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Steady-State Thermal-Hydraulics Analyses for the Conversion of BR2 to Low Enriched Uranium Fuel

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ABSTRACT

The code PLTEMP/ANL version 4.2 was used to perform the steady-state thermal-hydraulic analyses of the BR2 research reactor for conversion from Highly-Enriched to Low Enriched Uranium fuel (HEU and LEU, respectively). Calculations were performed to evaluate different fuel assemblies with respect to the onset of nucleate boiling (ONB), flow instability (FI), critical heat flux (CHF) and fuel temperature at beginning of cycle conditions. The fuel assemblies were characteristic of fresh fuel (0% burnup), highest heat flux (16% burnup), highest power (32% burnup) and highest burnup (46% burnup). Results show that the high heat flux fuel element is limiting for ONB, FI, and CHF, for both HEU and LEU fuel, but that the high power fuel element produces similar margin in a few cases. The maximum fuel temperature similarly occurs in both the high heat flux and high power fuel assemblies for both HEU and LEU fuel. A sensitivity study was also performed to evaluate the variation in fuel temperature due to uncertainties in the thermal conductivity degradation associated with burnup.

1. Introduction

BR2 is a research reactor used for radioisotope production and materials testing. It’s a tank-in-pool type reactor cooled by light water and moderated by beryllium and light water (Figure 1). The reactor core consists of a beryllium moderator forming a matrix of 79 hexagonal prisms in a hyperboloid configuration; each having a central bore that can contain a variety of different components such as a fuel element, a control or regulating rod, an experimental device, or a beryllium or aluminum plug. Based on a series of tests performed in 1963, BR2 is currently limited to a maximum heat flux limit of 470 W/cm^2 for routine operation (and a temporary heat flux limit of 600 W/cm^2) to ensure fuel plate integrity at steady-state and after a loss-of-flow/loss-of-pressure accident [1].

A feasibility study [2] for the conversion of the BR2 reactor from highly-enriched uranium (HEU) to low-enriched uranium (LEU) fuel was previously performed to verify it can operate safely at the same maximum nominal steady-state heat flux. An assessment was also performed to quantify the heat fluxes at which the onset of flow instability and critical heat flux occur for each fuel type [3]. This document updates and expands these results for the current representative core configuration (assuming a fresh beryllium matrix) by evaluating the onset of nucleate boiling ratio (ONBR), onset of fully developed nucleate boiling ratio (FDNBR), flow instability ratio (FIR) and critical heat flux ratio (CHFR). In addition, the highest heat flux fuel element from each fuel cycle group, at beginning of cycle (BOC) conditions, was evaluated to compare the thermal hydraulic (TH) margins and fuel centerline temperatures. These limiting fuel elements are characteristic of fresh fuel (0% burnup), the highest heat flux (16% burnup), the highest power (32% burnup) and the highest burnup (46% burnup). This paper discusses key modeling assumptions used to define the representative life cycle of the limiting fuel element, its thermal resistance as function of burnup, and the TH margins and fuel temperatures for both HEU and LEU fuel.

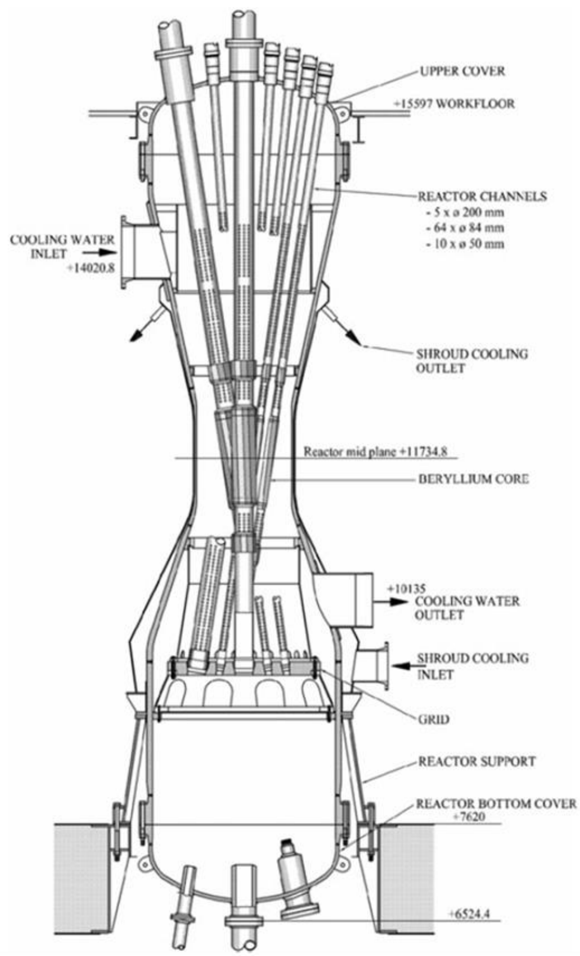


Figure 1. BR2 reactor schematic.

2. Methods

The code PLTEMP/ANL version 4.2 [4] was used for all thermal hydraulic calculations of the BR2 fuel element. A standard BR2 fuel element is composed of 18 fuel plates arranged into six concentric fuel “tubes” divided by aluminum stiffeners into three sectors (Figure 2). Each fuel plate consists of a fuel meat (UAl_x-Al for HEU, assumes uncoated U7Mo dispersed in Al for LEU) clad by aluminum (AG3NE). The PLTEMP model was based on a detailed description of the fuel element geometry given in Ref. [5], including fuel plate materials, dimensions such as radius of curvature, clad thickness, meat thickness, plate full and heated length, as well as coolant channel thickness and areas. The nominal dimensions are identical for each fuel type although the LEU fuel element has cadmium wires in the aluminum stiffeners to replace the integral burnable absorbers (B_4C and Sm_3O_2) used in the HEU fuel. Previous analysis has shown that coolant mixing and azimuthal heat conduction are limited if it is assumed that the azimuthal power peaking occurs in the center of a plate [6]. Using this conservative assumption, only the hot stripe, as shown in Figure 2, has been included in the PLTEMP model.

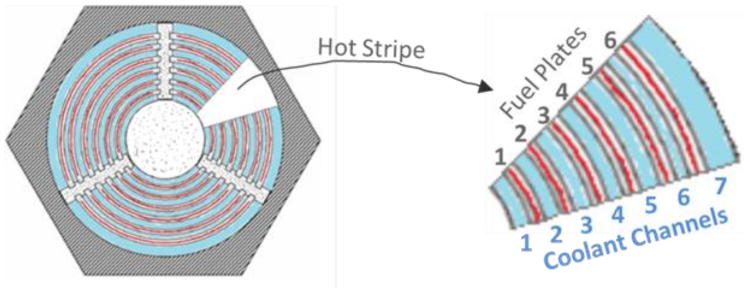


Figure 2. Cross section of the BR2 fuel element and the hot stripe modeled in PLTEMP.

The specific geometry and material properties for each fuel element in BR2 is difficult to define since the core configuration and shuffling scheme are variable. To simplify the modeling and analysis, a representative fuel element life cycle was defined. Briefly, it was assumed that a representative fuel element is shuffled to four locations in the core (four burnup groups) throughout its lifecycle with an average BOC burnup value of 0%, 16%, 32% and 46% for each location. These fuel assemblies are characteristic of a fresh fuel element (0% burnup), the highest heat flux fuel element within the reactor (16% burnup), the highest power fuel element within the reactor[1] (32% burnup) and the highest burnup element within the reactor (46% burnup). Within each burnup group there is a fuel element that operates at the highest heat flux. Although it is highly unlikely that a given fuel element will operate at the highest heat flux of each burnup group during its lifecycle, this was the case considered for these analyses. Thus, it is conservatively assumed that the fuel element used for this analysis was operated at the maximum heat flux during its lifecycle in each burnup group. The heat flux and burnup for an HEU fuel element are shown in Figure 3 (Although not shown, the results for an LEU fuel element are similar). Since only the power distribution at BOC is available, it was assumed that the heat flux and burnup values change linearly from beginning to end of cycle.

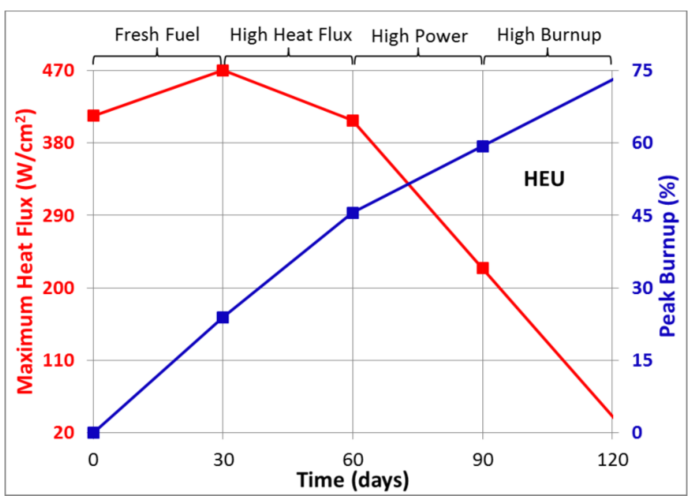
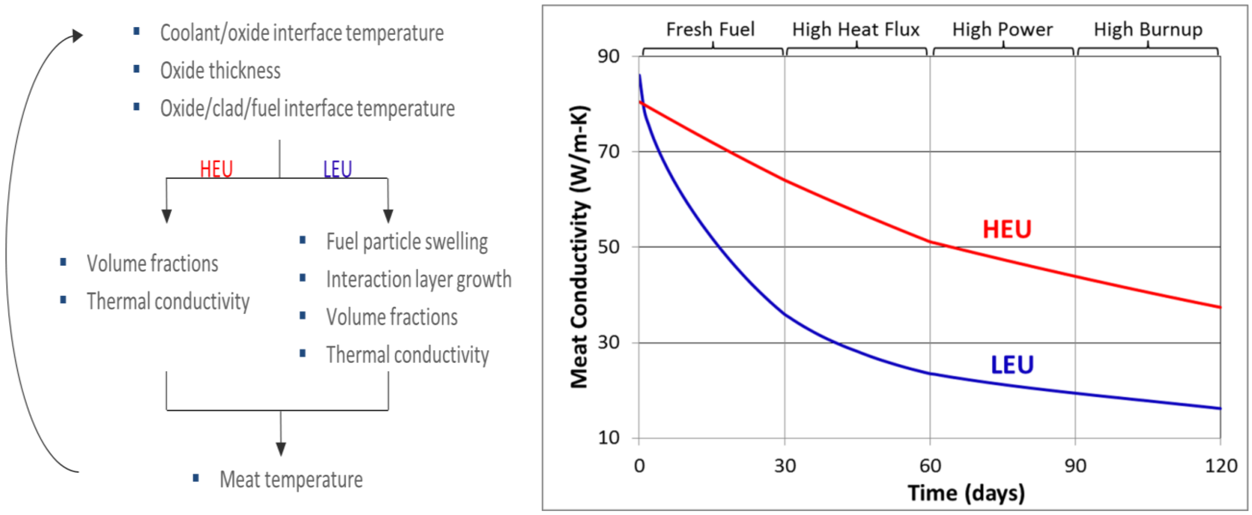


Figure 3. Peak burnup and maximum heat flux for HEU fuel element.

[1] The highest power fuel element occurs in the central channel designated H1.

These heat flux and burnup values were used to calculate the thermal resistance (dimensions and thermal conductivities) for the HEU and LEU fuel element models of each burnup group. Figure 4a outlines the calculation procedure described in detail in Ref. [7]. The HEU model contained factors such as porosity, fuel particle volume fraction and burnup. The LEU model was significantly more detailed and included factors such as swelling, porosity, interaction layer growth, matrix consumption, fuel temperature, heat flux and burnup. The models for HEU and LEU fuel element both included an equation to describe the oxide growth at the surface of the cladding. Figure 4b shows the meat conductivity determined from these calculations. The HEU and LEU meat conductivity is quite similar for fresh fuel but the LEU value drops significantly by the end of its life cycle.



(a) (b)

Figure 4. (a) Calculation procedure for HEU and LEU thermal resistance. (b) Meat thermal conductivity results obtained for HEU and LEU fuel elements.

To obtain the TH safety margins, the PLTEMP search capability was used to determine the limiting heat flux for HEU and LEU fuel at nominal BR2 conditions with various flow rates (1%, 20%, 100% and 161% of nominal). The peak fuel temperature was determined for the maximum heat flux limit of 470 W/cm^2 and the temporary heat flux limit of 600 W/cm^2. For all of these calculations, hot channel factors (HCFs) are used to account for manufacturing tolerances and uncertainties that impact the bulk coolant temperature rise, film temperature rise and heat flux (see Ref. [4]). It was assumed that the manufacturing tolerances that are known for HEU fuel are applicable to LEU fuel since the plate designs are almost identical. Table 1 shows details for the HCFs applicable to the high heat flux fuel element. Similar results were obtained for the fresh fuel, high power and high burnup fuel element with differences mainly due to the axial power distribution of the hot stripe.

Table 1. Hot channel factors for high heat flux fuel element.

Uncertainty	Type of tolerance	Effect on bulk dT (fraction)	Tolerance or uncertainty (fraction)		Heat flux, F_{flux}		Heat transfer coefficient, F_h	Channel temperature rise, F_{bulk}		Film temperature rise, F_{film}	
^{235}U homogeneity	Random		0.20		1.20					1.20	
^{235}U loading per plate		0.50	0.02		1.02			1.01		1.02	
Power density		0.50	0.19		1.19			1.10		1.19	
Plate spacing (HEU/LEU)		1.00	1.11	1.11				1.20	1.20	1.04	1.04
Flow distribution		1.00	1.10					1.10		1.10	
Random errors combined (HEU/LEU)					**1.28**			**1.25**	**1.25**	**1.30**	**1.30**
Heat transfer Coefficient	Systematic		1.15				1.15				
Hot stripe (HEU/LEU)			1.09	1.09	1.09	1.09		1.09	1.09	1.09	1.09
HCF, product of random errors and systematic errors (HEU/LEU)					**1.39**	**1.40**	**1.15**	**1.36**	**1.36**	**1.41**	**1.42**

3. Computational Results and Discussion

The TH criteria and fuel temperature results for the high heat flux fuel element, as presented in **Error! Reference source not found.**] and **Error! Reference source not found.**], have been updated for the current representative core. Figure 5 shows the calculated heat flux as a function of the percentage of nominal flow (10.4 m/s at 100% flow), for both HEU and LEU cores. The HEU and LEU cores have nearly identical margins for all TH criteria. The allowed operating regions are illustrated for both heat flux limits: 470 W/cm^2 (short dashes) and 600 W/cm^2 (long dashes). The FIR and CHFR are greater than 1.5 for both heat flux values for mass flow rates above ~70% nominal. For nominal operating conditions the margins are greater than 2. The most conservative criterion (ONBR) is met for both heat flux limits when the mass flow rate is above 74% of nominal for a heat flux of 470 W/cm^2. The ONBR limit for a heat flux of 600 W/cm^2 occurs very near 100% of nominal flow.

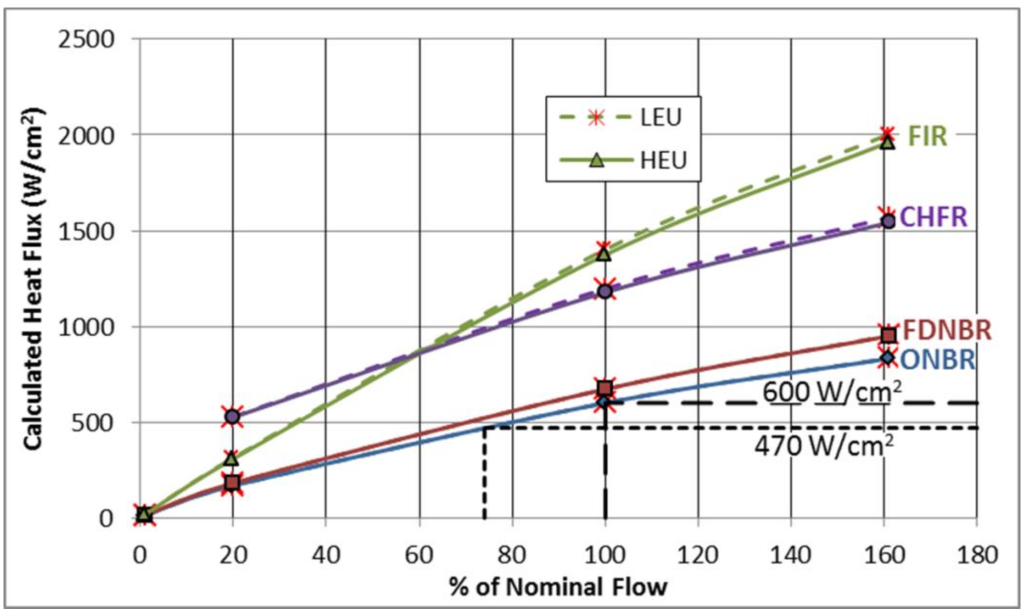


Figure 5 HEU core limiting conditions as a function of average coolant flow.

TH margins were also calculated for the limiting fuel element in each cycle group (fresh fuel, high power, and high burnup) for comparison with the limiting fuel element (high heat flux). Figure 6 shows these results for nominal flow conditions with the margins of each fuel element normalized to the high heat flux element. Again, both the HEU and LEU cores show similar results. The high heat flux fuel element is the limiting fuel element for all TH margins. However, CHFR and OFIR margins for the high power fuel element are comparable to the high heat flux fuel element.

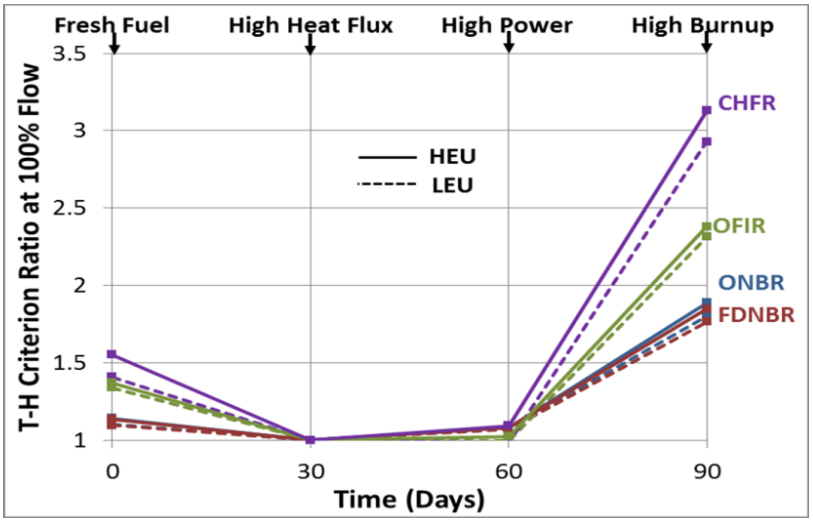


Figure 6. TH margins of for limiting fuel element of each cycle group normalized to the high heat flux fuel element at nominal flow conditions.

Figure 7 shows the maximum fuel temperature in plate 6 for each of the fuel assemblies at the maximum heat flux limits (470 W/cm^2 and 600 W/cm^2) for nominal flow conditions. The fuel temperatures for the four fuel element locations in the LEU core are relatively higher than the HEU core (by about 4% to 11%) due to the degradation in thermal conductivity associated with burnup. For HEU fuel, it can be seen that the highest fuel temperature occurs in the high heat flux fuel element. For LEU fuel, the fuel temperatures are nearly identical for the high heat flux and high power fuel elements. Despite the degradation in meat conductivity and increased thermal resistance due to oxide growth at the cladding surface, the high burnup fuel element has the lowest fuel temperature for both cores.

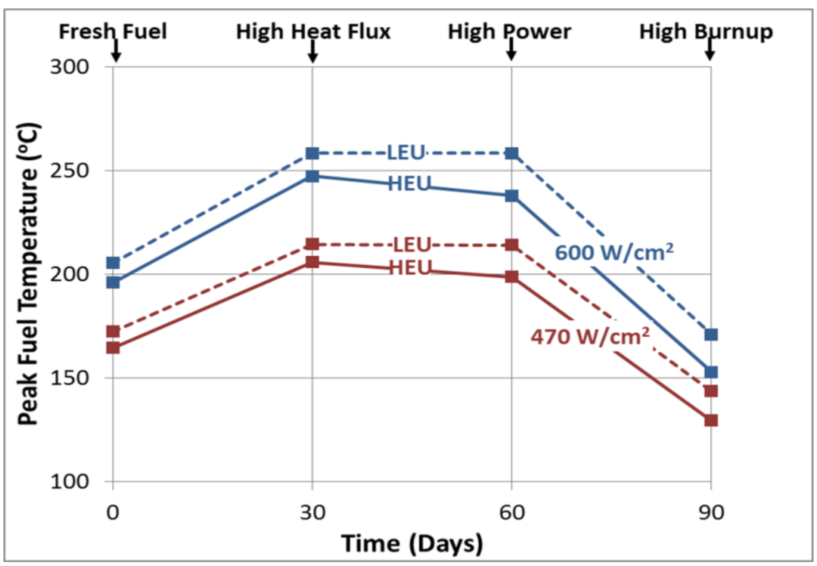


Figure 7. Maximum fuel temperature in limiting fuel element of each cycle group for HEU and

LEU cores.

Because of the significant uncertainty in predicting the thermal resistance of the fuel plate, a propagation of uncertainties was performed for the 470 W/cm^2 case to further investigate the peak fuel temperature, its uncertainty and the dominant contributing factors. Figure 8 and Figure 9 show the results for the HEU and LEU core using, where applicable, the following values and estimated uncertainties [7]:

coolant velocity = ± 9%,	interaction layer (IL) conductivity = 16 ± 5 W/m-K,
channel gap = ± 100 μm,	initial clad thickness = 381 ±20 μm,
Si weight fraction = 4% ± 0.2%,	Initial fuel particle radius = 30 ± 5 μm,
interaction layer growth rate = ± 50%,	swelling rate = ± 20%,
oxide penetration % = 40 ± 10,	coolant pH = 5.6 ± 0.3,
clad conductivity = 130 ± 5 W/m-K,	matrix conductivity = 230 ± 10 W/m-K,
meat conductivity = ± 25%,	oxide conductivity = 2.25 ± 0.45 W/m-K.

The magnitude and evolution of the fuel temperatures and uncertainties are similar for the HEU and LEU cores. However, the LEU fuel temperature uncertainty appears larger than the HEU core since it was calculated with a more detailed model containing additional uncertainty factors. The coolant velocity was found to be the largest contributor for fresh fuel at beginning of cycle, although the magnitude of the fuel temperature uncertainty is relatively small at this time. The relevance of the coolant velocity uncertainty decreases continuously for fresh fuel as the uncertainty contribution of the pH steadily increases. For the remaining fuel assemblies, the pH is the dominate uncertainty contributor. The pH not only impacts the thermal resistance of the cladding oxide, but also other parameters that are dependent on the fuel temperature; such as the interaction layer growth rate and conductivity. Ultimately, the uncertainty in fuel temperature shows that despite the limited knowledge on parameters impacting the heat transfer from the fuel, the high heat flux or high power fuel element contains the maximum fuel temperature. Even taking into account the uncertainties in determining the thermal resistance of the fuel plate, the LEU fuel temperature remains below the recommended blister threshold temperature of 450^{o}C [8] by ~200^{o}C for a heat flux of 470 W/cm^2.

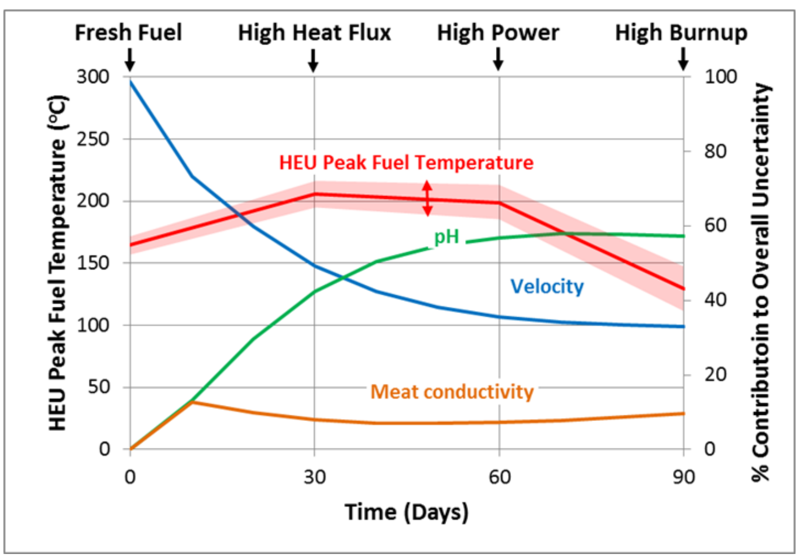


Figure 8. HEU fuel temperature with uncertainty and contributing factors for 470 W/cm^2.

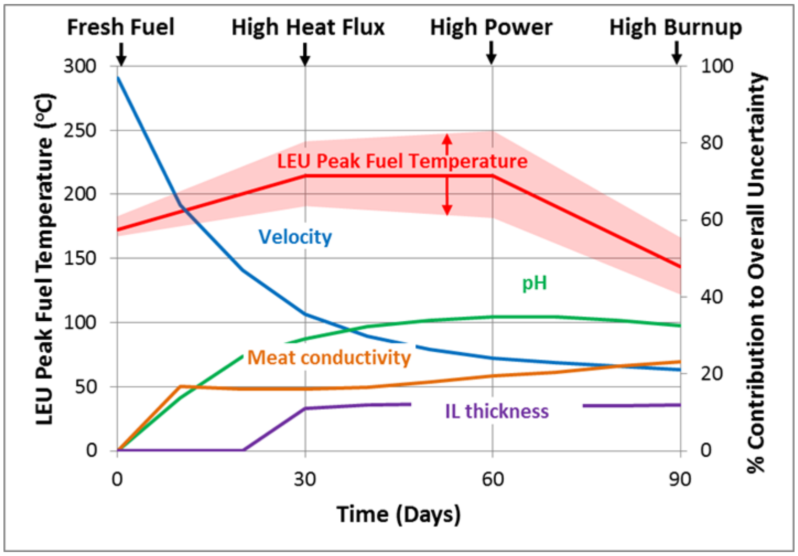


Figure 9. LEU fuel temperature with uncertainty and contributing factors for 470 W/cm^2.

4. Summary and Conclusions

The objective of this work was to evaluate the steady-state thermal-hydraulic safety margins and fuel temperatures associated with converting the BR2 reactor core with the proposed LEU fuel element. The analysis compared results for a fuel element at the limiting location for each stage of its lifecycle; characterized by fresh fuel (0% burnup), high heat flux (16% burnup), high power (32% burnup), and high burnup (46% burnup).

For the limiting fuel element, the HEU and LEU fuel elements have nearly identical margins for all TH criteria (ONBR, FDNBR, FIR and CHF). For nominal operating conditions, the margins to CHFR and FIR are greater than 2 for the temporary heat flux limit of 600 W/cm^2. The most conservative criterion (ONBR) is met for both heat flux limits when the mass flow rate is above 74% of nominal for a heat flux of 470 W/cm^2. The ONBR limit for a heat flux of 600 W/cm^2 occurs very near 100% of nominal flow.

Further analyses of the fresh fuel, high power and high burnup fuel elements shows that the high heat flux fuel element was the limiting element with respect to ONB, FDNB, OFI and CHF. However, in some instances the TH margins of the high power fuel element was similar to the high heat flux fuel element at nominal flow (i.e. CHF and OFI).

The fuel temperatures for the four fuel element locations in the LEU core are relatively higher than the HEU core (by about 4% to 11%) due to the degradation in thermal conductivity associated with burnup. For both cores, it was found that the highest temperature occurs in both the high heat flux and high power fuel elements, as both produced similar values. A propagation of uncertainties was performed to better characterize the uncertainty in parameters impacting the fuel temperature. From this it was determined that, despite limited knowledge of thermal conductivities and surface oxide thickness, both the high heat flux and high power fuel element can obtain similar fuel temperatures and that they are significantly greater than the fresh fuel and high burnup fuel elements. It was shown that the LEU fuel temperature, including uncertainties, was below the recommended blister threshold temperature of 450^{o}C by ~200^{o}C for the maximum heat flux limit of 470 W/cm^2.

Finally, it should be stated that this work provides preliminary conclusions that will need to be updated once the LEU fuel element has been finalized and measurements of the blister threshold temperature, fuel thermal conductivity, etc. have been made available.

5. Acknowledgment

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6. References

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