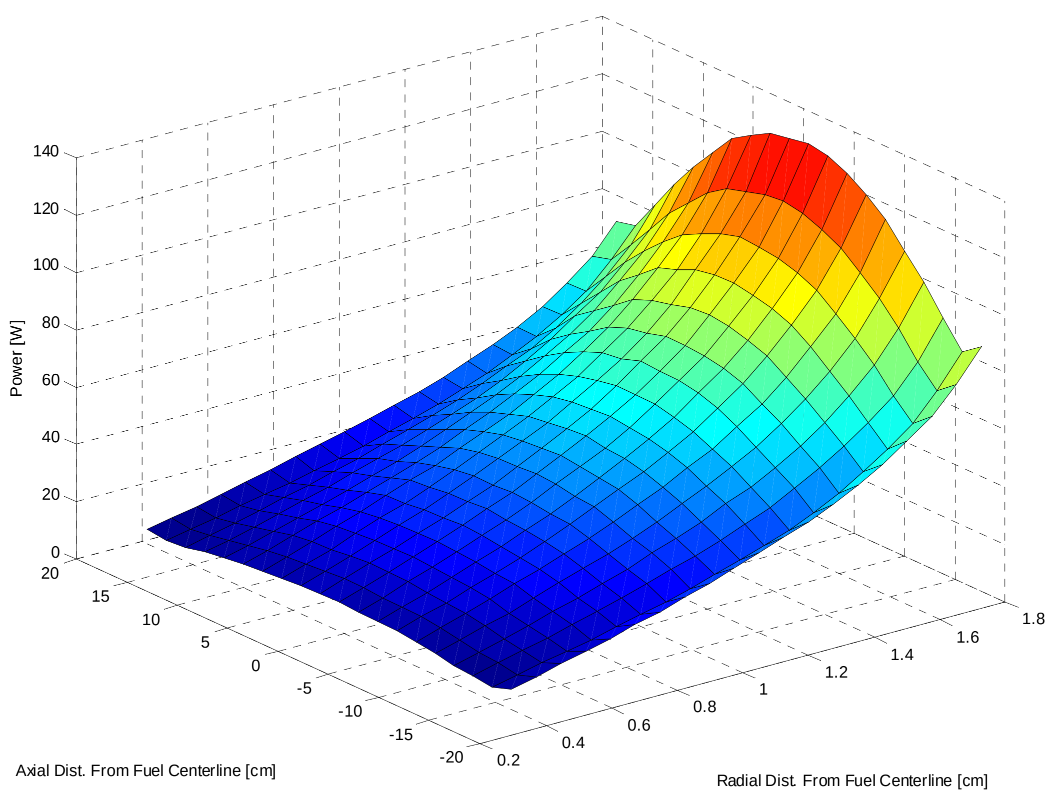

Figure 6, OSU LEU Fuel Element Power Profile from Fuel Centerline.

Thermal Hydraulic Analysis

A detailed review of the thermal-hydraulic analysis been previously published[6]. In summary, the thermal hydraulic analysis was conducted using RELAP5-3D[7]. The predicted parameters produced from this code for steady state operation include: channel flow rate, axial fuel centerline temperature distribution, axial clad temperature distribution, axial bulk coolant temperature distribution and axial DNBR. To simplify the RELAP5-3D model, it was assumed that there is no cross flow between adjacent channels. This assumption is conservative since higher values of temperature and lower margins to DNB are predicted when cross flow between adjacent channels is ignored. The parametric inputs into RELAP5-3D included the inlet coolant temperature, system pressure at the top of the core, radial and axial heat source distribution, discretized spacing of heat source nodes, and inlet and exit pressure loss coefficients. Critical heat flux conditions were evaluated for a hot channel operating at the maximum power identified by the MCNP5 model. RELAP5-3D was also used to calculate coolant flow rate as a function of rod power. The Bernath correlation and the 2006 Groeneveld critical heat flux tables were used to determine the Departure from Nucleate Boiling Ratio (DNBR).

Of particular note is the gap thickness utilized for this analysis. A RELAP5-3D model was run, simulating the Instrumented Fuel Element (IFE) at conditions present during the startup of the HEU core (i.e., power of 15.81kW while using a gap thickness of 0.1 mils). As shown in Figure 7, predicted steady state IFE temperature is larger than measured steady state IFE temperature by approximately 17°C or 34°C, depending on which IFE measurement is used. A gap thickness of 0.1 mils was used in all analyses since it provided the most accurate yet still conservative temperature prediction. The content of the gap gases was chosen to be the default setting for RELAP which assumes a mixture of He, Kr, and Xe at molar fractions of 0.1066, 0.134 and 0.7594, respectively. Although the backfill gas at the BOL for TRIGA® fuel is air, the content at MOL and EOL is unknown. However, because of the difference in thermal conductivity between air and the fission gas mixture, the default RELAP mixture will produce higher fuel temperatures and is therefore conservative.

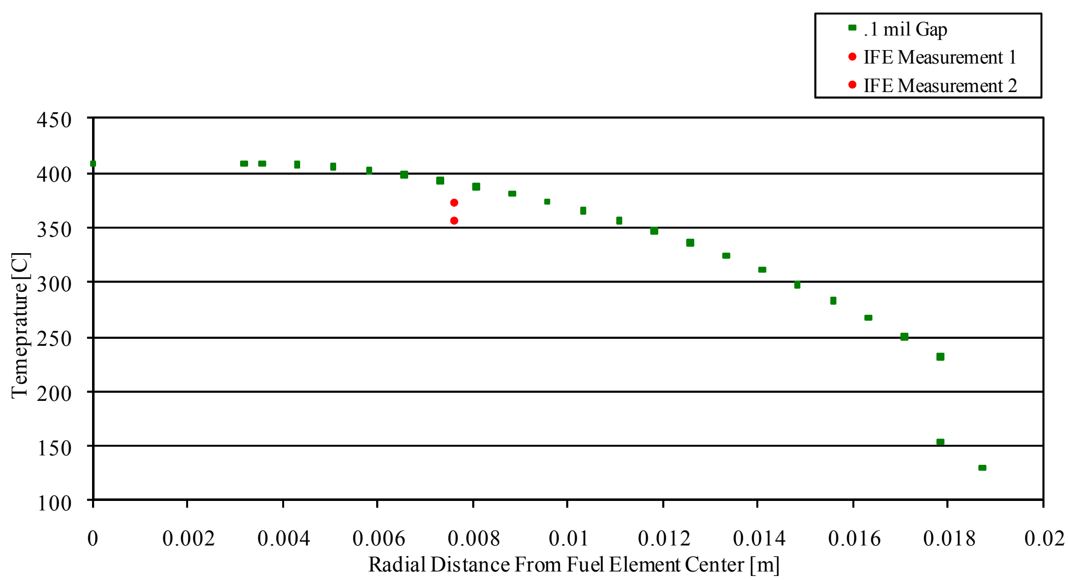

Figure 7, IFE Radial Temperature Distribution at 15.81 kW (HEU-BOL Core).

The LEU steady state results shown in Figures 5 through 9 are for a typical core configuration. This core configuration had the highest effective peaking factor of the three configurations analyzed, and thus is the bounding core for steady state operation. All LEU core configurations analysed contain fuel elements that are geometrically similar and exhibit the most conservative geometry. Therefore the hot channel geometric parameters (i.e. hydraulic diameter, length, etc.) do not change from those defined for the HEU Core. The core configuration analyzed has a MDNBR of 2.083 at 1.1 MW_{th} steady state using the Bernath Correlation. Figure 8 shows that the MDNBR in the hot channel will reach a value of 2.00 at approximately 20.0 kW hot channel steady state power. This is 108.3% of the 18.47 kW produced in the hot channel of the LEU BOL core operating at 1.1 MW_{th}. Using either the Bernath or the Groeneveld 2006 correlations, the LEU BOL core (the most limiting core) is operating at power well below that required for departure from nucleate boiling.

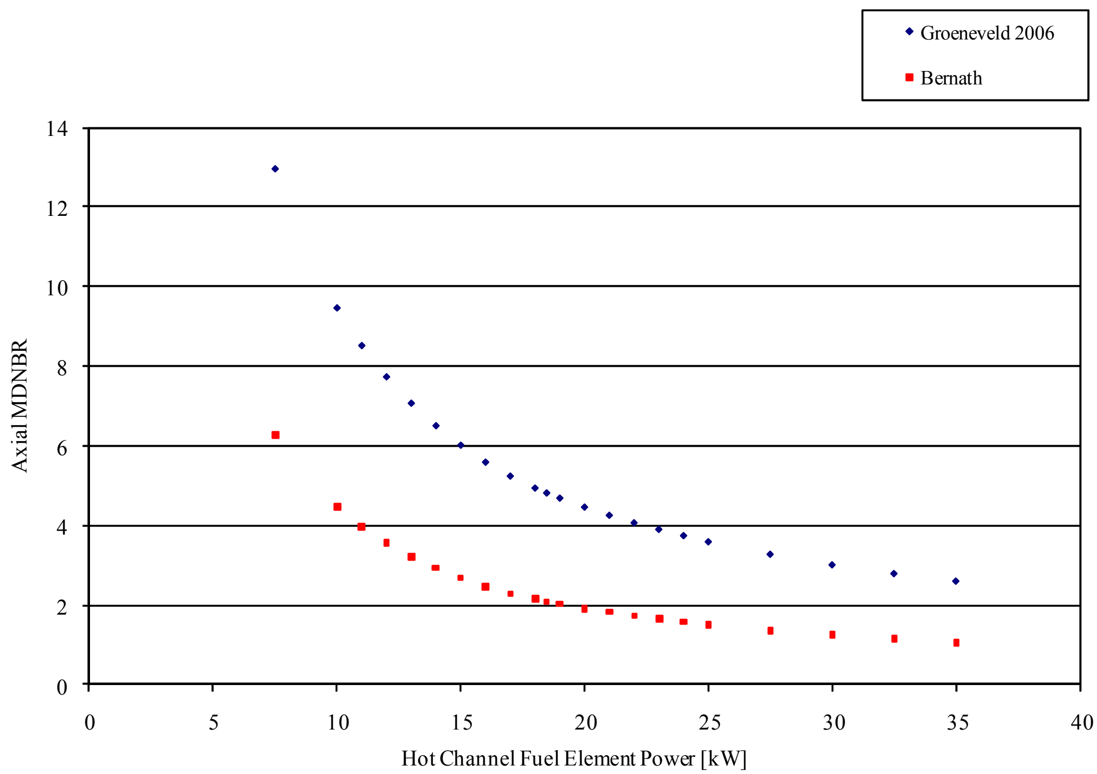

Figure 8, Hot Channel MDNBR (LEU BOL Core).

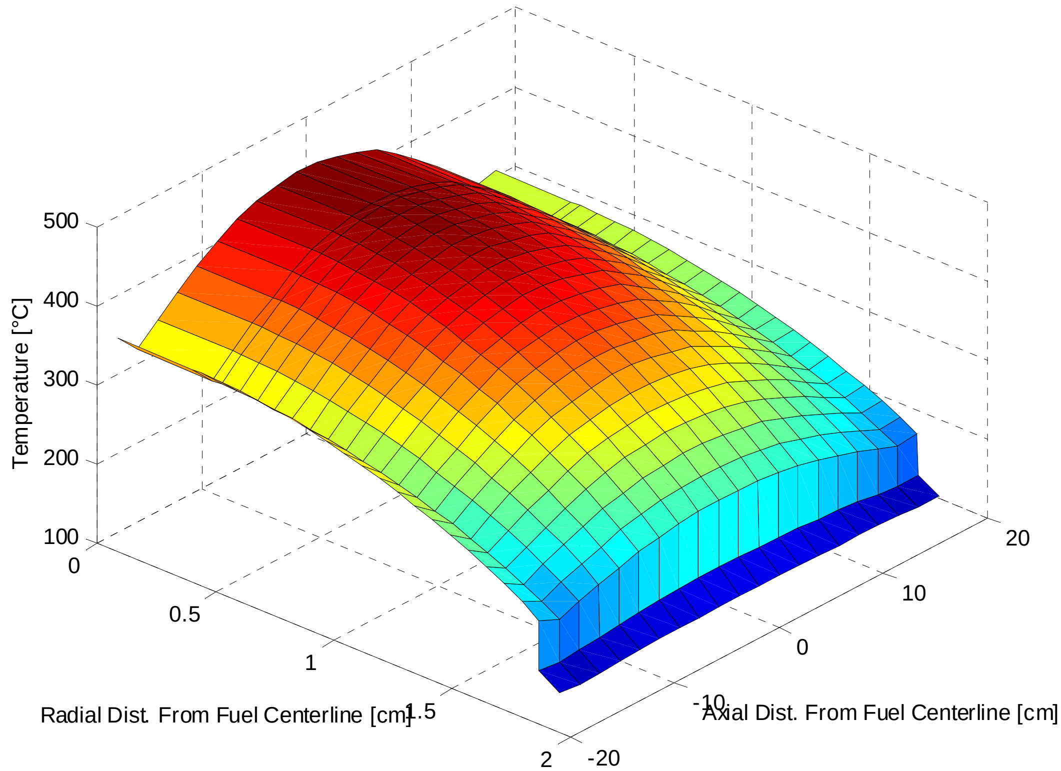

Figure 9, Hot Channel Fuel Element Temperature Distribution (LEU BOL Core)

Conclusion

The Oregon State TRIGA® Reactor has successfully undergone a conversion from HEU to LEU fuel. In support of this effort, an extensive and thorough analysis was performed and approved by the U.S. Nuclear Regulatory Commission. Future work includes elimination of the bias observed in the MCNP5 model, publishing the neutronic analysis results and publishing results for the transient (pulse) operational condition.

References

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