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EVALUATION OF THE THERMAL-HYDRAULICS OPERATING LIMITS OF THE HEU-LEU TRANSITION CORES FOR THE MITR

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ABSTRACT

The MIT Research Reactor (MITR) is in the process of conducting a design study to convert from High Enrichment Uranium (HEU) fuel to Low Enrichment Uranium (LEU) fuel. The currently selected LEU fuel design contains 18 plates per element, compared to the existing HEU design of 15 plates per element. A transitional conversion strategy, which consists of gradual replacement of HEU elements with fresh LEU elements over several fuel cycles, is proposed. This study analyzed the thermal hydraulic safety margins in order to determine the operating power limits of the MITR for each mixed core configuration. The analysis was performed using PLTEMP/ANL code version 3.6a. The minimum onset of nucleate boiling (ONB) margins of the hottest fuel plates were evaluated in nine different core configurations, the HEU core, the LEU core and seven mixed cores that consist of both HEU and LEU elements. The maximum radial power peaking factors were assumed constant at 2.0 for HEU and 1.76 for LEU in all the analyzed core configurations. The calculated results indicate that the LEU fuel elements yielded higher ONB margins than HEU elements in all mixed core configurations. In addition to full coolant channels, side channels next to the support plates that form half coolant channels were analyzed and found to be more limiting due to higher flow resistance. The maximum operating powers during the HEU to LEU transition were determined by maintaining the minimum ONB margin corresponding to that of the homogeneous HEU core at 6 MW. The recommended steady-state power is 5.8 MW for all transitional cores if the maximum radial peaking is adjacent to a full coolant channel and 4.9 MW if the maximum radial peaking is adjacent to a side coolant channel.

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1. Introduction

In 1978, the United States Department of Energy (DOE) began the Reduced Enrichment for Research and Test Reactors (RERTR) Program to support reactor conversion from using High Enrichment Uranium (HEU) to Low Enrichment Uranium (LEU). The RERTR Program was initiated for the purpose of reducing the use of weapons-grade uranium. LEU is defined as fuel containing less than 20 wt% of U-235. Currently, 11 US reactors have fully converted to Low Enrichment Uranium (LEU) fuel and 8 US reactors are scheduled to be converted [1].

For the MITR-II, conversion from HEU to LEU has raised concerns of neutronic performance, specifically whether LEU fuel would produce the same levels of neutron flux for both in-core and ex-core experiments. Fortunately, studies at MIT have shown that by using high-density uranium-molybdenum (U-Moly) fuel (U density of 17.5 g/ cm^3), a switch to LEU is a viable option for the MITR-II [2]. From the study by Newton [2], using LEU would even have the added benefit of potentially increasing fuel cycle length to twice that of the current HEU fuel [2]. In addition, a thermal-hydraulic study by Ko using the MULti-CHannel-II (MULCH-II) code has shown that the LEU can operate at power levels higher than 6 MW and can thus produce higher neutron fluxes by increasing the number of fuel plates per element [3].

The objective of this study is to analyze the thermal-hydraulic operating limits of the MITR-II during each step of the transition. Between homogeneous HEU core and homogeneous LEU core, there will be a series of transitional, or MIX, cores containing different numbers of HEU and LEU fuel elements. The factors considered in this study are the flow disparity between the different types of fuel elements, the peak cladding temperature of the hottest fuel plates, and the onset of nucleate boiling (ONB) margins at those hot spots in each of the different MIX-Cores. ONB corresponds to the Limiting Safety Systems Settings (LSSS) of the MITR and therefore it is selected as the maximum allowable steady-state clad temperatures in this analysis. The goal of this project is to determine the safe operating power limits for the MIX cores during the transition from HEU to LEU core. The operating limits are obtained by scaling the ONB margins of the MIX cores to that of the homogeneous HEU core with steady-state power of 6 MW. Finally the maximum achievable steady-state powers were determined by evaluating the minimum ONB margins in each transitional cores and comparing them with the reference ONB margins established for the HEU core. If the ONB margins of the transitional cores are smaller, then the reactor powers are scaled down in order to maintain the same safety margins. These thermal-hydraulic calculations were performed using PLTEMP/ANL version 3.6a.

2 Proposed LEU Fuel Design and HEU to LEU Core Conversion Strategy

2.1 Current HEU Fuel

The MITR-II is unique in that it is the only reactor that utilizes MTR-type fuel elements with longitudinal fins to enhance heat transfer. The HEU element currently used in the MITR-II is rhombic shape and contains 15 fuel plates per element. On the ends of the 15 fuel plates are 2 Al-6061 side plates for support. Thus, each element consists of 14 full coolant channels (between fuel plates) and 2 side channels [1].

Figure 1 shows a top view of an inner coolant channel formed between two fuel plates [3]. The water gap and plate-to-plate dimensions are 2.24 mm and 4.03 mm, respectively. The water gap measures the distance from mid-fin to mid-fin. The plate to plate distance measures the distance from mid fuel plate to mid fuel plate. The coolant flow direction is perpendicular to the coolant flow area [3].

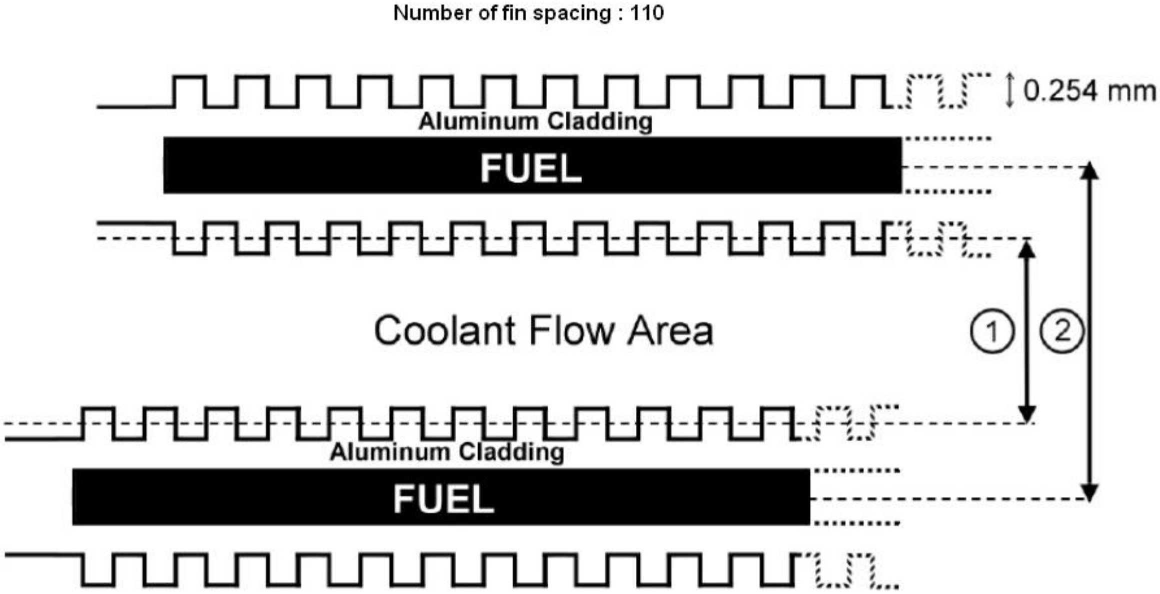


Figure Error! No text of specified style in document.**:** Cross-sectional view of an inner coolant channel. [3]

2.2 Proposed LEU Design

The design of the LEU fuel elements was studied in Ko's recent work [3]. The most important design constraint is that the LEU fuel elements must have identical outer geometry as that of the HEU fuel elements in order to maintain the same core housing configuration. In addition, the thermal-hydraulic impact of the LEU fuel must not be excessively different from that of the HEU to minimize the flow disparity during HEU-LEU core transition. Utilizing these constraints, Ko considered several geometries for the LEU fuel plates by varying the number of plates per element and reducing the fuel meat and cladding thicknesses. Ko analyzed the pressure drop across LEU elements with various numbers of plates and compared the results to the pressure drop across HEU elements. The intention of this analysis was to design an LEU fuel element that would have the most number of fuel plates per element and has a friction pressure drop that does not exceed that of an HEU element. The results are shown in Table 1 [3].

The pressure drops listed in Table 1 is based on a 6 MW core with the core flow rate of 1800 gpm, as according to the MITR-II Reactor Systems Manual [4]. Additionally, all cores were assumed to consist of 22 fuel elements. The calculations were performed using RELAP5-3D [3].

Table 1: Friction pressure drop for various LEU fuel element designs [3]

	Plates Per Element	Pressure Drop (Pa)
LEU# b1	15	26893
LEU# b2	16	30673
LEU# b3	17	35107
LEU# b4	18	39934
HEU	15	41403

From Table 1, it is observed that the 18 plate LEU fuel element gives a pressure drop that is closest to the existing HEU element and, as a result, leads to a slightly lower mechanical loading on the core tank. Thus, the 18-plate LEU fuel design is recommended for the MITR core conversion [3]. Table 2 shows a comparison between HEU and LEU fuel dimensions.

Table 2: HEU and LEU fuel element and plate dimensions [3]

	HEU	**LEU**
Fuel Type	U-Alx	Monolithic U-7Mo
Fuel Length	0.5842 m	0.5842 m
Fuel Plates per Assembly	15	18
Fuel meat Thickness	0.76 mm	0.55 mm
Al-Clad thickness*	0.38 mm	0.25 mm

*From fuel meat interface to fin base

2.3 Conversion Strategy

The current plan for the transition to LEU core at the MITR is to gradually replace HEU elements with LEU elements in the reactor core, which will allow reactor personnel to monitor the performance of the LEU fuel without necessitating a long-term reactor shutdown. Such an extended shutdown would adversely affect the MITR's utilization program. The core will begin the transition with a 24 element HEU core and; over time, the HEU fuel elements will be replaced using fresh LEU elements, ending eventually with a 24 element LEU core. Currently, it is planned to add three LEU fuel elements during each transition fuel cycle and the conversion process should be completed within 2 years. In the event that the LEU element failed during the transition, the LEU elements can be switched back to HEU. This incremental conversion strategy allows the reactor staff to handle a small quantity of LEU. By adding a smaller quantity of fresh fuel, the excess reactivity in the beginning of a fuel cycle is reduced [5].

The goal during the LEU transition is to maintain steady-state reactor power at 6 MW, the requested full power in the current licensing application [6]. The new elements will be added first into the B-rings of the reactor core where the radial power peaking is lower. The C-ring is adjacent to the outer plate, which is surrounded by water. This additional moderation causes high power peaking in the C-ring, which should be avoided when adding new, unburned fuel [5].

3. Thermal-Hydraulic Modeling

3.1 PLTEMP Descriptions

The calculations for this project were mostly conducted using PLTEMP/ANL v. 3.6a. PLTEMP/ANL is a FORTRAN-based computer code developed and maintained at Argonne National Laboratory. The program is designed to obtain steady-state flow and temperature solutions for thermal-hydraulic performance in the sub-cooled regime for a single plate and channel configuration, a single element of heated plates and channels, or an entire reactor core of fuel elements. The code is capable of analyzing elements with up to 30 fuel plates and cores of up to 30 fuel elements of up to five different types of element geometries and fuel types. The elements analyzed can be either slab or cylindrical in geometry. For each element in a core, PLTEMP/ANL allows the option of incorporating radial and axial peaking factors to ensure a more accurate analysis [4, 7].

3.2 Correlations Utilized for Finned Coolant Channel

The correlations adopted for finned channel analysis are the Carnavos correlations and the Wong correlation. The Carnavos correlations were empirically developed by T.C. Carnavos in 1979 and are the most commonly used correlation for finned channel analysis. The Carnavos correlations were within ± 10% accuracy for both the friction factor and the heat transfer coefficient. In addition, the correlation fits the empirical data to the ± 10% accuracy for helix angles between 0-30 degrees, Reynolds number of between 10,000 and 100,000, and Prandtl numbers between 0.7 and 30 [8]. It is also applicable when the fin height to hydraulic ratio is greater than 0.02 [9]. The MITR fuel channels are within all aforementioned limits for the Carnavos correlations. The Carnavos correlations are the ones that are built into PLTEMP/ANL for finned channel thermal-hydraulic analysis. The Carnavos correlations for friction factor and heat Nusselt number are shown below.

Friction Factor:

$$f_a = \frac{0.184}{Re_a^{0.2}} \left(\frac{A_{fn}}{A_{fa}} \right)^{0.5} (cos\alpha)^{0.75} \tag{1}$$

Nusselt number:

$$Nu = 0.023\, Re_a^{0.8}\, Pr^{0.4} \left(\frac{A_{fa}}{A_{fc}} \right)^{0.1} \left(\frac{P_n}{P_a} \right)^{0.5} sec^3 \alpha \tag{2}$$

Where Re_a is the actual Reynolds number, Pr is the Prandtl number, A_{fa} is the actual flow area (m^2), A_{fc} is the flow area of the core flow region (m^2), P_n is the nominal wetted perimeter (m), P_a is the actual wetted perimeter (m), α is the helix angle, and A_{fn} is the nominal flow area (m^2).

The Wong correlation was developed empirically by Susanna Wong in 2008 specifically for MITR coolant channel geometry. Wong devised an experimental system to measure the pressure drop through the MITR-II coolant channels. In the experiment, Wong analyzed the flow and pressure drop through aluminum channels, whose dimensions are identical to those of the MITR fuel [1]. Wong's correlation for friction factor is shown below.

$$f = 0.575\,\mathrm{Re}^{-0.25} \tag{3}$$

When using the Wong correlation for friction factor, the Nusselt number was calculated via the Dittus-Boelter correlation assuming geometries of a flat plate without fin structures. Thus, enlarged heat transfer area by 1.9 was used to incorporate the actual fin geometry [11]. The correlations are shown below.

Dittus-Boelter [10]

$$Nu = \frac{hD}{k} = 0.023\, Re^{0.8}\, Pr^{0.4} \tag{4}$$

Clad-Coolant heat transfer

$$Q = 1.9hWL(T_{clad} - T_{bulk}) \tag{5}$$

Where D is the hydraulic diameter of a smooth channel and W and L are the length and width of the channel.

The results from the two sets of correlations were compared. However, it should be noted that the Wong correlations were developed specifically for the MITR fuel plates, and therefore are expected to give more accurate results. In addition, the Wong correlation was formulated for both laminar and turbulent flows, and therefore offers a wider range of applicability than the Carnavos correlations [1].

3.3 Core Configurations

With the two sets of correlations, 9 cores were modeled using PLTEMP/ANL: a homogeneous 24-element HEU core, a homogeneous 24-element LEU core, and 7 MIX-Core configurations. The different MIX-Cores varied in number of HEU and LEU elements, the total number of elements remaining constant at 24 [5]. Table 3 shows a list of the core configurations evaluated.

Table Error! No text of specified style in document.**:** MIX-Core configurations

Core	HEU Elements	LEU Elements
HEU	24	0
MIX-1	21	3
MIX-2	18	6
MIX-3	15	9
MIX-4	12	12
MIX-5	9	15
MIX-6	6	18
MIX-7	3	21
LEU	0	24

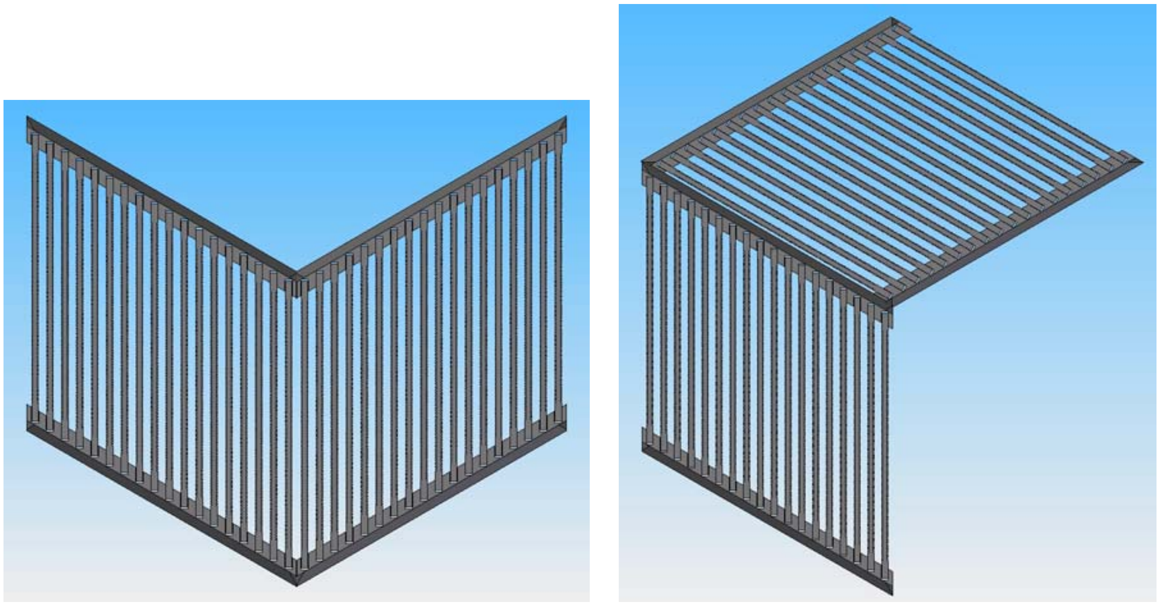
For all cores evaluated, the total volumetric flow rate through the core was held constant at 1800 gpm, which was specified by the MITR Limiting Safety System Setting for operation at 6 MW [4]. The power for the examined 9 cores was all set to 6 MW. The inlet conditions for all cores were 45 ºC and 0.2 MPa [4].

3.4 Peaking Factors

For determining the maximum steady operating power of the MITR-II during the HEU to LEU fuel transition, the limiting temperature conditions at the hottest areas in the MIX-Cores were calculated. In order to study these hot spots, the power of the hottest plates in each transitional core was evaluated with a series of peaking factors. The two types of peaking factors such as the Radial Peaking Factor (F_r) and the Axial Peaking Factor (F_a) were used in the current study. The Radial Peaking Factors represent the relative power of a particular plate in the core to the average power of the plates in a given fuel element. The Axial Peaking Factors characterize the relative heat flux of a particular axial location in the core to the average axial heat flux in that fuel plate. The fuel plates with the highest radial and axial peaking factors will contain the hottest cladding temperatures and also the lowest ONB margins. Additionally, the channels adjacent to these plates will have the hottest bulk coolant temperatures. Note that these two conditions rarely occur in the same coolant channel and thus this condition should be considered a worst-case scenario. For the HEU elements in all cores, the maximum radial peaking factor was set to 2.0, which was the peaking factor used for the 6 MW 24-element HEU license application [13 xx]. For the LEU elements in all cores, the maximum radial peaking factor was set to 1.76, which was the peaking factor set by Ko during his design of the LEU fuel element [3]. Finally, the maximum axial peaking factor was determined using MCNP/ORIGIN linkage code (MCODE) [12] and set to 1.68 for all cores evaluated.

3.5 Channel Analysis

Based on the element type, element placement, and element orientation in the core, the MIX-Cores contain a number of different combinations of flow channel geometries. Within the same type of element, there are two different types of channels: full channels (between two fuel plates) and side channels (adjacent to the side fuel plates). Figure 2 gives a schematic of the different coolant channel layouts. Depending on the orientation of the element, a side channel may be adjacent to another side channel, forming a combined coolant channel that is equivalent or larger than a full coolant channel. When a side channel is adjacent to a support plate, it forms a half-coolant channel with the gap width approximately half that of a full channel. These different flow geometries must be analyzed separately to determine where the hottest spot in the core is.



(a) (b)

Figure 2: Schematics of possible side coolant channel configurations (a) Two side channels adjacent to each other and form a full coolant channel (b) A side channel adjacent to support plate and forms a half-coolant channel

4. Modeling Results and Analysis

4.1 Channel ONB Margin

Using the two correlations and the axial and radial peaking factors, the ONB margins (ΔT_{ONB}) of the hottest plates in all 9 cores were determined. The results are shown in Table 4. From Table 4, a consistent trend is observed as the ONB margin decreases slightly for all channels as more HEU elements are switched for LEU. This is because the friction pressure drop across the core decreases with increased number of LEU elements, which have greater flow area per element than HEU elements. This decreased friction pressure drop causes slower flow velocity, since the total flow rate is held constant at 1800 gpm. Reduced flow velocity causes a decrease in clad-coolant heat transfer, resulting in smaller ONB margins.

Table 4 also shows the ONB margins of the different channel types (except for the hybrid combined channel) in the HEU and LEU elements of the 9 core configurations. From Table 4, it is apparent that for all cores, the side channels will always be more limiting than the full channels. This is due to the reduced flow area of a side channel, which impedes the clad-coolant heat transfer.

Between the HEU and LEU elements, the HEU elements appear to be much more limiting than LEU mainly because the HEU hot plate powers are greater than those of LEU hot plates.

The conclusion that can be drawn from Table 4 is that the most limiting case during the HEU-LEU transition will be MIX-Core 7, which is the core with the smallest pressure drop and still contains HEU elements.

The results of the hybrid combined side channel are not shown in Table 4 because PLTEMP/ANL is currently unable to model inter-element heat transfer within a core, and thus cannot be used for the hybrid combined side channel analysis [7]. However, an estimated calculation was performed on MIX-Core 7, which showed that the hybrid combined side channel is less limiting than the side channels.

4.2 Operating Power Limits

Using the ONB Margin from the 6 MW 24-element HEU core as a reference, the powers of all the other cores during the transition were scaled down so that their minimum ONB Margins were the same as the all HEU core to determine the maximum allowable operating powers. During this analysis, the maximum radial peaking factors were kept constant at 2.0 for HEU elements and 1.76 for LEU elements and the total flow rate through the cores was 1800 gpm. The results are shown in Figures 3 and 4.

In addition, the maximum allowable operating power for the cores during the transition were determined if the maximum radial peaking factors varied from 2.0 for HEU and 1.76 for LEU. These calculations were performed using MIX-Core 7, which was shown to be the most limiting of the transitional cores. Again, the operating powers were rescaled using the results from the 6 MW 24-element

HEU core and the power and flow rate were held constant at 6 MW and 1800 gpm. The results are shown in Figures 5 and 6.

Table 4: Channel Analysis results. All temperatures in ºC.

CARNAVOS		**HEU**							**LEU**						
			Full Channels		**Combined Side**		**Side Channel**			**Full**		**Combined Side**		**Side**	
RUN	**ΔP_f (kPa)**	**$\dot{q}_{\max}$ (kW)**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**	**$\dot{q}_{\max}$ (kW)**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**
HEU	14.278	33.35	90.46	34.97	89.05	36.46	96.35	29.61							
MIX-1	14.190	33.34	90.62	34.82	89.19	36.33	96.51	29.46	24.45	80.83	43.76	80.83	43.76	85.13	39.95
MIX-2	14.104	33.32	90.72	34.72	89.34	36.19	96.64	29.34	24.44	80.94	43.67	80.94	43.67	85.17	39.91
MIX-3	14.019	33.33	90.85	34.60	89.26	36.25	96.52	29.45	24.45	81.05	43.55	81.13	43.48	85.17	39.91
MIX-4	13.935	33.32	90.95	34.50	89.54	35.99	96.92	29.06	24.44	81.13	43.48	81.13	43.48	85.44	39.65
MIX-5	13.851	33.34	91.09	34.37	89.63	35.90	97.02	28.96	24.44	81.23	43.38	81.23	43.38	85.52	39.57
MIX-6	13.768	33.34	91.20	34.26	89.48	36.03	97.07	28.91	24.44	81.34	43.28	81.34	43.28	85.59	39.50
MIX-7	13.686	33.33	91.29	34.17	89.82	35.71	97.26	28.72	24.44	81.42	43.20	81.42	43.20	85.68	39.42
LEU	13.605								24.46	81.54	43.09	81.54	43.09	85.75	39.35

WONG		**HEU**							**LEU**						
			Full		**Combined Side**		**Side**			**Full**		**Combined**		**Side**	
RUN	**ΔP_f(kPa)**	**$\dot{q}_{\max}$ (kW)**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**	**$\dot{q}_{\max}$ (kW)**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**	**T_{clad}**	**ΔT_{ONB}**
HEU	13.591	33.35	82.73	42.60	81.44	43.99	88.11	36.98							
MIX-1	13.512	33.32	82.86	42.47	81.55	43.88	88.23	36.86	24.45	74.98	49.54	74.98	49.54	81.08	42.38
MIX-2	13.433	33.34	82.94	42.39	81.67	43.76	88.35	36.75	24.44	75.07	49.45	75.07	49.45	81.11	42.35
MIX-3	13.354	33.33	83.05	42.29	81.70	43.73	88.35	36.74	24.45	75.17	49.36	75.17	49.36	81.21	42.26
MIX-4	13.277	33.32	83.13	42.21	81.84	43.60	88.58	36.52	24.44	75.23	49.30	75.23	49.30	81.36	42.11
MIX-5	13.200	33.33	83.24	42.10	81.91	43.53	88.67	36.44	24.44	75.32	49.21	75.32	49.21	81.44	42.04
MIX-6	13.124	33.29	83.28	42.06	81.79	43.63	88.72	36.39	24.41	75.36	49.17	75.36	49.17	81.50	41.97
MIX-7	13.591	33.33	83.40	41.94	82.06	43.38	88.88	36.24	24.44	75.47	49.07	75.47	49.07	81.58	41.90
LEU	12.973								24.44	75.58	48.97	75.58	48.97	81.65	41.83

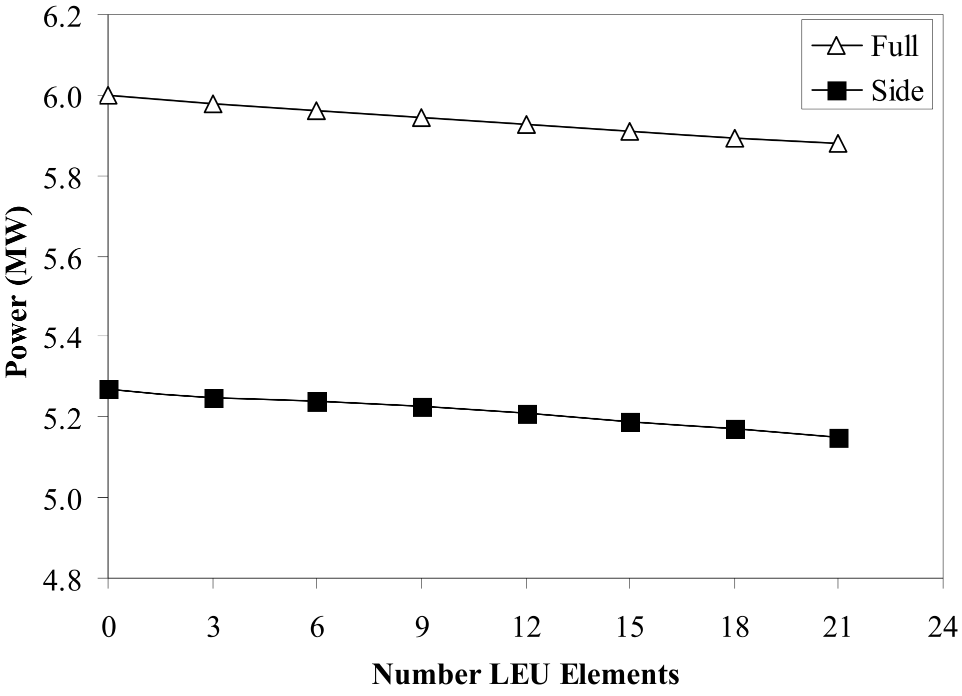


Figure 3: Fixed peaking factor power limits using Carnavos correlations

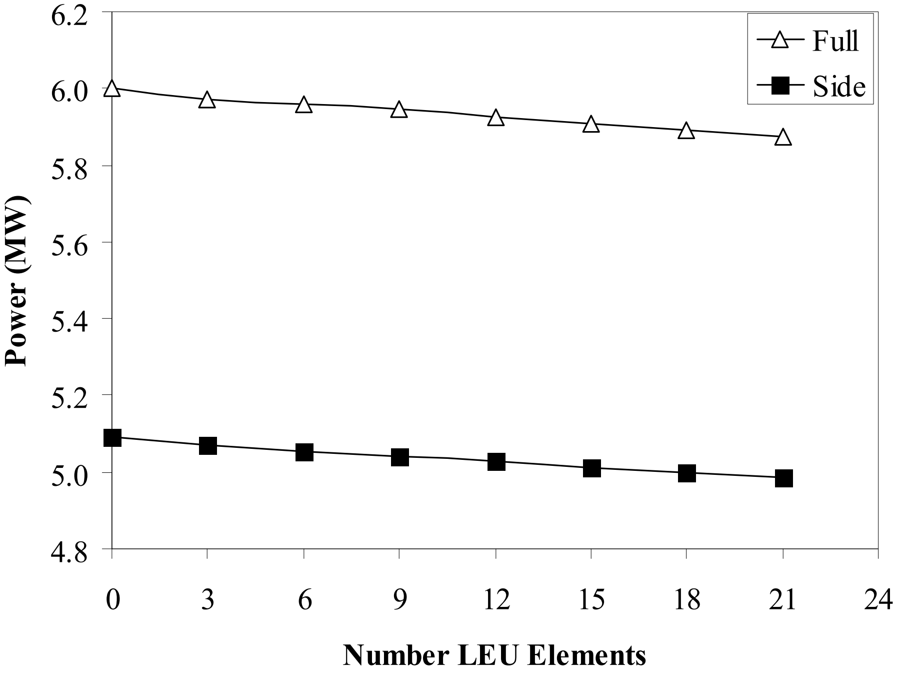


Figure 4: Fixed peaking factor power limit using Wong correlations

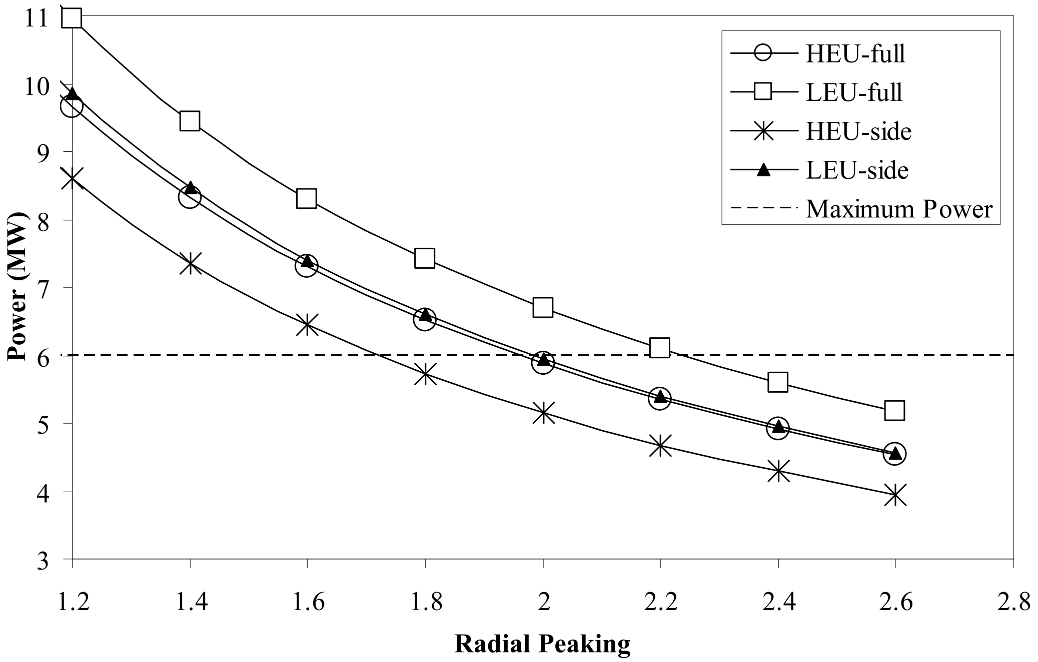


Figure Error! No text of specified style in document.**:** Variable peaking factor power limits from Carnavos correlation in MIX-Core 7.

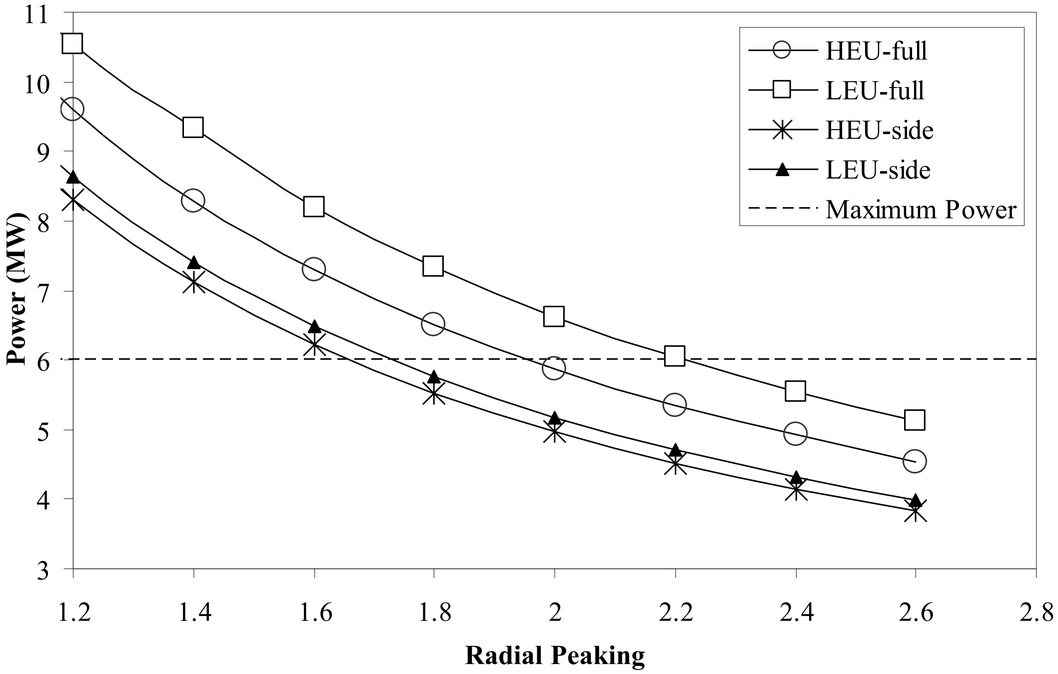


Figure 6: Variable peaking factor power limits from Wong correlation in MIX-Core 7

5. Conclusions

From the systematic thermal-hydraulic analysis using the PLTEMP/ANL, maximum achievable operating powers were obtained for 9 different core configurations during the LEU core transition process. The findings can be summarized as follows:

(i) MIX-core 7, which consists of 3 HEU and 21 LEU elements, has shown to be the most limiting transitional core with the smallest ONB margins. Therefore, the results drawn from this core are applied to determine the maximum achievable steady-state operation power.

(ii) The side channel adjacent to a support plate that forms a half coolant channel is more limiting than the full or combined side channels for a given core configuration. This is attributed to the higher flow resistance and lower coolant velocity.

(iii) Given the maximum radial peaking factors Fr=2.0 for HEU and Fr=1.76 for LEU, the maximum allowable steady-state operating power will be between 6 and 5.8 MW with the HEU hot plates adjacent to a full channel and between 5.3 and 4.8 MW with the HEU hot plates adjacent to a side channel.

(iv) In order to operate the reactor at 6 MW, the radial power peaking factor must be below 2.0 for the HEU hot plates adjacent to a full channel and below 1.6 for the HEU hot plates adjacent to a side channel.

The main conclusion that can be drawn from these results is that a mixed core conversion strategy is feasible, provided that the radial power peaking factors can be maintained at less than 2.0 for HEU and 1.76 for LEU, and that care should be taken in the fuel management program to avoid the placement of the fuel element with maximum radial peaking next to a support plate. The MITR can operate at steady-state power of 6 MW for all the mixed core configurations analyzed. Operating at a lower steady-state power is also feasible in the event that a higher radial power peaking exists in the transitional cores.

Acknowledgement

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