ANL/RERTR/TM-12-38
Revision 1

Conceptual Design Parameters for MURR LEU U-Mo Fuel Conversion Design Demonstration Experiment

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Nuclear Engineering Division

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by
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ABSTRACT

The design parameters for the conceptual design of a fuel assembly containing U-10Mo fuel foils with low-enriched uranium (LEU) for the University of Missouri Research Reactor (MURR) are described. The Design Demonstration Experiment (MURR-DDE) will use a prototypic MURR-LEU element manufactured according to the parameters specified here. Also provided are calculated performance parameters for the LEU element in the MURR, and a set of goals for the MURR-DDE related to those parameters.

The conversion objectives are to develop a fuel element design that will ensure safe reactor operations, as well as maintaining existing performance. The element was designed by staff members of the Global Threat Reduction Initiative (GTRI) Reactor Conversion Program at the Argonne National Laboratory (ANL) and the MURR Facility. A set of manufacturing assumptions were provided by the Fuel Development (FD) and Fuel Fabrication Capability (FFC) pillars of the GTRI Reduced Enrichment for Research and Test Reactors (RERTR) program to reliably manufacture the fuel plates.

The proposed LEU fuel element has an overall design and exterior dimensions that are similar to those of the current highly-enriched uranium (HEU) fuel elements. There are 23 fuel plates in the LEU design. The overall thickness of each plate is 44 mil, except for the exterior plate that is furthest from the center flux trap (plate 23), which is 49 mil thick. The proposed LEU fuel plates have U-10Mo monolithic fuel foils with a ^{235}U enrichment of 19.75% varying from 9 mil to 20 mil thick, and clad with Al-6061 aluminum. A thin layer of zirconium exists between the fuel foils and the aluminum as a diffusion barrier. The thinnest nominal combined zirconium and aluminum clad thickness on each side of the fuel plates is 12 mil. The LEU U-10Mo monolithic fuel is not yet qualified as driver fuel in research reactors, but is under intense development under the auspices of the GTRI FD and FFC programs.

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1.0 INTRODUCTION

The University of Missouri is working in conjunction with the Global Threat Reduction Initiative (GTRI) Reactor Conversion Program at Argonne National Laboratory (ANL) to perform fuel element design and fuel cycle performance [1], and steady state thermal-hydraulic safety analyses [2] to support conversion of the University of Missouri Research Reactor (MURR) from highly-enriched uranium (HEU) to low-enriched uranium (LEU) fuel. The goals of the conversion are to ensure acceptable shutdown and safety margins, as well as maintain the existing experimental performance of the facility.

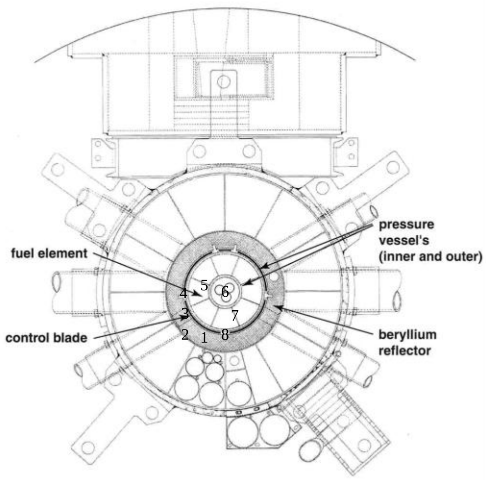
A prototypic LEU element for MURR will be irradiated as part of the Design Demonstration Experiment (MURR-DDE). The irradiation will take place in the Belgian Reactor 2 (BR2). The dimensions of the element were developed to meet the conversion goals and provide the best fuel cycle performance, while adhering to a set of manufacturing assumptions provided by the Fuel Development (FD) and Fuel Fabrication Capability (FFC) pillars of the GTRI Reduced Enrichment for Research and Test Reactors (RERTR) program. Reference 1 describes the fuel design process.

The MURR-DDE is being conducted to observe how the prototypic LEU element behaves under conditions comparable to what will be experienced in MURR. The element will be placed in an irradiation vehicle that will support the element in an experimental location in BR2. The irradiation vehicle for the MURR-DDE should be designed so that the element operates at conditions comparable to those that are expected for typical operations in the MURR. This includes the nominal plate-by-plate heat flux profiles, temperatures, flow conditions, and discharge fission density. The data provided in this report are intended to assist in the design of the irradiation vehicle, as well as plan the experimental campaign.

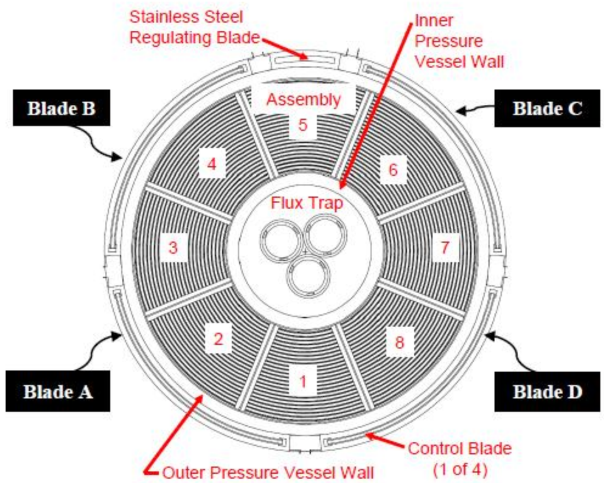
In addition to the MURR-DDE, other experiments are also being conducted, or will be conducted. The maximum allowable fission density of the U-10Mo fuel will be experimentally determined based on irradiation testing performed by FD. It must be confirmed by experiment that fission-induced distortion of the fuel plate does not occur. Other material properties, such as blister temperatures, will also be determined experimentally for both the unirradiated and irradiated fuel plates. The fundamental characteristics of the monolithic U-10Mo fuel will be addressed in a fuel qualification report issued prior to submission of the MURR conversion SAR.

2.0 CORE AND FUEL ELEMENT GEOMETRY

The MURR core has a fixed geometry consisting of eight fuel elements, each having identical physical dimensions. The fuel elements are placed vertically around an annulus between two cylindrical aluminum reactor pressure vessels. Cross-sectional views of the MURR reactor core and a close-up view of the core are shown in Figure 2.1.



MURR Reactor



MURR Core

Figure 2.1. Cross-Sectional Views of MURR.

The current HEU fuel element used in MURR has 24 curved plates that form a 45-degree arc. A cross-sectional drawing of the fuel plates in the element is shown in Figure 2.2. The HEU fuel plates are 50 mil thick (0.050 inches). The fuel meat is 20 mil thick in each plate and consists of UAl_x aluminide fuel containing uranium with a ^{235}U enrichment of approximately 93%. The HEU plates are clad with 15 mil of Al-6061 aluminum. The fuel plates are 25.5 inches long, with an active fuel meat length of 24 inches. While the plate and meat width varies by plate, each plate has two unfueled edges that are each 145 mil wide.

Figure 2.3 provides an illustration of the MURR fuel element. The fuel plates are swaged into two Al-6061 aluminum side plates that are 0.150 inches (150 mil) thick, 3.16 inches wide, and 31.75 inches long. The plates fit into grooves cut into the side plate that are 75 mil deep, leaving 70±30 mil of the unfueled portion of the fuel plate that extends out of the side plate. A comb is fitted over the fuel plates at their top and bottom to provide additional structural support. The side plates are attached to top and bottom end fittings. Roller pins on the inside and outside edges of the end fittings facilitate insertion of the elements into the annular pressure vessel of the MURR. The overall length of the element is 32.5 inches.

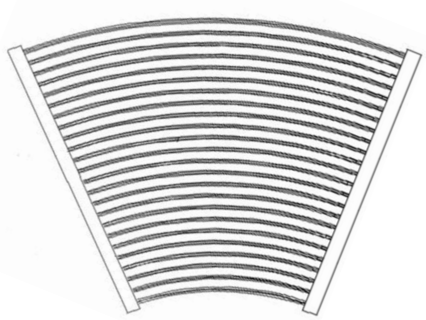


Figure 2.2. Cross-Sectional View of MURR Fuel Element Plates.

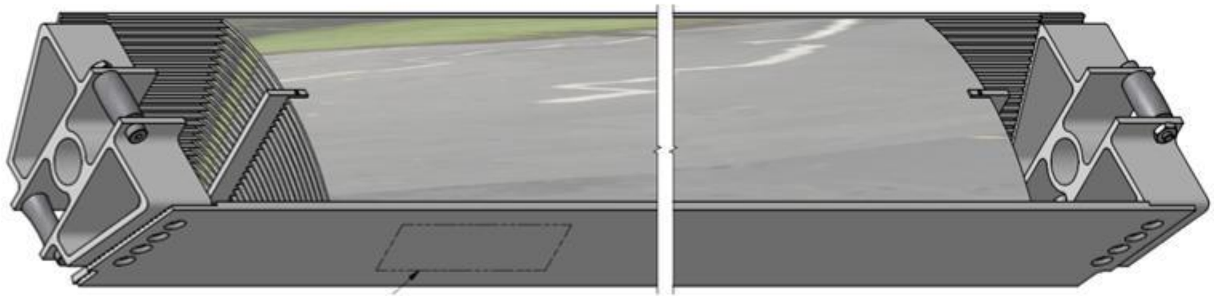


Figure 2.3. MURR Fuel Element.

In order to meet the reactivity requirements of the MURR operating cycle with LEU fuel, it is necessary to have a much higher uranium density than the current UAl_x fuel (1.53 gU/cm^3) or silicide dispersion fuel (7.2 gU/cm^3). U-10Mo foils that can provide a uranium density of 15.3 gU/cm^3 have been selected for the LEU fuel. A fuel element design with U-10Mo LEU fuel developed in Reference 1 was found to safely meet the MURR operating cycle requirements and maintain existing reactor performance.

The LEU fuel element has 23 fuel plates. Each fuel plate is 25.5 inches long, with a 24.0 inch fueled length. The unfueled edge on each side of the fuel plates is 145 mil, of which 75±30 mil extends into a groove cut into the element side plates. The other portions of the element construction (e.g., side plate length, width, and thickness; and end fittings) will be identical to the HEU fuel element.

A summary comparison of the HEU and LEU design parameters is provided in Tables 2.1 and 2.2. The LEU element uses graded foil thicknesses to flatten the radial heat flux profile. This can be seen in Figure 2.4 which shows a cross sectional view of the MURR LEU element plates 1-5 and 19-23. Note that plates 6-18 have the same fuel meat and clad thicknesses as plates 4-5 and 19-22. The clad thickness varies by plate, with the thinnest nominal clad being 12 mil. The clad thicknesses on plates 1 and 23 are thicker (17.5 and 16 mil, respectively) because the outer plates are more susceptible to being scratched. The fuel cladding consists of Al-6061 aluminum and a thin (1 mil) zirconium layer at the fuel-clad interface. Plates 1 to 22 are designed to be nominally 44 mil thick. Making the plates thinner than the HEU fuel element, as well having one less plate, gives a higher water-to-fuel ratio in the LEU element and increases the reactivity. Plate 23 is the widest fuel plate and is designed to be 49 mil thick. This gives greater resistance against bending forces in the MURR coolant flow field.

Table 2.1. Nominal HEU and LEU Fuel Element and Plate Dimensions.

	HEU				LEU			
Channel or Plate	Meat thickness (mil)	Al-6061 Clad thickness (mil)	Plate thickness (mil)	Coolant Channel thickness (mil)	Meat thickness (mil)	Al-6061+Zr Clad thickness (mil)	Plate thickness (mil)	Coolant Channel thickness (mil)
1	20	15	50	95[1]	9	17.5	44	80.5[1]
2	20	15	50	80	12	16	44	93
3	20	15	50	80	16	14	44	93
4	20	15	50	80	20	12	44	93
5	20	15	50	80	20	12	44	93
6	20	15	50	80	20	12	44	92
7	20	15	50	80	20	12	44	92
8	20	15	50	80	20	12	44	92
9	20	15	50	80	20	12	44	92
10	20	15	50	80	20	12	44	92
11	20	15	50	80	20	12	44	92
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18	20	15	50	80	20	12	44	92
19	20	15	50	80	20	12	44	92
20	20	15	50	80	20	12	44	93
21	20	15	50	80	20	12	44	93
22	20	15	50	80	20	12	44	93
23	20	15	50	80	17	16	49	93
24	20	15	50	80				80.5[3]
25				75[2]				

[1] Plate 1 to outer edge of inner roller
[2] Plate 24 to outer edge of outer roller
[3] Plate 23 to outer edge of outer roller

Table 2.2. Nominal HEU and LEU Fuel Plate Dimensions and Loadings.

Plate	HEU			LEU		
	Clad I.R. (inches)	Nominal Meat width (inches)	^{235}U Content (grams)*	Clad I.R. (inches)	Nominal Meat width (inches)	^{235}U Content (grams)**
1	2.77	1.703	19.26	2.7555	1.6895	18.09
2	2.90	1.805	20.39	2.8925	1.7971	25.66
3	3.03	1.907	21.53	3.0295	1.9047	36.26
4	3.16	2.010	22.66	3.1665	2.0123	47.89
5	3.29	2.112	23.79	3.3035	2.1199	50.45
6	3.42	2.214	24.93	3.4395	2.2267	52.99
7	3.55	2.316	26.06	3.5755	2.3335	55.53
8	3.68	2.418	27.19	3.7115	2.4403	58.07
9	3.81	2.520	28.33	3.8475	2.5472	60.61
10	3.94	2.622	29.46	3.9835	2.6540	63.16
11	4.07	2.724	30.59	4.1195	2.7608	65.70
12	4.20	2.826	31.73	4.2555	2.8676	68.24
13	4.33	2.928	32.86	4.3915	2.9744	70.78
14	4.46	3.031	33.99	4.5275	3.0812	73.32
15	4.59	3.133	35.12	4.6635	3.1880	75.86
16	4.72	3.235	36.26	4.7995	3.2949	78.41
17	4.85	3.337	37.39	4.9355	3.4017	80.95
18	4.98	3.439	38.52	5.0715	3.5085	83.49
19	5.11	3.541	39.66	5.2075	3.6153	86.03
20	5.24	3.643	40.79	5.3445	3.7229	88.59
21	5.37	3.745	41.92	5.4815	3.8305	91.15
22	5.50	3.847	43.06	5.6185	3.9381	93.71
23	5.63	3.949	44.19	5.7555	4.0477	81.87
24	5.76	4.052	45.32			
Total			**775.0**			**1506.8**

*± 1.0% per plate
**± 11% in plate 1; ± 8.3% in plate 2; ± 6.3% in plate 3; ± 5.0% in plates 4-22; ± 5.9% in plate 23

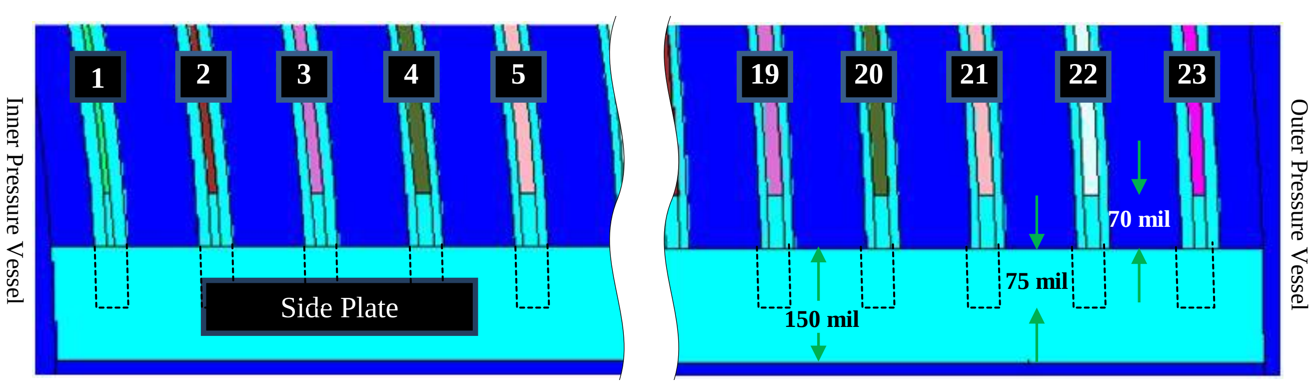


Figure 2.4. Cross Section View of MURR LEU Element Plates 1-5 and 19-23.

3.0 LEU OPERATIONS DATA

The MURR is currently licensed for a maximum core power of 10 MW. This power level provides neutron flux levels in the center flux trap and irradiation positions in the graphite reflector to enable MURR to fulfill its mission of providing experimental and irradiation services to a variety of users. The goal of the conversion to LEU fuel is to develop a fuel element design that will ensure safe reactor operations, as well as maintaining existing performance. The LEU fuel was designed according to a set of manufacturing assumptions that were provided by the FD and FFC pillars of the RERTR program to reliably manufacture the fuel plates. However, it was found in Reference 1 that a power uprate to 12 MW will be needed for the LEU fueled core to continue to meet the facility's mission.

In order to characterize the power distributions, temperatures, and fuel burnup for the DDE that will be representative of the LEU fuel element, a number of core states were evaluated. The MURR operates continuously with the exception of a weekly scheduled shutdown. Over the past 35 years of operation, the MURR has averaged approximately 6.3 days/week at full power. The weekly shutdown provides an opportunity to access samples in the center test hole, to perform surveillance tests and maintenance, and to replace all eight fuel elements in the core. Replacing the fuel elements provides a xenon free core for restart and the chance to remix or shuffle which elements will be used in the core. A core loading will always consist of four different pairs of elements, with the two elements of each pair loaded opposite of each other in the core. Typically a fuel element will be used in 18 to 20 different core loadings before being retired from the fuel cycle.

A fuel cycle model that simulated the typical MURR weekly operations and fuel shuffling was developed and calculations were performed with the REBUS-DIF3D [3] code, as described in Reference 1. A typical core loading state with fresh elements, partially-depleted elements, and elements at their end-of-life was selected for further analysis. The depleted fuel compositions were extracted from the REBUS-DIF3D results and input to an MCNP [4] model for detailed power distribution analysis.

3.1 Calculation Methodology for Power Distributions

The power distributions calculated for the LEU element are based on a plate-by-plate discretization with 24 equal-height axial zones and 9 azimuthal zones. Consequently, each fuel element is divided into 4,968 zones (23x24x9). While the power distribution varies most significantly in the axial and radial (plate-by-plate) dimensions, it also varies along the width of the fuel meat, and can peak sharply at the edge of the fuelled section of the plate due to an increase in the local water-to-fuel ratio near the edge of the fuel meat. The calculated azimuthal peaking factor, i.e., the maximum ratio of stripe-averaged to fuel-meat averaged volumetric heat generation rate for the plate, is sensitive to the size of the calculation zone along the edge of the fuel meat. Analyses were performed to determine the proper discretization of the fuel plates in the azimuthal dimension.

Although the MURR plates are very thin, the cladding and fuel have a very good thermal conductivity. Significant temperature gradients in the azimuthal direction could lead to a convective heat flux distribution that is significantly different than the power distribution. To determine the impact of lateral conduction in the azimuthal and axial directions on the azimuthal distribution of the convective heat flux, 3-D CFD [5] simulations, which account for conduction and convection, were performed at steady-state conditions of the MURR [6]. The analysis was performed for a hot channel in a preliminary LEU fuel element design.

The results in Figure 3.1 show that the effect of lateral conduction on the convective heat flux is insignificant at distances greater than 5 mm from the edge of the fuel meat. The convective heat flux peaks at about 3 mm from the edge of the fuel meat and drops sharply towards the edge of the meat (moving towards the side plate). The effect of the zirconium layer between the fuel foil and the aluminum cladding and the effect of any gap between the plates and the side plate (i.e., incomplete contact) on the azimuthal distribution of the convective heat flux are also insignificant. From this analysis, it was concluded that the representation of the fuel meat at the edge of the fuel plate by a 5 mm stripe at the average power density in the stripe would give a conservative estimate of the convective heat flux into the water channel at the hot stripe location. The MCNP power distributions were calculated by azimuthally subdividing the meat of each fuel plate into nine tally stripes; three stripes of 5 mm each along both edges of the fuel meat, and three stripes of equal angle in the middle of the plate to cover the balance of the plate.

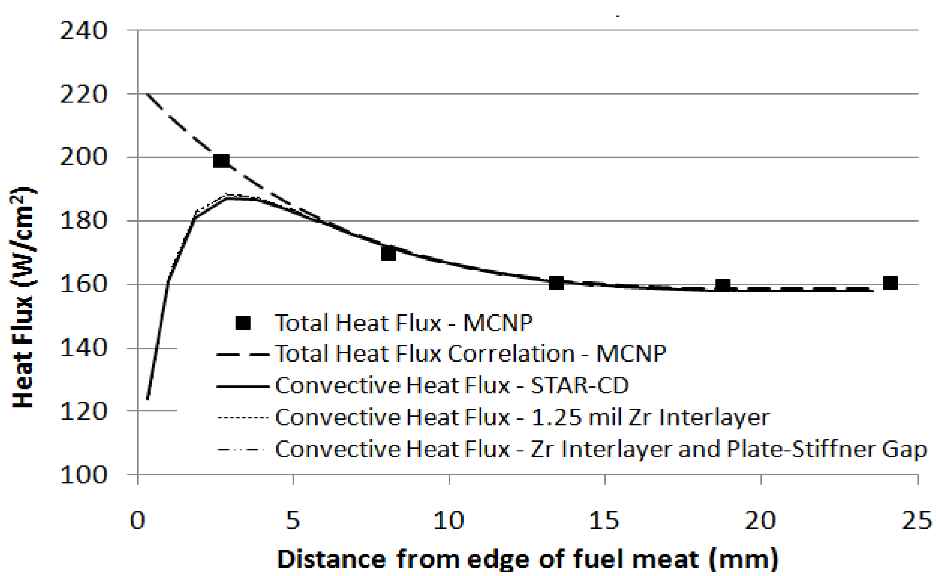


Figure 3.1. Azimuthal Heat Flux Distribution for MURR Hot Channel.

A comparative basis should be maintained between the calculations that form the LEU safety basis [1], and calculations performed to support the DDE irradiations. To this end, unless there is a specific rationale, the size scale of regions of depletion and power distribution used for DDE irradiation planning and results should correspond with those used in the LEU reactor safety basis in order to represent the various physical phenomena accounted for in the safety basis calculations. Where variations exist, the DDE irradiation planning should compare results based on the discretization presented the LEU reactor safety basis in order to ensure that alterations do not impact accurate modeling of the underlying phenomena.

3.2 Limiting Heat Flux Distributions of LEU Fuel

Power distributions were calculated with MCNP by tallying the fission power (f7 tally) within 24 axial, 9 azimuthal, and 23 radial segments (plate-by plate) of the fuel meat in the entire core of eight elements (i.e., 4,968 segments per element). The MCNP tallies were normalized by a post-processing code to facilitate studies of different core power levels and different levels of tally detail. It should be noted that credit for power deposition outside the fuel is not modeled here, but was taken into account in the thermal-hydraulic safety margin calculations [2].

Power peaking is dependent upon the mix of burnup states among the elements in the core, upon the core xenon state, upon critical control blade compositions and positions, and upon the experiment/sample loadings, particularly in the flux trap. A number of cases that covered the range of expected variations in these conditions were examined as part of the technical basis for the steady-state LEU safety basis [1]. However, for the characterization of the power distribution for the DDE, a typical equilibrium core state with fresh elements, partially-depleted elements, and elements at their end-of-life was selected. Furthermore, typical experiment/sample loadings in the center flux trap and graphite reflector were assumed. The four control blades were assumed to be at their nominal fresh composition and banked at the critical position.

Figure 3.2 plots the average heat flux by plate for a fresh LEU element at BOL with no xenon, a fresh element with equilibrium xenon, and for an LEU element near the end-of-life with equilibrium xenon. It should be noted that the fresh element results are for an element in the so-called X1 position of the core (see Figure 2.1, where the X1 position is indicated by a “1”), while the end-of-life heat flux profile is for an element in the X8 position that had been depleted in the core following the typical shuffling sequence in MURR. Fresh elements are inserted in positions X1 or X5, and elements at or near end-of-life are inserted in positions X4 or X8. The height of the banked control blades also affects the heat flux profile in MURR. The control blade positions for the xenon-free and equilibrium xenon core conditions are noted in the figure. Under xenon-free conditions, the control blades are inserted to 8.4 inches from the top of the fuel, which decreases the heat flux in plate 23 relative to the equilibrium xenon state when the blades are withdrawn to 1.7 inches from the top of the fuel. As the fuel element reaches its end-of-life, the thin fuel foils near the center flux trap become severely depleted, so that the heat flux profile decreases significantly in the innermost plates. These results show that the average plate heat flux in MURR will vary significantly over the life of the fuel. Modeling of the DDE should be performed to determine how closely the experiment would match this fluctuation.

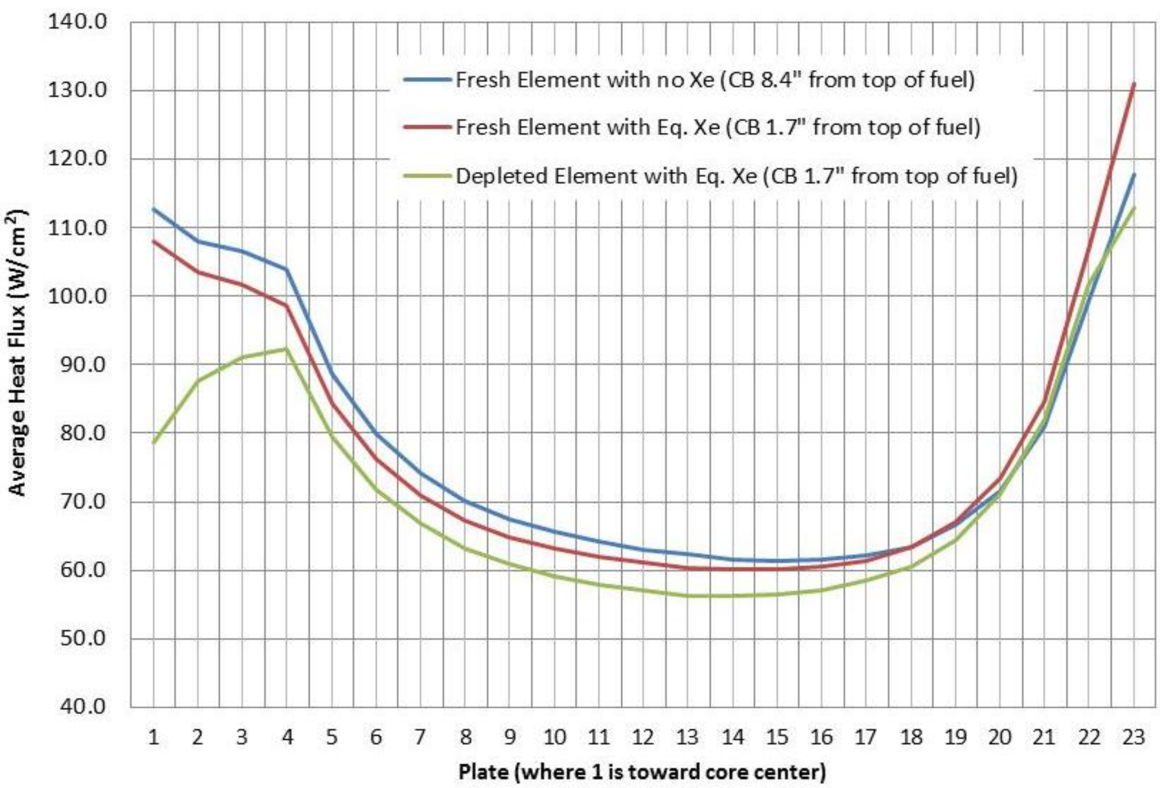


Figure 3.2. Average Heat Flux by Plate in LEU Element.

The results above show that the average heat flux is expected to be greatest in plate 23 over the entire lifetime of the fuel element under typical operating conditions (typical fuel shuffling scheme and sample loadings, banked control blades). Figure 3.3 illustrates how the heat flux profile in plate 23 evolves axially and azimuthally over the life of the fuel. The three charts show the plate 23 heat flux profile under the same core conditions as in Figure 3.2: a) a fresh plate at BOL with no xenon, b) for the same plate with equilibrium xenon, and c) plate 23 in an element at end-of-life that is about to be discharged. The flux trap and reflector are loaded with typical samples for MURR, and the control blades are all fresh and banked together. For the fresh element at equilibrium xenon conditions, the blades are nearly fully withdrawn to compensate for the reactivity loss from the xenon. Although the average heat flux for plate 23 under equilibrium xenon conditions is greater than under xenon-free conditions (see Figure 3.2), the axial profile under equilibrium xenon conditions is more cosine-shaped, so that the peak heat flux is lower. The calculated peak local heat flux for a fresh element in MURR is 210.8 W/cm^2 (BOL, plate 23, xenon-free conditions). By the end-of-life, the peak heat flux in the plate has decreased by nearly 30%, to 153.5 W/cm^2. It should be noted that all of the heat flux values given in this report are based on the MCNP model, and the assumption that half of the power emanates from each face of the plate.

Appendix A, Figures A.1 to A.6, provide plots of the heat flux profile for selected plates in fresh and end-of-life elements in the MURR core. Tables A.1 to A.16 provide the detailed heat flux distributions for these same plates in MURR LEU elements over the life of the fuel.

3.3 Nominal Temperatures for LEU Fuel

The detailed power distributions calculated by MCNP were input to a robust PLTEMP [7] model in which all eight elements of the MURR core were represented. Temperatures were calculated at nominal conditions of 12 MW for the total core power. Previous analyses showed that for the LEU fueled core, 96.4% of the energy from fission is deposited in the primary system, with the balance being deposited in ex-core materials such as the beryllium reflector that surrounds the core. Consequently, since the PLTEMP model represented only the primary system of the MURR, the power distributions input to PLTEMP were normalized to a power of 11.57 MW. Table 3.1 summarizes the core operating parameters, which are the anticipated nominal operating conditions of the MURR with LEU fuel.

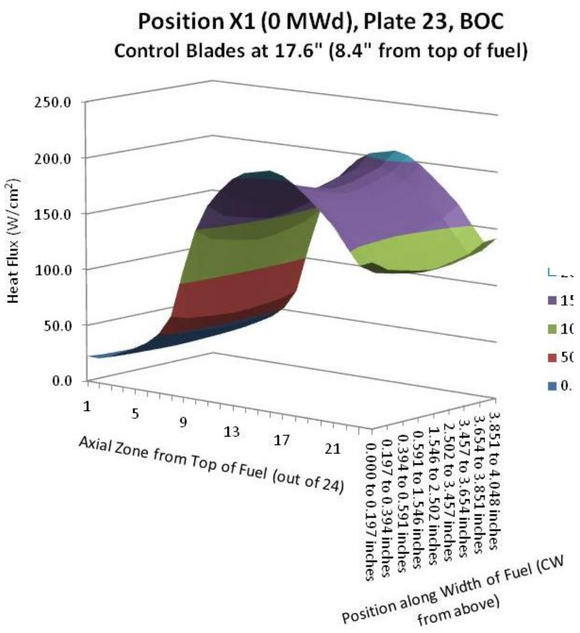
When thermal-hydraulic safety calculations are performed, hot channel factors are applied to account for factors such as the statistical variations in manufacturing of the fuel element and the uncertainty of the method used for the neutronics calculation, which would affect the heat flux realized in the reactor. This

Table 3.1. MURR Core Operating Parameters with LEU Fuel.

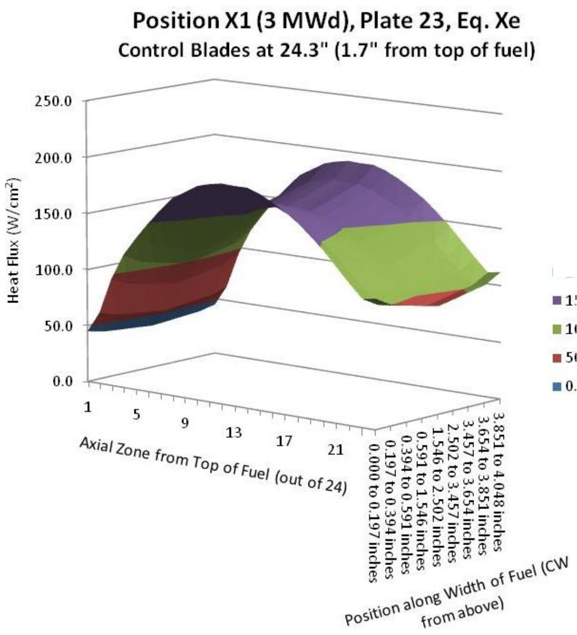
Total Reactor Power	12 MW
Fraction of Power Deposited in Primary System	96.4%
Total Core Power	11.57 MW
Coolant Inlet Temperature	122 ^{o}F (50 ^{o}C)[1]
Total Core Coolant Flow Rate	3800 gpm
Pressurizer Pressure	84 psia
Coolant Pressure at Fuel Plate Entrance[2]	69.1 psia
Pressure Drop	10.4 psia

[1]The nominal coolant inlet temperature for MURR is 120 ^{o}F. The inlet temperature varies throughout the year, and is more frequently hotter than the nominal temperature than cooler than nominal. For the purpose of this analysis, 122 ^{o}F was used.

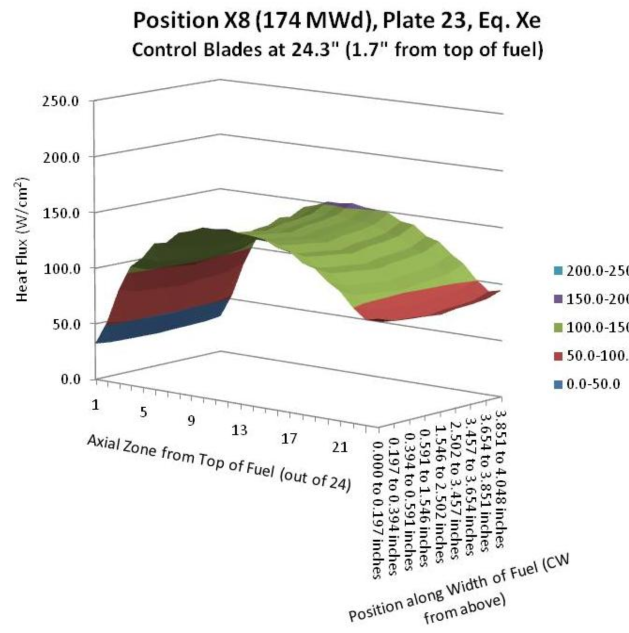
[2]Location is just below the top of the plates where the water enters the coolant channel between the fuel plates. The coolant flow area at this location for the entire core is 0.3715 ft^2. For an LEU element at this location, the flow area is 0.0464 ft^2.



a)Fresh element, no xenon



b)Fresh element, equilibrium xenon



c)Depleted element, equilibrium xenon

Figure 3.3. Heat Flux Profile in Plate 23 in LEU Reference Mixed Burnup Core

then ensures that the thermal-hydraulic safety margins are maintained under even the most extreme conditions. However, the goal here is to determine the nominal temperatures of the fuel components under normal operating conditions. These temperatures will serve as a comparison with the DDE that will take place in the BR2, to ensure that the experiment operates under conditions that are close to the expected nominal conditions of the LEU element when it is operating in MURR. Other fuels testing being performed by FD will assess the temperature and burnup limits of the U-10Mo monolithic fuel for safe operations. As such, hot channel factors related to the fuel manufacturing or calculational uncertainty were not included in the PLTEMP temperature analysis performed here.

However, the impact of coolant channel restriction that will occur with depletion of the fuel under normal operating conditions was included in the temperature analysis of the conceptual element that will be tested in the DDE. The coolant channels between the fuel plates will become constricted as a result of three phenomena. First, as the fuel undergoes fission, swelling of the fuel meat due to fission gas production will occur. The second phenomenon is the effect of irradiation-enhanced creep of the fuel meat which will cause localized bulging of the fuel plate near the edges, which are constrained by the side plate. Third, oxide growth from the aluminum-water reaction will constrict the coolant channel. The amount of oxide growth on the fuel plate depends on the temperature at the water-plate surface, operating time, water pH level, and any protective coating placed on the outside surface of the fuel clad.

The fuel swelling and fuel creep effects were assessed from experimental data reported in References 8 and 9. Based on correlations in the references, the calculated maximum increase in the fuel meat thickness over the life of the LEU fuel from these two phenomena will be 4 mil. For coolant channels 2 through 23 of the LEU element, which are each bounded by two fuel plates, it was assumed that the channel will be restricted by 4 mil at the end-of-life from these effects (2 mil growth into the coolant channel from each plate). For channels 1 and 24, the constriction will be half that amount.

The growth of an oxide layer on the surface of the aluminum clad causes both a restriction of the coolant channel, as well as increasing the thermal resistance of the clad, raising the ΔT across the clad material. A correlation of the oxide growth rate developed by Griess [10] was modified to take into account the specific operating conditions of the MURR. The correlation parameters were altered based on experimental measurements of the oxide layer thickness formed on a MURR HEU fuel element. The resulting oxide growth correlation for the LEU fuel in the MURR is shown in Figure 3.4. The LEU fuel in MURR is expected to reach a discharge burnup of 180 MWd after 2,880 full-power hours of operation. The correlation shown in Figure 3.4 was used to calculate the oxide thickness and associated thermal resistance of the clad for each fuel element in the PLTEMP model.

While the correlation indicates that the oxide thickness at the discharge burnup will be less than 1 mil, it was conservatively assumed for the purpose of estimating the channel restriction that the oxide layer grows to 2 mil at the end of the fuel life. The oxide layer will tend to flake off the fuel plates at thicknesses greater than 2 mil. Consequently, the coolant channel restriction due to oxide growth will be a maximum of 4 mil for channels between fuel plates (2 mil oxide on each plate adjacent to the channel), and 2 mil restriction for channels 1 and 24 that are heated by only one plate.

Thus, the total maximum channel restriction due to fuel swelling, irradiation-enhanced creep, and oxide growth for the LEU fuel in MURR will be 8 mil for channels that are heated by two fuel plates (channels 2-23), and 4 mil for channels heated by only one plate (channels 1 and 24). This affect was included in the PLTEMP model, with the assumption that the channel restriction increases linearly with burnup over the life of the fuel from 0 to 180 MWd.

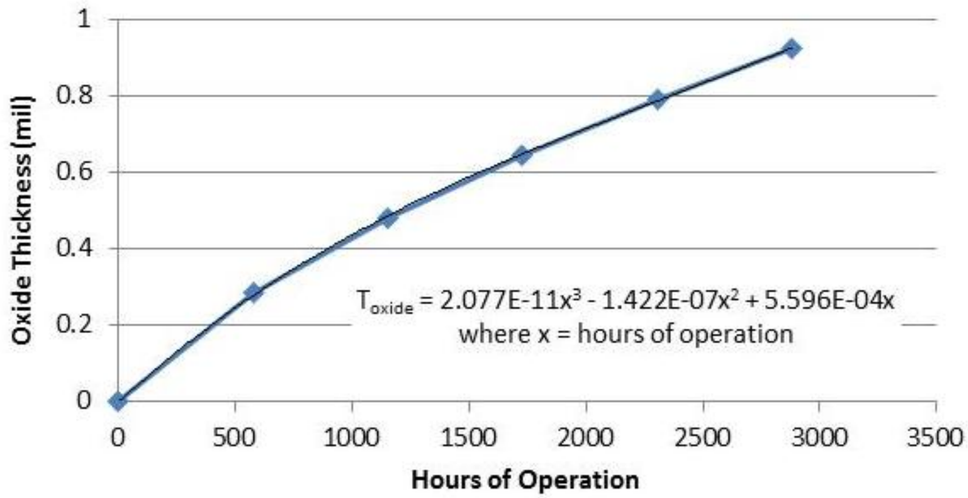


Figure 3.4. Oxide Growth Rate Correlation for LEU Fuel Element in MURR.

Temperatures for the hot stripes were calculated in PLTEMP for the same mixed burnup core used to calculate power distributions in Section 3.2. As discussed in Section 3.1 above, the hot stripe is one of the 5 mm azimuthal power stripes along the edge of the fuel meat (adjacent to the unfueled portion of the plate that is swaged into the side plate). It is conservatively assumed that there was no coolant mixing between adjacent fueled and unfueled stripes in the PLTEMP model. PLTEMP simultaneously analyzes the entire core in order to obtain the limiting temperatures in each fuel element. After a complete thermal solution is obtained for this model, the code applies appropriate peaking factors to all of the individual bulk coolant, film, and material temperature rises determined by the model. Thus, the PLTEMP results presented here represent the so-called “hot stripe” conditions.

Table 3.2 provides the burnup of each element in the core, total power produced by the element, and peak temperatures of the fuel and plate surface at conditions with no xenon and equilibrium xenon. Under xenon-free conditions, the power fraction for the fresh element in the X1 position is about 10% greater than the element in the adjacent position X8 that is at the end of its life. However, the peak fuel temperature in the element at end-of-life is about 14 ^{o}C greater than for the fresh element. This is largely due to the temperature rise through the oxide layer that forms on the clad surface of the depleted element, and causes a higher fuel temperature in spite of a lower power. Although the peak heat flux in the end-of-life element is greatest in plate 23, the peak fuel temperature occurs in plate 22. This could be because of the larger restriction of the coolant channels on either side of the plate due to irradiation and oxide-growth effects; channels 22 and 23 are constricted by 8 mil at end-of-life, while channel 24 on the outboard side of plate 23 is constricted only 4 mil. Additionally, channel 24 is heated on only one side so that the bulk coolant temperature is lower than in channel 23; this also could contribute to the lower fuel meat temperature in plate 23. Under equilibrium xenon conditions, the control blades are nearly fully withdrawn, which decreases the axial power peaking, as shown in Figure 3.3. Consequently, the peak fuel temperature is lower in all elements at equilibrium xenon conditions. The peak fuel temperature still occurs in the end-of-life element in position X8. The peak temperature at the plate surface (which is either the exterior clad surface or the exterior surface of the oxide if it exists) always occurs in the fresh fuel element because of the higher heat flux relative to burned elements.

Figure 3.5 plots the peak fuel temperature by plate for the end-of-life element under xenon-free conditions. It can be seen that the axial power and temperature distributions in the outermost plates are strongly affected by the control blade position. The curves show that the peak fuel temperature occurs in plate 22, followed closely by plate 23.

Table 3.2. Fuel Conditions for Limiting Core with LEU Fuel.

Position	BOC Burnup (MWd)	No Xe (BOC) Control blades at 8.4" from top of fuel			Eq. Xe (Day 2 of week) Control blades at 1.7" from top of fuel		
		Power (MW)	Peak Temperature, °C (Plate)		Power (MW)	Peak Temperature, °C, (Plate)	
			Fuel	Plate Surface		Fuel	Plate Surface
X1	0	1.52	131.9 (23)	**111.5 (23)**	1.52	127.1 (23)	**108.5 (23)**
X2	96	1.44	140.7 (23)	107.6 (23)	1.46	133.0 (23)	103.5 (23)
X3	77	1.44	137.0 (23)	106.8 (23)	1.44	132.4 (23)	104.2 (23)
X4	170	1.38	144.4 (22)	104.6 (23)	1.38	136.6 (22)	101.4 (23)
X5	0	1.52	127.0 (23)	108.4 (23)	1.47	123.1 (23)	105.4 (23)
X6	96	1.44	141.9 (23)	108.4 (23)	1.44	135.5 (23)	105.1 (23)
X7	77	1.44	137.5 (23)	106.9 (23)	1.45	134.0 (23)	105.3 (23)
X8	171	1.39	**145.8 (22)**	105.2 (22)	1.41	**137.2 (22)**	101.6 (22)

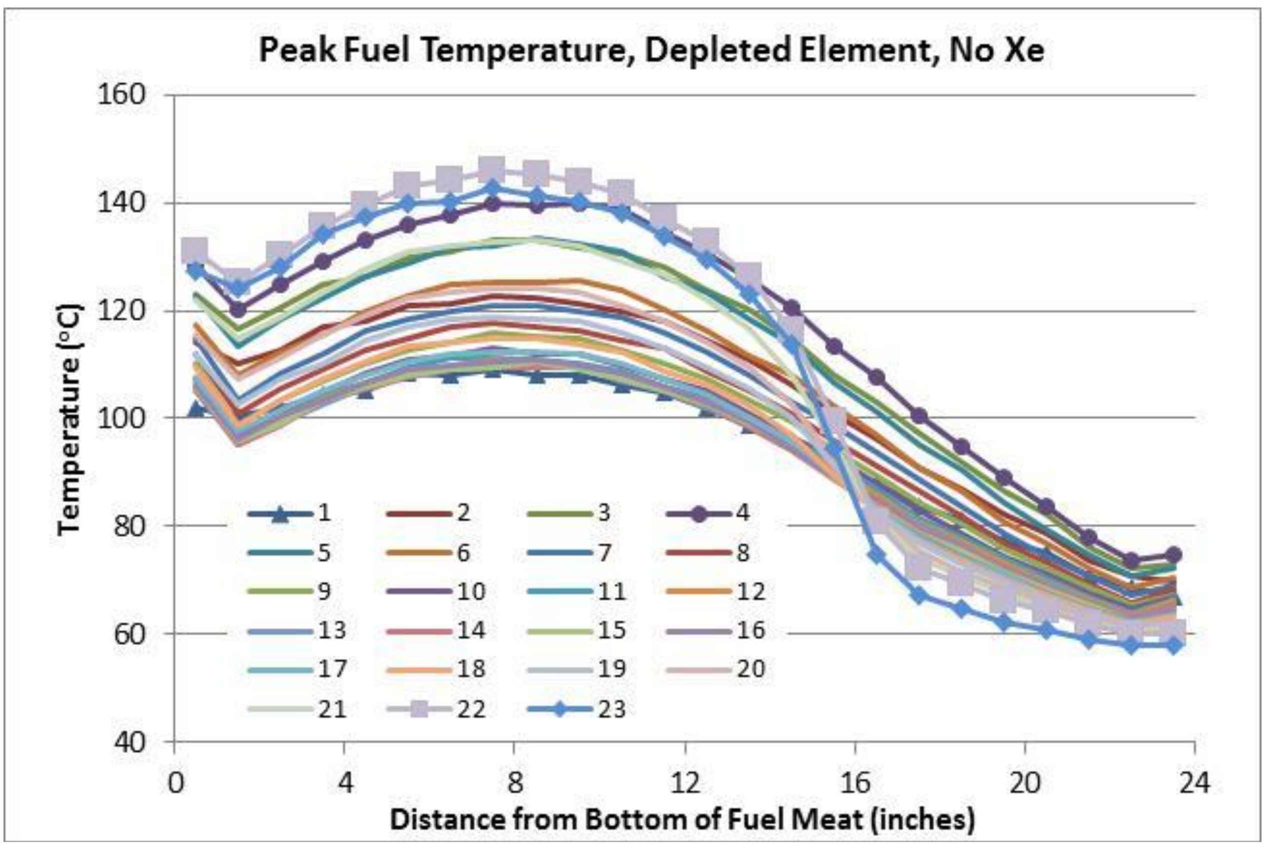


Figure 3.5. Peak Fuel Temperature by Plate for LEU Element at End-of-Life, No Xe.

Figures 3.6 and 3.7 plot the axial temperature profiles for plates 22 and 23, respectively, in fresh and end-of-life LEU elements under xenon-free and equilibrium xenon conditions. This illustrates how the temperature profiles in the plates evolve with depletion and control blade position. The coolant temperature profile in channel 23 (channel between hottest plates 22 and 23) is roughly the same for all cases. Because of the lower heat flux in the end-of-life element, the temperature at the plate-water interface (or oxide surface if it exists) is lower. However, the thermal resistance across the oxide layer in the depleted element causes a greater ΔT across the clad, giving a higher peak fuel temperature.

3.4 Burnup Data

The MURR operates at a utilization factor of 90%, with reactor shutdown, refueling, and restart occurring on a weekly basis. For the proposed LEU fuel element design, it is anticipated that elements will be loaded in the core about 19 times before discharge from the fuel cycle. This is the same number of times the HEU fuel is typically loaded in the MURR before discharge from the fuel cycle. While the core residence time is the same for both the LEU and HEU fuel, the discharge burnup of the LEU elements is 20% greater (180 MWd vs. 150 MWd) due to the higher core operating power level. About 22 LEU elements will be consumed every year.

Table 3.3 provides the plate-by-plate burnup in the discharged LEU fuel. For the U-10Mo fuel form that will be utilized for the LEU fuel elements, the calculated peak fission density in the MURR fuel cycle is 3.37×10^{21} fissions/cm^3, corresponding to 43.5 atom % burnup relative to the initial U-235 in the fuel. The calculated fission density includes fissions from all fissionable species.

Figure 3.8 plots the average and peak fission density burnup by plate in the discharged LEU element.

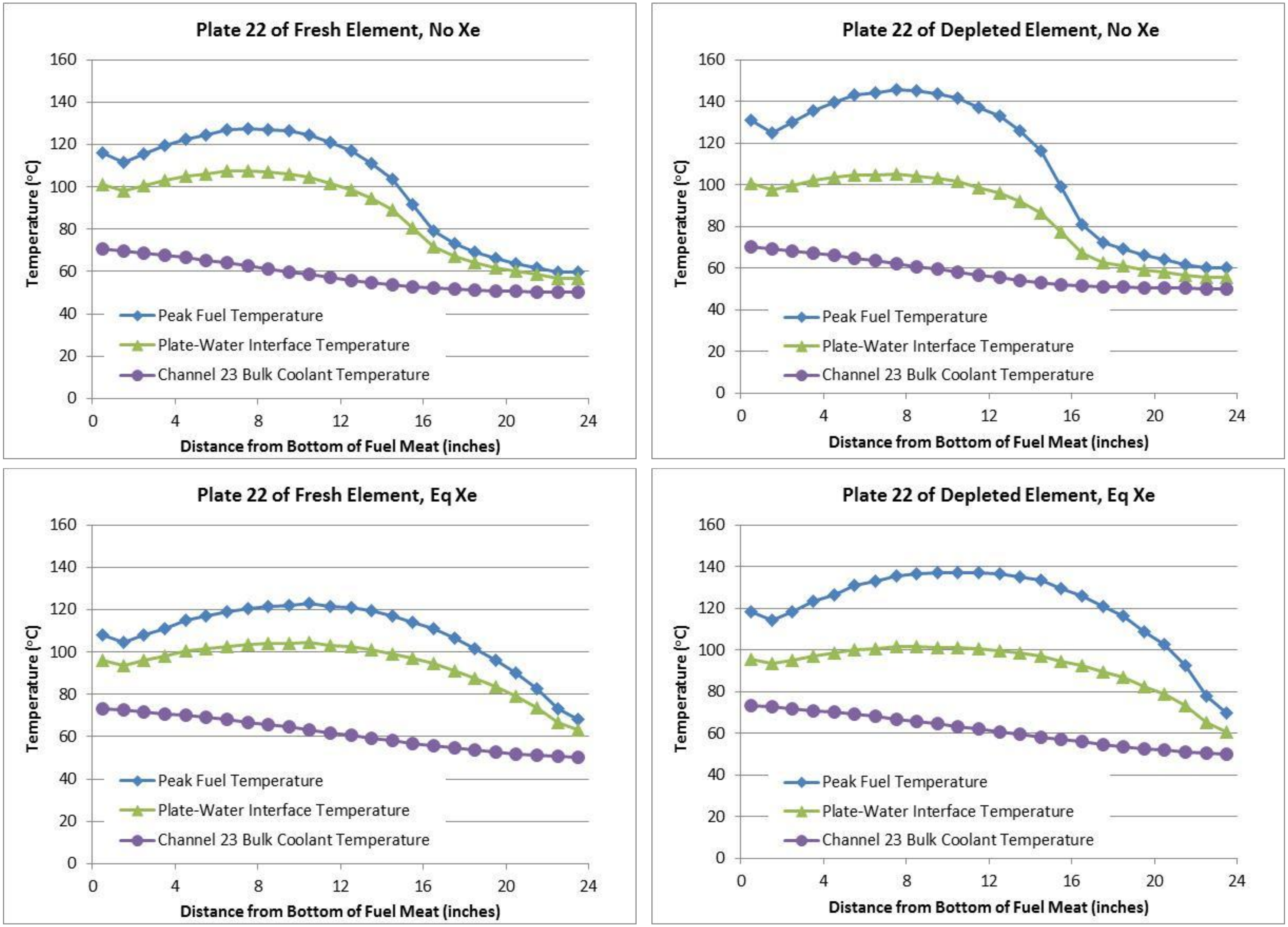


Figure 3.6. Temperature Profiles for Plate 22 in LEU Element.

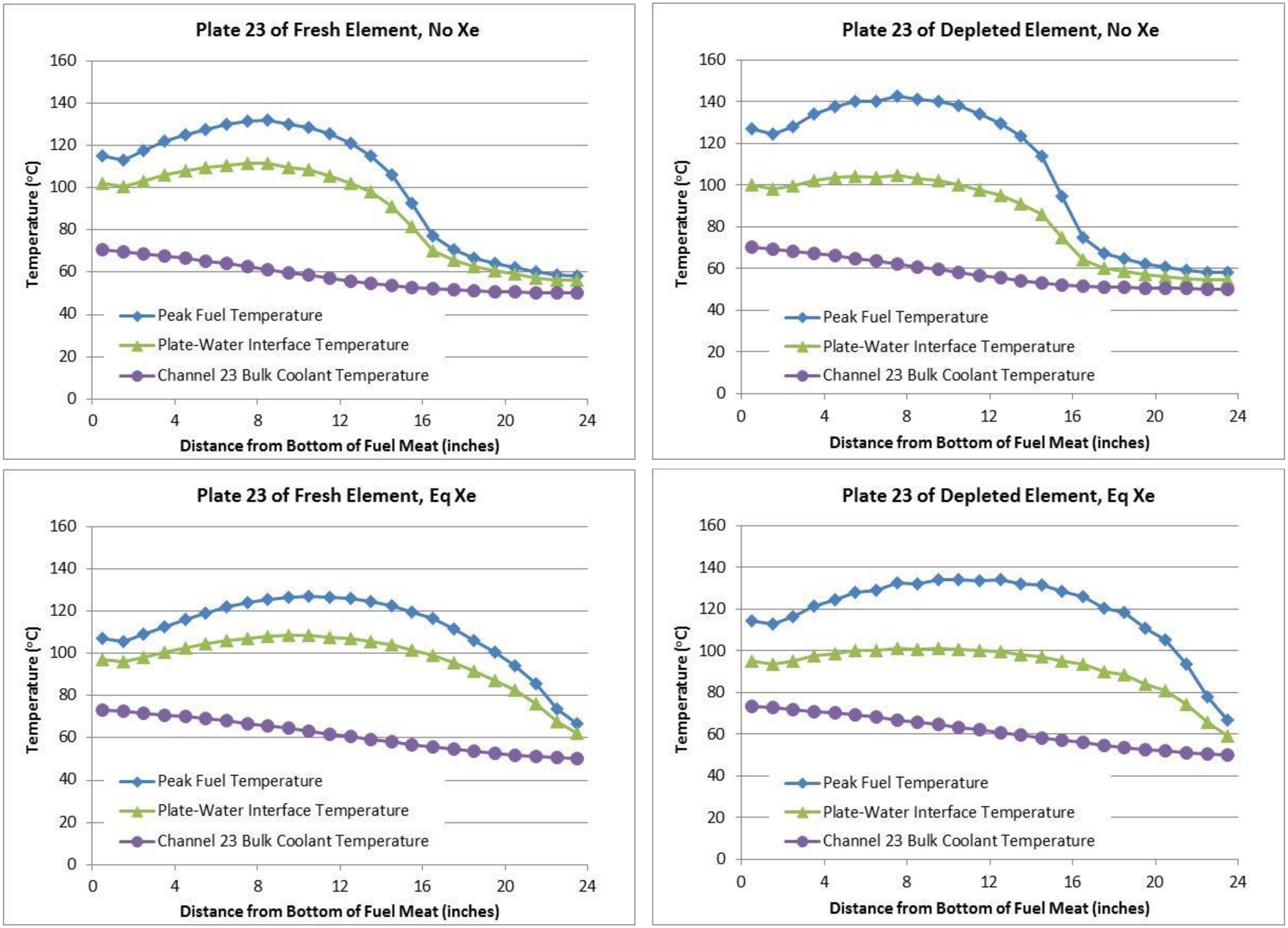


Figure 3.7. Temperature Profiles for Plate 23 in LEU Element.

Table 3.3. Plate Discharge Fission Density for LEU Fuel.

Plate	Plate Average Fission Density (x10^{20} fiss/cm^3)	Axial Burnup Peaking Factor	Azimuthal Peaking factor	Peak Local Burnup	
				Fission Density (x10^{20} fiss/cm^3)	Atom % Burnup
1	26.56	1.223	1.038	33.72	43.5%
2	20.60	1.245	1.087	27.86	35.9%
3	15.68	1.254	1.144	22.50	29.0%
4	12.25	1.262	1.196	18.49	23.9%
5	10.36	1.264	1.234	16.17	20.9%
6	9.34	1.263	1.251	14.76	19.0%
7	8.58	1.263	1.250	13.54	17.5%
8	8.07	1.263	1.251	12.75	16.4%
9	7.72	1.263	1.247	12.16	15.7%
10	7.46	1.264	1.241	11.71	15.1%
11	7.28	1.265	1.240	11.43	14.7%
12	7.15	1.266	1.243	11.26	14.5%
13	7.18	1.267	1.245	11.33	14.6%
14	7.13	1.269	1.255	11.35	14.6%
15	7.11	1.271	1.264	11.42	14.7%
16	7.15	1.274	1.273	11.60	15.0%
17	7.28	1.278	1.288	11.98	15.5%
18	7.52	1.282	1.302	12.55	16.2%
19	8.05	1.287	1.307	13.53	17.5%
20	8.84	1.293	1.297	14.83	19.1%
21	10.34	1.297	1.268	17.01	22.0%
22	13.22	1.300	1.202	20.66	26.7%
23	18.01	1.289	1.115	25.89	33.4%

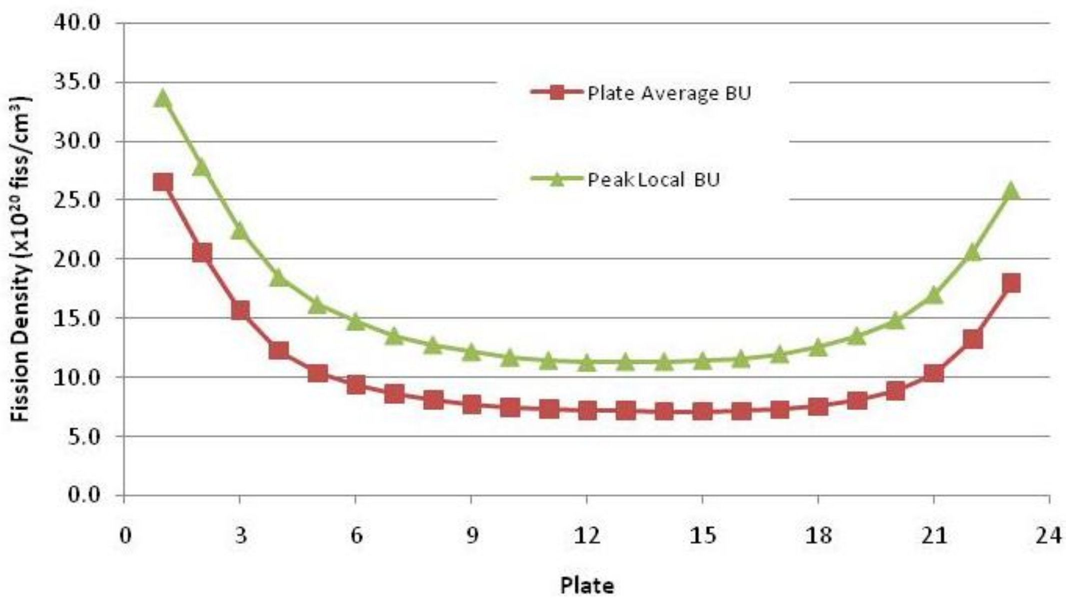


Figure 3.8. Fission Density by Plate in Discharged LEU Fuel.

4.0 SUMMARY OF MURR-DDE GOALS

The preceding sections provide performance data for the conceptual design of an LEU fuel element under normal operating conditions in the MURR. The MURR-DDE of a prototypic element is being conducted to observe how the prototypic LEU element behaves under conditions comparable to what will be experienced in MURR. The element will be placed in an irradiation vehicle which will support the element in an experimental location in BR2. The irradiation vehicle and experimental campaign of the MURR-DDE should be designed so that the element operates at conditions comparable to those which are expected for typical operations in the MURR. This includes the nominal plate-by-plate heat flux profiles, temperatures, flow conditions, and discharge fission density.

The MURR-DDE is not intended to test limits of the fuel or element performance (e.g., maximum allowable fission density). Other experiments being conducted by FD will be conducted for that purpose. However, the MURR-DDE should be designed and conducted so that the performance parameters in the experiment are representative of the nominal performance parameters expected in actual MURR operations. As such, a set of goals for the MURR-DDE are summarized in Table 4.1. The goal values were set by taking the performance values calculated for the LEU element operating in the MURR and applying a nominal increase. For example, heat flux and temperature values were rounded up so that the goal is within 5%, or 5 ºC, respectively, of the calculated performance parameter in MURR. The target fission density for the MURR-DDE was derived by allowing a 20% increase over the calculated local fission density. These data will assist in the design of the irradiation vehicle, as well as plan the experimental campaign.

Table 4.1. Summary of MURR-DDE Goals.

Parameter	Plate 1	Plate 4	Plate 22	Plate 23
Peak Local Heat Flux (W/cm^2)				
Fresh, No Xe	170	180	190	215
Fresh, Eq. Xe	150	160	175	200
EOL, No Xe	115	160	170	175
EOL, Eq. Xe	100	140	155	155
Target Local Fission Density (total fissions/cm^3 from all isotopes)	4.0E+21	2.2E+21	2.5E+21	3.1E+21
Channel Coolant Flow Rate (kg/s)	0.76	0.86	1.67	1.72
Coolant Velocity (m/s)	7.0	7.0	7.0	7.1
Peak Plate Surface Temperature (^{o}C)				
Fresh, No Xe	100	110	110	115
Fresh, Eq. Xe	100	100	105	110
EOL, No Xe	90	105	110	105
EOL, Eq. Xe	85	100	105	105
Peak Fuel Meat Temperature (^{o}C)				
Fresh, No Xe	115	125	130	135
Fresh, Eq. Xe	110	120	125	130
EOL, No Xe	110	140	150	145
EOL, Eq. Xe	105	135	140	135

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Appendix A: Heat Flux Profiles for LEU Plates in MURR.

Figures A.1 to A.6 provide the heat flux profile for selected LEU plates in MURR from fresh to discharge conditions. Plates 1, 4, 22, and 23 were selected because they represent potentially limiting or near limiting plates in the LEU element.

Tables A.1 to A.16 provide the detailed heat flux profiles for the same plates at fresh, middle-of-life, and end-of-life conditions.

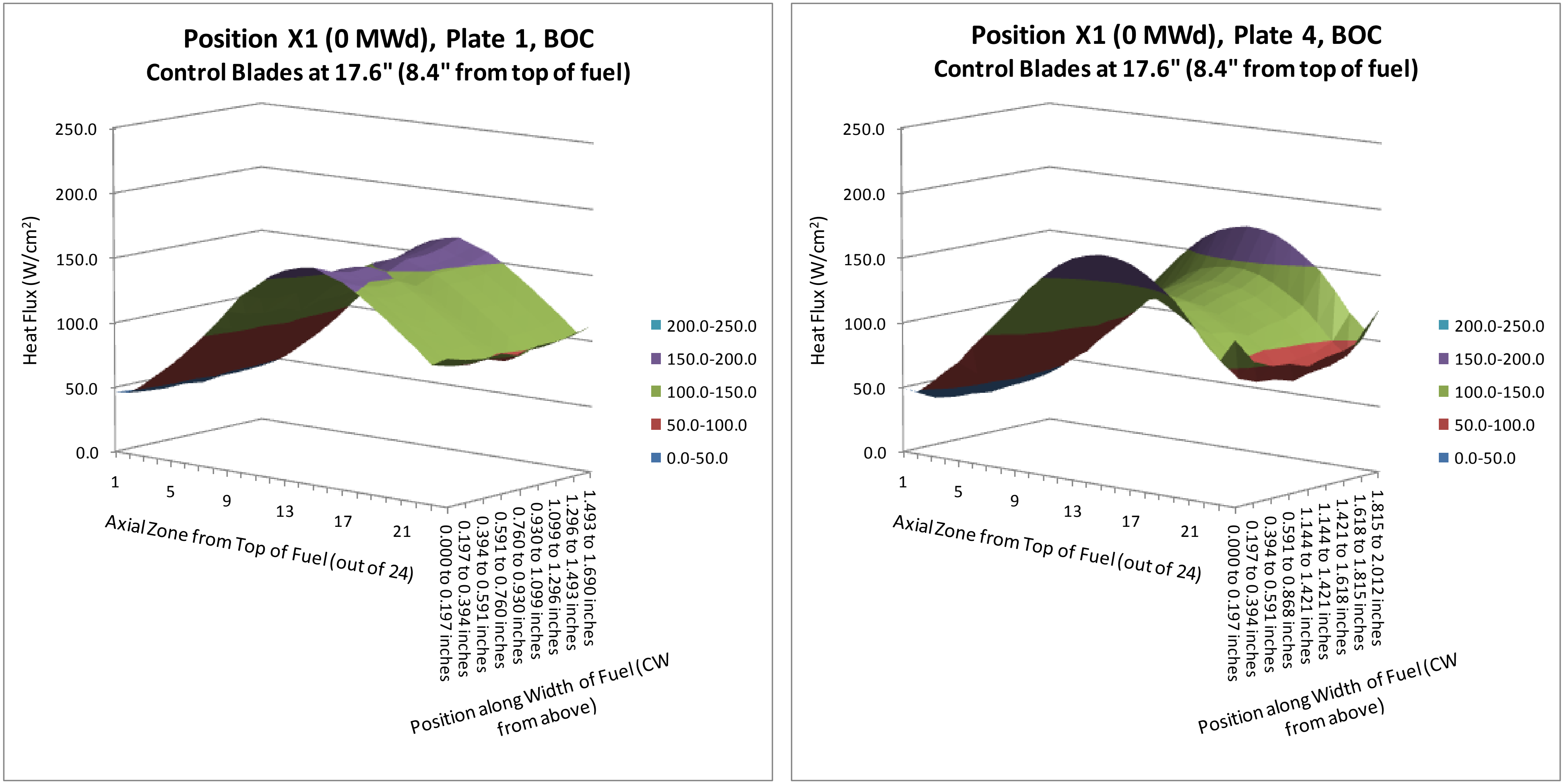
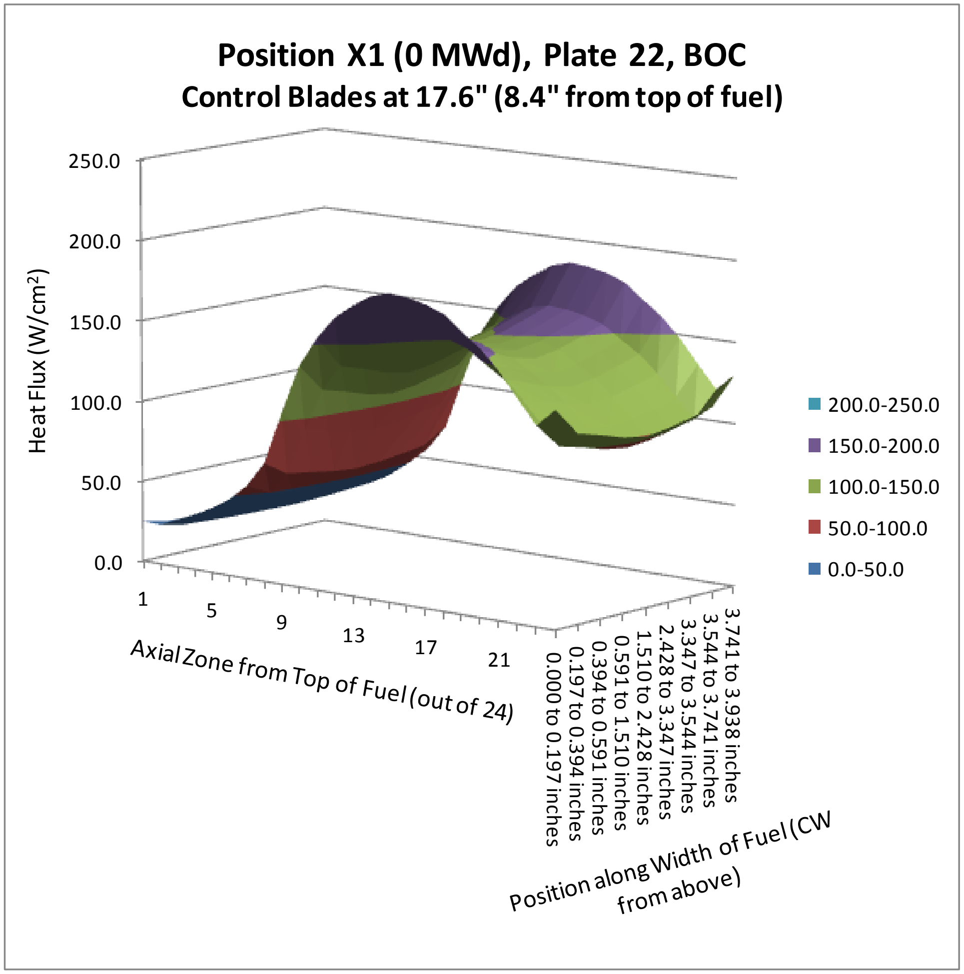


Figure A.1. Heat Flux Profile in MURR for Fresh LEU Element: No Xenon, Plates 1 and 4.



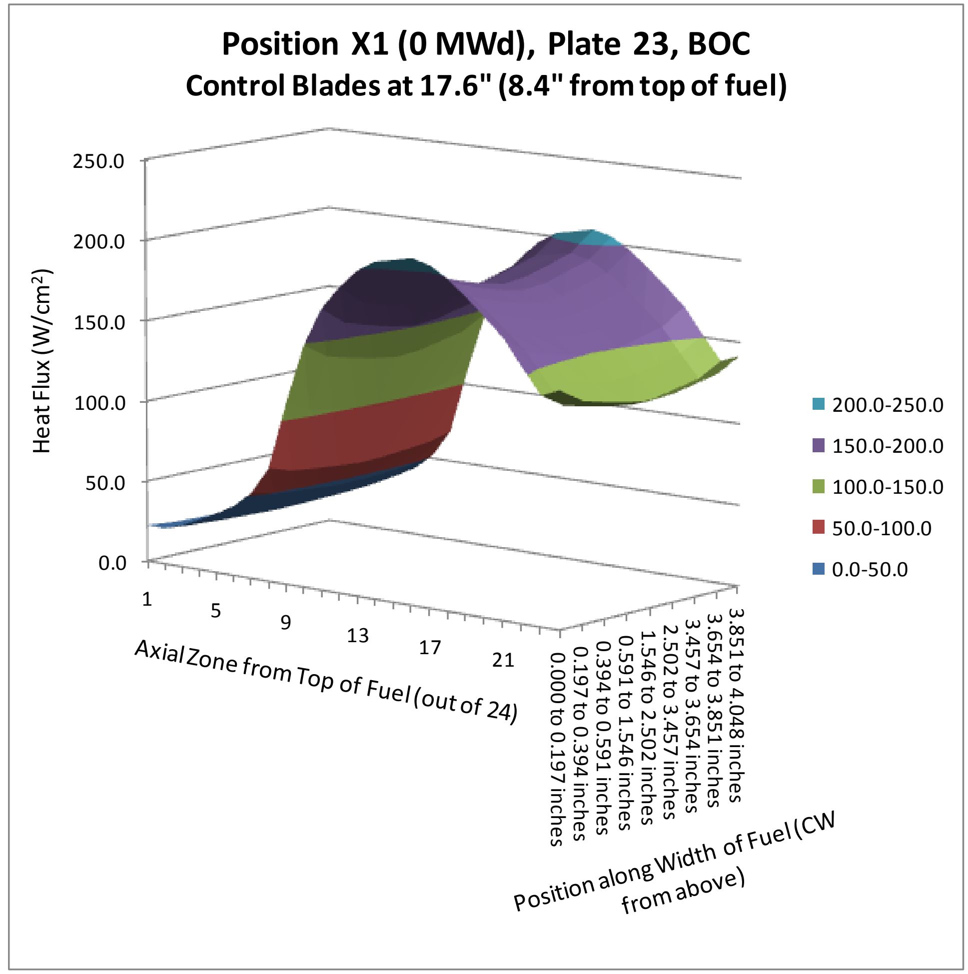


Figure A.2. Heat Flux Profile in MURR for Fresh LEU Element: No Xenon, Plates 22 and 23.

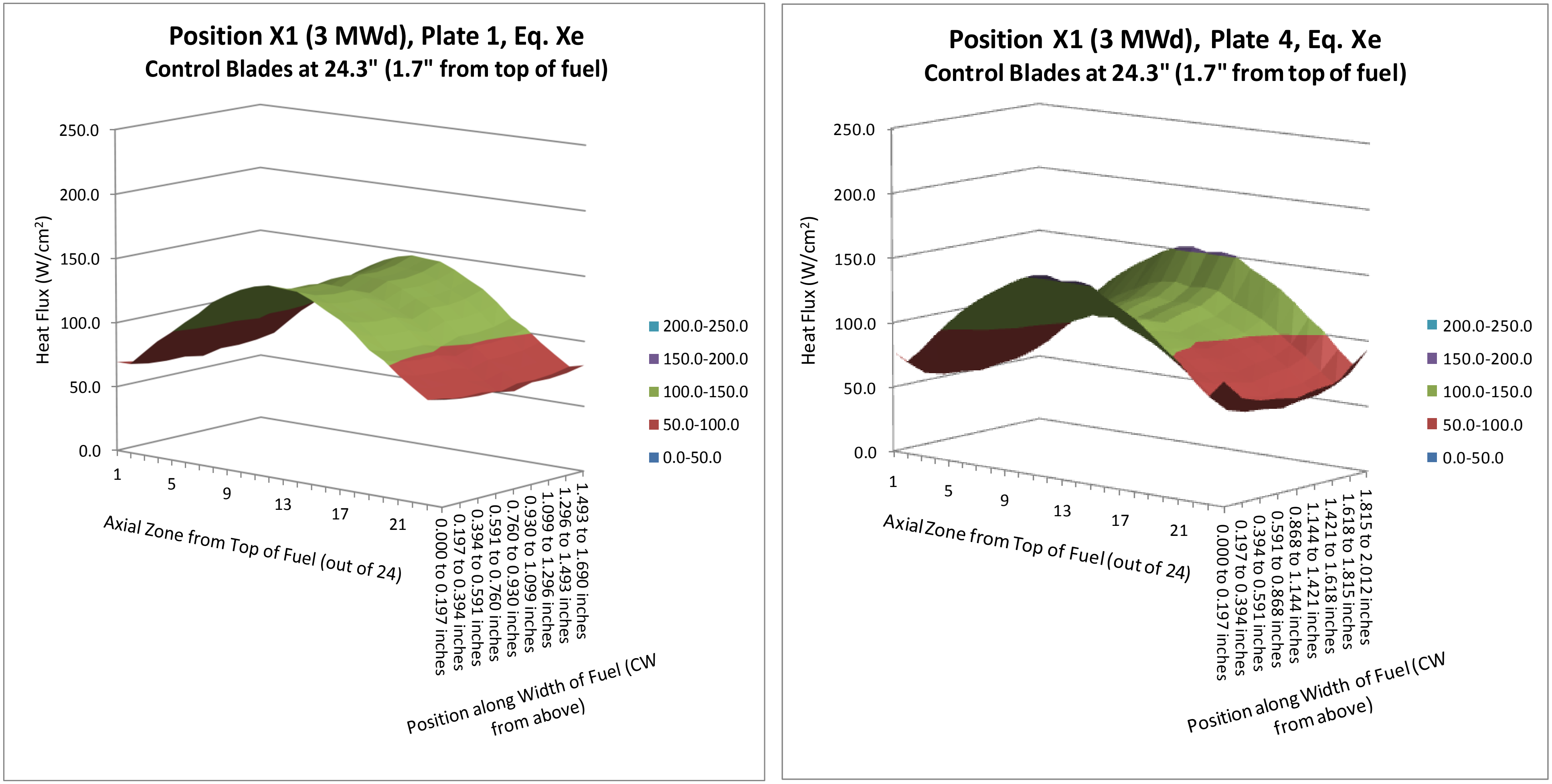


Figure A.3. Heat Flux Profile in MURR for Fresh LEU Element: Equil. Xenon, Plates 1 and 4.

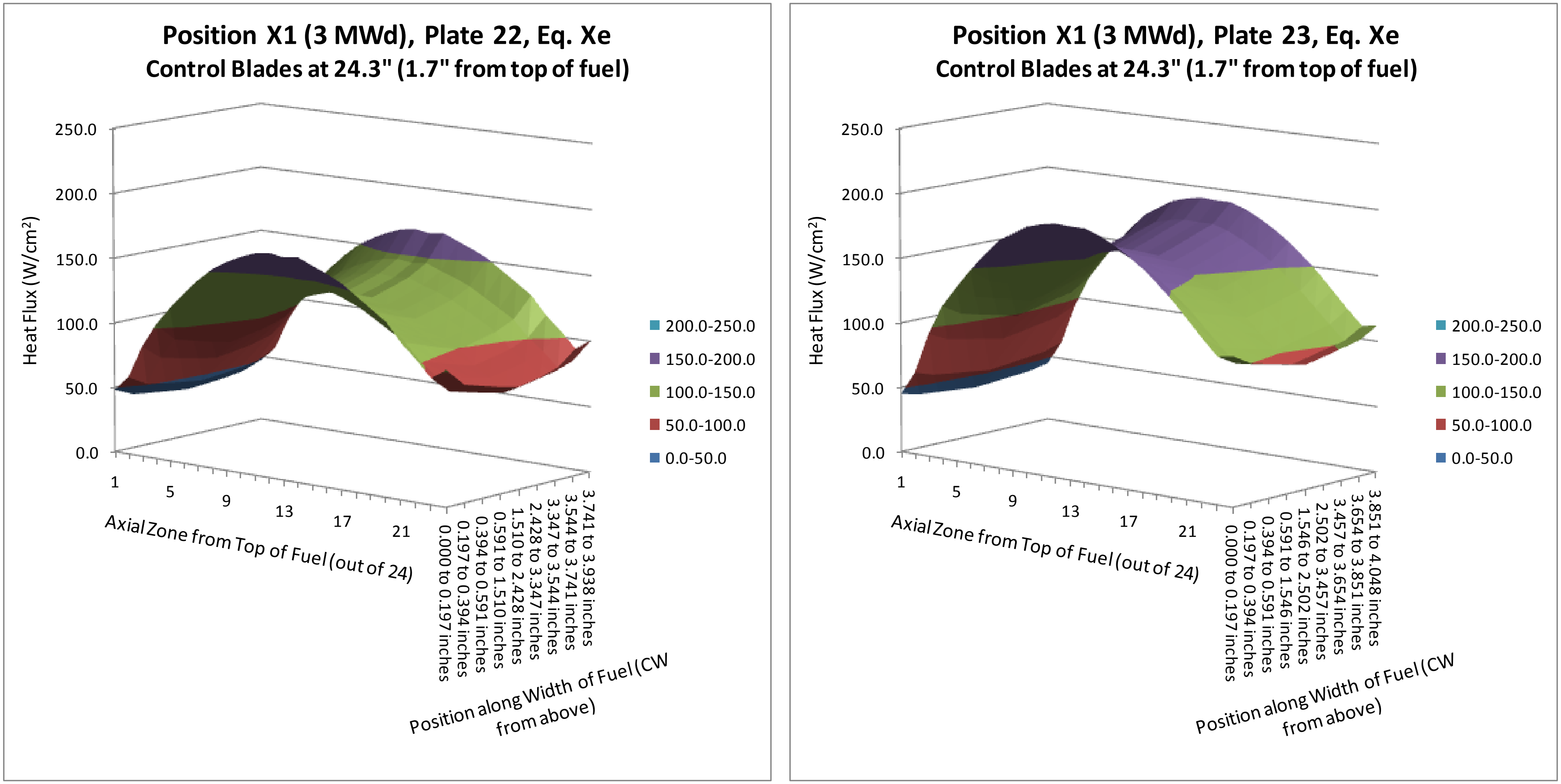


Figure A.4. Heat Flux Profile in MURR for Fresh LEU Element: Equil. Xenon, Plates 22 and 23.

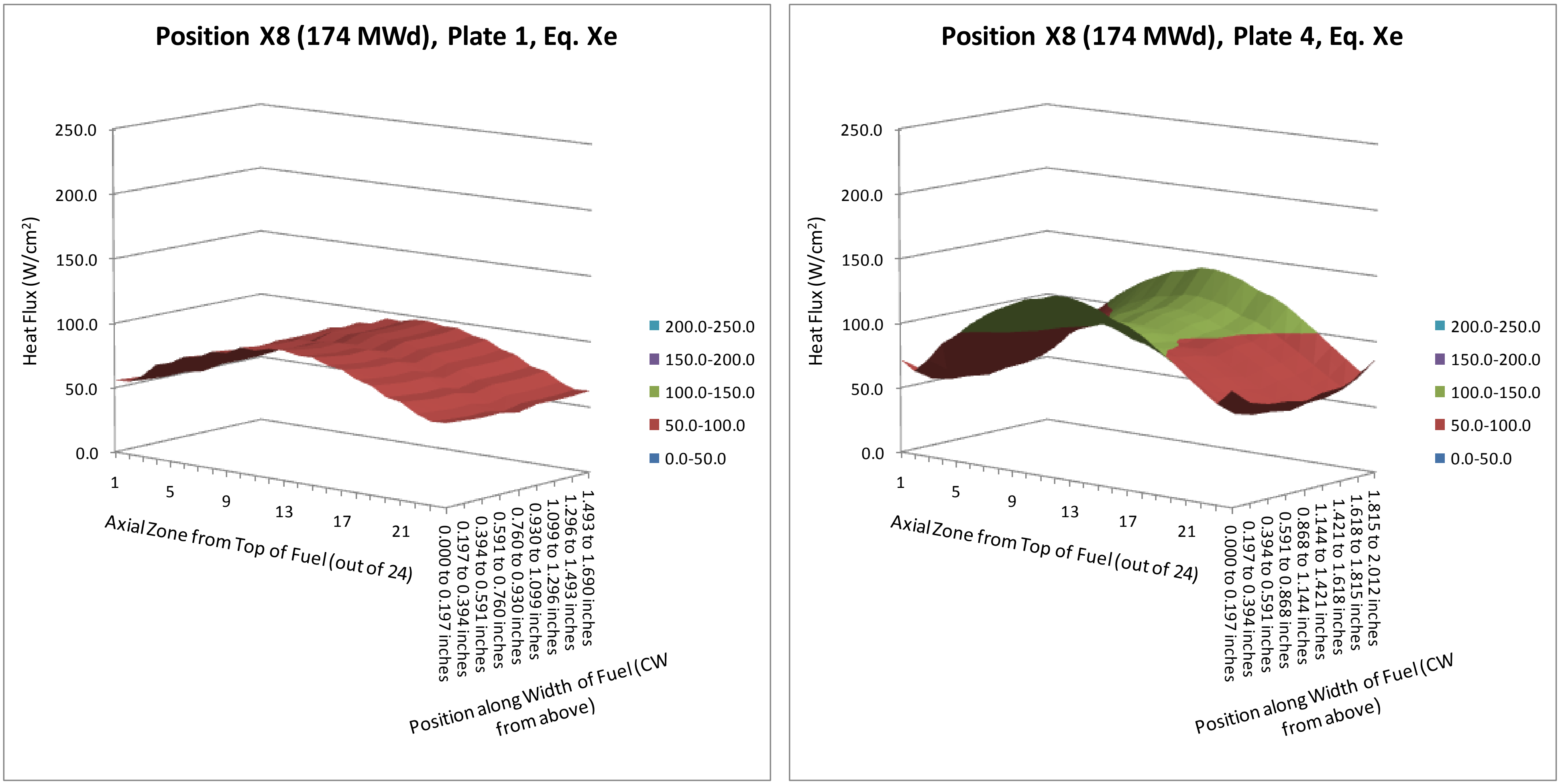


Figure A.5. Heat Flux Profile in MURR for EOL LEU Element: Equil. Xenon, Plates 1 and 4.

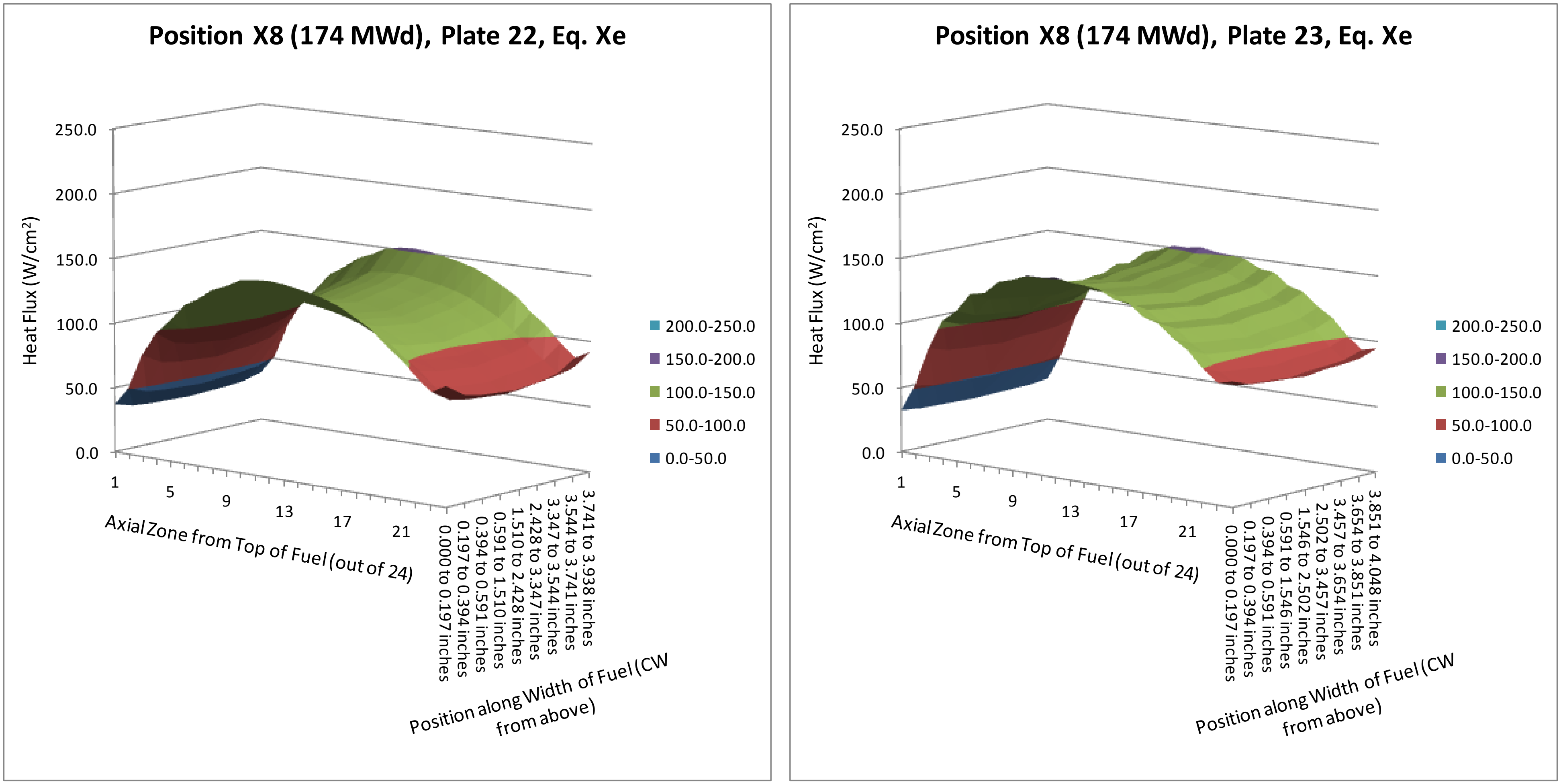


Figure A.6. Heat Flux Profile in MURR for EOL LEU Element: Equil. Xenon, Plates 22 and 23.

Table A.1. Heat Flux Profile (W/cm^2) in Fresh LEU Element, No Xe, Plate 1.

Axial position from top of fuel (inches)	Meat width	1.690	inches			Meat thickness		9	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.760 inches	0.760 to 0.930 inches	0.930 to 1.099 inches	1.099 to 1.296 inches	1.296 to 1.493 inches	1.493 to 1.690 inches
0.5	46.47	44.82	43.92	44.32	42.35	44.32	44.37	45.18	46.74
1.5	47.51	45.81	44.90	45.31	43.30	45.31	45.36	46.18	47.78
2.5	55.02	53.06	52.00	52.48	50.14	52.48	52.53	53.48	55.34
3.5	64.50	62.20	60.96	61.52	58.79	61.52	61.58	62.70	64.88
4.5	73.72	71.10	69.67	70.31	67.19	70.31	70.38	71.66	74.15
5.5	84.35	81.34	79.72	80.45	76.87	80.45	80.53	81.99	84.84
6.5	95.84	92.43	90.58	91.41	87.35	91.41	91.50	93.17	96.40
7.5	108.09	104.24	102.15	103.09	98.51	103.09	103.19	105.07	108.71
8.5	121.35	117.02	114.69	115.74	110.59	115.74	115.85	117.96	122.05
9.5	135.19	130.37	127.76	128.93	123.20	128.93	129.06	131.41	135.97
10.5	143.69	138.57	135.80	137.05	130.96	137.05	137.19	139.68	144.53
11.5	153.01	147.55	144.61	145.93	139.45	145.93	146.08	148.73	153.89
12.5	158.94	153.27	150.21	151.59	144.85	151.59	151.74	154.50	159.86
13.5	162.51	156.72	153.59	155.00	148.11	155.00	155.15	157.97	163.45
14.5	164.24	158.39	155.22	156.64	149.68	156.64	156.80	159.65	**165.19**
15.5	159.81	154.12	151.04	152.42	145.65	152.42	152.58	155.35	160.74
16.5	156.04	150.48	147.47	148.83	142.21	148.83	148.98	151.68	156.94
17.5	148.97	143.66	140.79	142.08	135.77	142.08	142.23	144.81	149.83
18.5	140.90	135.88	133.17	134.39	128.42	134.39	134.52	136.97	141.72
19.5	132.48	127.76	125.21	126.36	120.74	126.36	126.49	128.78	133.25
20.5	123.40	119.00	116.63	117.70	112.47	117.70	117.82	119.95	124.12
21.5	114.29	110.21	108.01	109.00	104.16	109.00	109.11	111.09	114.95
22.5	104.29	100.57	98.56	99.47	95.05	99.47	99.57	101.38	104.89
23.5	110.72	106.77	104.64	105.60	100.90	105.60	105.70	107.62	111.36
Ax. Avg.	**116.89**	**112.72**	**110.47**	**111.48**	**106.53**	**111.48**	**111.60**	**113.62**	**117.57**

Table A.2. Heat Flux Profile (W/cm^2) in Fresh LEU Element, No Xe, Plate 4.

Axial position from top of fuel (inches)	Meat width	2.012	inches			Meat thickness	20	mil	
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.868 inches	0.868 to 1.144 inches	1.144 to 1.421 inches	1.421 to 1.618 inches	1.618 to 1.815 inches	1.815 to 2.012 inches
0.5	49.89	42.28	39.74	39.15	37.20	38.82	39.53	41.82	49.89
1.5	47.78	40.49	38.05	37.50	35.62	37.18	37.86	40.05	47.78
2.5	56.52	47.90	45.02	44.36	42.15	43.98	44.79	47.38	56.52
3.5	66.88	56.67	53.27	52.49	49.87	52.04	52.99	56.06	66.88
4.5	76.08	64.47	60.60	59.71	56.72	59.20	60.28	63.77	76.08
5.5	89.97	76.24	71.66	70.61	67.09	70.01	71.29	75.41	89.97
6.5	102.08	86.50	81.30	80.11	76.11	79.43	80.88	85.56	102.08
7.5	114.36	96.91	91.09	89.75	85.27	88.99	90.61	95.86	114.36
8.5	127.28	107.86	101.38	99.89	94.90	99.04	100.85	106.69	127.28
9.5	140.22	118.82	111.68	110.04	104.55	109.11	111.10	117.53	140.22
10.5	151.33	128.23	120.53	118.76	112.83	117.75	119.90	126.84	151.33
11.5	161.22	136.61	128.41	126.53	120.21	125.45	127.74	135.13	161.22
12.5	167.98	142.34	133.80	131.83	125.25	130.71	133.10	140.80	167.98
13.5	171.67	145.47	136.74	134.73	128.00	133.59	136.02	143.90	171.67
14.5	**173.81**	147.29	138.44	136.41	129.60	135.25	137.72	145.69	**173.81**
15.5	173.04	146.63	137.83	135.81	129.03	134.65	137.11	145.05	173.04
16.5	169.98	144.04	135.39	133.41	126.74	132.27	134.68	142.48	169.98
17.5	163.90	138.89	130.55	128.63	122.21	127.54	129.86	137.38	163.90
18.5	155.80	132.02	124.10	122.28	116.17	121.24	123.45	130.59	155.80
19.5	146.75	124.35	116.88	115.17	109.42	114.19	116.27	123.00	146.75
20.5	133.45	113.08	106.29	104.73	99.50	103.84	105.73	111.86	133.45
21.5	118.42	100.34	94.32	92.94	88.29	92.15	93.83	99.26	118.42
22.5	107.52	91.11	85.64	84.38	80.17	83.67	85.19	90.12	107.52
23.5	124.64	105.61	99.27	97.82	92.93	96.99	98.75	104.47	124.64
Ax. Avg.	**124.61**	**105.59**	**99.25**	**97.79**	**92.91**	**96.96**	**98.73**	**104.45**	**124.61**

Table A.3. Heat Flux Profile (W/cm^2) in Fresh LEU Element, No Xe, Plate 22.

Axial position from top of fuel (inches)	Meat width	3.938	inches			Meat thickness		20	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.510 inches	1.510 to 2.428 inches	2.428 to 3.347 inches	3.347 to 3.544 inches	3.544 to 3.741 inches	3.741 to 3.938 inches
0.5	24.97	21.74	21.01	20.16	19.73	20.08	20.74	21.47	24.64
1.5	24.36	21.21	20.50	19.67	19.24	19.59	20.24	20.94	24.04
2.5	29.31	25.52	24.67	23.67	23.16	23.57	24.35	25.20	28.93
3.5	34.19	29.76	28.77	27.60	27.01	27.49	28.40	29.39	33.73
4.5	39.98	34.81	33.65	32.28	31.59	32.15	33.21	34.38	39.45
5.5	47.18	41.07	39.70	38.10	37.28	37.94	39.19	40.57	46.56
6.5	57.30	49.88	48.21	46.26	45.27	46.07	47.60	49.26	56.53
7.5	72.98	63.53	61.41	58.93	57.65	58.68	60.62	62.74	72.01
8.5	105.66	91.98	88.91	85.32	83.48	84.97	87.77	90.84	104.26
9.5	136.20	118.57	114.61	109.98	107.60	109.53	113.14	117.10	134.39
10.5	154.78	134.74	130.24	124.98	122.28	124.46	128.57	133.07	152.72
11.5	168.82	146.97	142.06	136.32	133.38	135.76	140.24	145.15	166.58
12.5	177.48	154.50	149.35	143.31	140.22	142.72	147.43	152.59	175.12
13.5	184.78	160.86	155.49	149.20	145.98	148.59	153.50	158.86	182.32
14.5	**187.97**	163.64	158.18	151.78	148.51	151.16	156.15	161.61	185.48
15.5	186.86	162.67	157.24	150.89	147.63	150.27	155.23	160.66	184.38
16.5	184.35	160.48	155.13	148.86	145.64	148.25	153.14	158.50	181.90
17.5	179.88	156.59	151.37	145.25	142.11	144.65	149.43	154.65	177.49
18.5	170.71	148.61	143.66	137.85	134.87	137.28	141.81	146.77	168.45
19.5	161.94	140.97	136.27	130.76	127.94	130.22	134.52	139.23	159.79
20.5	149.98	130.56	126.21	121.10	118.49	120.61	124.59	128.94	147.99
21.5	135.24	117.73	113.81	109.20	106.85	108.76	112.35	116.28	133.45
22.5	121.16	105.48	101.96	97.84	95.72	97.43	100.65	104.17	119.56
23.5	132.04	114.95	111.11	106.62	104.32	106.18	109.69	113.52	130.29
Ax. Avg.	**119.51**	**104.03**	**100.56**	**96.50**	**94.41**	**96.10**	**99.27**	**102.74**	**117.92**

Table A.4. Heat Flux Profile (W/cm^2) in Fresh LEU Element, No Xe, Plate 23.

Axial position from top of fuel (inches)	Meat width	4.048	inches			Meat thickness	17	mil	
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.546 inches	1.546 to 2.502 inches	2.502 to 3.457 inches	3.457 to 3.654 inches	3.654 to 3.851 inches	3.851 to 4.048 inches
0.5	22.30	20.85	20.31	19.85	19.52	19.70	20.19	20.69	21.95
1.5	22.16	20.72	20.18	19.72	19.40	19.58	20.06	20.56	21.82
2.5	25.87	24.19	23.56	23.02	22.65	22.86	23.42	24.00	25.47
3.5	31.12	29.10	28.34	27.70	27.25	27.50	28.17	28.87	30.64
4.5	36.65	34.27	33.38	32.62	32.09	32.39	33.18	34.00	36.08
5.5	43.04	40.25	39.20	38.31	37.69	38.04	38.97	39.94	42.38
6.5	52.81	49.38	48.10	47.01	46.24	46.67	47.81	49.00	52.00
7.5	70.02	65.48	63.77	62.32	61.31	61.88	63.40	64.97	68.95
8.5	111.78	104.53	101.81	99.50	97.89	98.79	101.21	103.73	110.07
9.5	148.74	139.10	135.48	132.40	130.25	131.46	134.67	138.02	146.47
10.5	172.59	161.40	157.20	153.62	151.14	152.54	156.27	160.15	169.95
11.5	187.30	175.15	170.59	166.71	164.01	165.53	169.58	173.80	184.43
12.5	198.72	185.83	180.99	176.87	174.01	175.62	179.92	184.39	195.67
13.5	205.65	192.31	187.30	183.04	180.08	181.75	186.19	190.82	202.50
14.5	208.14	194.64	189.57	185.26	182.26	183.95	188.45	193.14	204.95
15.5	**210.77**	197.10	191.97	187.60	184.57	186.28	190.83	195.58	207.54
16.5	207.83	194.35	189.29	184.99	181.99	183.68	188.17	192.85	204.65
17.5	200.71	187.69	182.81	178.65	175.76	177.38	181.72	186.24	197.64
18.5	191.32	178.91	174.26	170.29	167.53	169.09	173.22	177.53	188.39
19.5	180.85	169.12	164.72	160.97	158.37	159.83	163.74	167.81	178.08
20.5	169.82	158.80	154.67	151.16	148.71	150.08	153.76	157.58	167.22
21.5	153.99	144.00	140.26	137.07	134.85	136.09	139.42	142.89	151.63
22.5	139.14	130.11	126.73	123.84	121.84	122.97	125.98	129.11	137.01
23.5	143.88	134.55	131.05	128.06	125.99	127.16	130.27	133.51	141.67
Ax. Avg.	**130.63**	**122.16**	**118.98**	**116.27**	**114.39**	**115.45**	**118.28**	**121.22**	**128.63**

Table A.5. Heat Flux Profile (W/cm^2) in Fresh LEU Element, Equilibrium Xe, Plate 1.

Axial position from top of fuel (inches)	Meat width	1.690	inches			Meat thickness		9	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.760 inches	0.760 to 0.930 inches	0.930 to 1.099 inches	1.099 to 1.296 inches	1.296 to 1.493 inches	1.493 to 1.690 inches
0.5	69.36	66.75	65.75	65.89	63.35	66.35	66.02	67.09	69.49
1.5	69.45	66.85	65.84	65.98	63.44	66.45	66.11	67.18	69.59
2.5	80.04	77.04	75.88	76.04	73.11	76.57	76.19	77.42	80.20
3.5	90.49	87.09	85.79	85.96	82.65	86.57	86.13	87.53	90.66
4.5	98.97	95.25	93.82	94.01	90.40	94.68	94.21	95.73	99.16
5.5	108.46	104.39	102.82	103.03	99.07	103.76	103.24	104.91	108.67
6.5	117.07	112.68	110.99	111.21	106.93	112.00	111.44	113.24	117.30
7.5	127.43	122.65	120.81	121.05	116.39	121.91	121.30	123.26	127.68
8.5	134.25	129.21	127.27	127.53	122.62	128.44	127.79	129.86	134.51
9.5	140.17	134.90	132.88	133.15	128.02	134.09	133.42	135.58	140.44
10.5	144.38	138.96	136.88	137.15	131.87	138.13	137.43	139.65	144.66
11.5	146.90	141.39	139.26	139.55	134.17	140.54	139.83	142.09	**147.18**
12.5	145.88	140.41	138.30	138.58	133.25	139.56	138.86	141.11	146.16
13.5	145.17	139.72	137.62	137.90	132.59	138.88	138.18	140.42	145.45
14.5	140.47	135.19	133.17	133.44	128.30	134.38	133.71	135.87	140.74
15.5	134.25	129.22	127.28	127.54	122.63	128.44	127.79	129.86	134.51
16.5	128.59	123.76	121.90	122.15	117.45	123.02	122.40	124.38	128.83
17.5	119.82	115.32	113.59	113.82	109.44	114.63	114.05	115.89	120.05
18.5	109.41	105.30	103.72	103.93	99.93	104.67	104.14	105.83	109.62
19.5	103.26	99.38	97.89	98.09	94.32	98.79	98.29	99.88	103.46
20.5	94.00	90.47	89.11	89.29	85.86	89.93	89.48	90.92	94.18
21.5	86.22	82.98	81.74	81.90	78.75	82.49	82.07	83.40	86.39
22.5	78.81	75.85	74.72	74.87	71.99	75.40	75.02	76.23	78.96
23.5	81.52	78.46	77.28	77.44	74.45	77.98	77.59	78.85	81.67
Ax. Avg.	**112.26**	**108.05**	**106.43**	**106.65**	**102.54**	**107.40**	**106.86**	**108.59**	**112.48**

Table A.6. Heat Flux Profile (W/cm^2) in Fresh LEU Element, Equilibrium Xe, Plate 4.

Axial position from top of fuel (inches)	Meat width	2.012	inches			Meat thickness		20	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.868 inches	0.868 to 1.144 inches	1.144 to 1.421 inches	1.421 to 1.618 inches	1.618 to 1.815 inches	1.815 to 2.012 inches
0.5	77.78	64.94	60.84	59.62	57.18	59.62	60.84	65.33	77.71
1.5	71.31	59.54	55.77	54.66	52.42	54.66	55.77	59.89	71.25
2.5	81.78	68.29	63.97	62.69	60.12	62.69	63.97	68.69	81.72
3.5	94.80	79.16	74.15	72.66	69.69	72.66	74.15	79.63	94.72
4.5	106.43	88.86	83.24	81.58	78.24	81.58	83.24	89.39	106.34
5.5	117.25	97.90	91.71	89.87	86.20	89.87	91.71	98.48	117.15
6.5	126.26	105.43	98.76	96.78	92.82	96.78	98.76	106.05	126.16
7.5	134.26	112.10	105.01	102.91	98.70	102.91	105.01	112.77	134.15
8.5	140.90	117.65	110.21	108.00	103.58	108.00	110.21	118.34	140.78
9.5	147.80	123.41	115.60	113.29	108.65	113.29	115.60	124.14	147.68
10.5	152.25	127.13	119.09	116.70	111.93	116.70	119.09	127.88	152.13
11.5	**153.80**	128.42	120.30	117.89	113.07	117.89	120.30	129.19	153.68
12.5	151.04	126.12	118.14	115.77	111.04	115.77	118.14	126.87	150.92
13.5	152.65	127.46	119.40	117.01	112.22	117.01	119.40	128.22	152.53
14.5	151.08	126.15	118.17	115.80	111.07	115.80	118.17	126.90	150.96
15.5	143.14	119.52	111.96	109.71	105.23	109.71	111.96	120.22	143.02
16.5	137.17	114.54	107.29	105.14	100.84	105.14	107.29	115.22	137.06
17.5	130.58	109.03	102.14	100.09	96.00	100.09	102.14	109.68	130.47
18.5	121.74	101.65	95.22	93.31	89.50	93.31	95.22	102.25	121.64
19.5	111.57	93.16	87.27	85.52	82.02	85.52	87.27	93.71	111.48
20.5	102.71	85.76	80.34	78.73	75.51	78.73	80.34	86.27	102.63
21.5	90.63	75.68	70.89	69.47	66.63	69.47	70.89	76.13	90.56
22.5	80.63	67.32	63.07	61.80	59.27	61.80	63.07	67.72	80.56
23.5	93.52	78.09	73.15	71.68	68.75	71.68	73.15	78.55	93.44
Ax. Avg.	**119.63**	**99.89**	**93.57**	**91.70**	**87.94**	**91.70**	**93.57**	**100.48**	**119.53**

Table A.7. Heat Flux Profile (W/cm^2) in Fresh LEU Element, Equilibrium Xe, Plate 22.

Axial position from top of fuel (inches)	Meat width	3.938	inches			Meat thickness	20	mil	
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.510 inches	1.510 to 2.428 inches	2.428 to 3.347 inches	3.347 to 3.544 inches	3.544 to 3.741 inches	3.741 to 3.938 inches
0.5	48.14	41.56	39.68	37.89	36.41	37.70	39.06	41.44	47.17
1.5	59.47	51.33	49.02	46.80	44.97	46.56	48.25	51.18	58.26
2.5	84.91	73.29	69.99	66.82	64.21	66.48	68.89	73.08	83.19
3.5	103.42	89.27	85.25	81.40	78.22	80.98	83.91	89.02	101.33
4.5	117.79	101.67	97.10	92.71	89.08	92.23	95.57	101.39	115.41
5.5	130.67	112.79	107.71	102.85	98.83	102.32	106.02	112.47	128.03
6.5	142.25	122.79	117.26	111.96	107.58	111.38	115.42	122.44	139.37
7.5	152.17	131.34	125.43	119.76	115.08	119.15	123.46	130.97	149.09
8.5	159.16	137.38	131.20	125.27	120.37	124.62	129.13	137.00	155.94
9.5	164.76	142.22	135.81	129.67	124.60	129.01	133.68	141.81	161.43
10.5	169.03	145.90	139.33	133.03	127.83	132.35	137.14	145.49	165.61
11.5	**170.81**	147.44	140.80	134.44	129.18	133.74	138.59	147.02	167.35
12.5	169.00	145.88	139.31	133.01	127.81	132.33	137.12	145.47	165.58
13.5	170.56	147.22	140.59	134.24	128.99	133.55	138.38	146.81	167.11
14.5	165.53	142.88	136.44	130.28	125.19	129.61	134.30	142.48	162.18
15.5	160.86	138.85	132.60	126.61	121.66	125.95	130.51	138.46	157.61
16.5	155.31	134.06	128.02	122.24	117.46	121.61	126.01	133.68	152.17
17.5	147.34	127.18	121.45	115.96	111.43	115.37	119.54	126.82	144.36
18.5	139.34	120.27	114.86	109.67	105.38	109.10	113.05	119.94	136.52
19.5	131.35	113.38	108.27	103.38	99.34	102.85	106.57	113.06	128.69
20.5	117.35	101.29	96.73	92.36	88.75	91.88	95.21	101.00	114.97
21.5	106.75	92.15	88.00	84.02	80.74	83.59	86.61	91.89	104.59
22.5	94.59	81.64	77.97	74.44	71.53	74.06	76.74	81.41	92.67
23.5	102.38	88.37	84.39	80.58	77.43	80.16	83.06	88.12	100.31
Ax. Avg.	**131.79**	**113.76**	**108.63**	**103.73**	**99.67**	**103.19**	**106.93**	**113.44**	**129.12**

Table A.8. Heat Flux Profile (W/cm^2) in Fresh LEU Element, Equilibrium Xe, Plate 23.

Axial position from top of fuel (inches)	Meat width	4.048	inches			Meat thickness		17	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.546 inches	1.546 to 2.502 inches	2.502 to 3.457 inches	3.457 to 3.654 inches	3.654 to 3.851 inches	3.851 to 4.048 inches
0.5	44.92	41.60	40.18	38.95	37.57	38.75	40.10	41.32	44.64
1.5	63.13	58.47	56.47	54.75	52.80	54.47	56.36	58.08	62.74
2.5	94.80	87.79	84.79	82.21	79.29	81.79	84.63	87.21	94.21
3.5	117.81	109.11	105.38	102.17	98.54	101.65	105.17	108.38	117.09
4.5	133.72	123.84	119.60	115.96	111.84	115.37	119.37	123.01	132.89
5.5	148.36	137.40	132.70	128.65	124.09	128.00	132.44	136.48	147.44
6.5	161.61	149.67	144.56	140.15	135.18	139.44	144.27	148.68	160.62
7.5	173.99	161.14	155.63	150.89	145.53	150.12	155.32	160.07	172.92
8.5	180.81	167.45	161.72	156.79	151.23	156.00	161.41	166.34	179.69
9.5	187.70	173.83	167.89	162.77	156.99	161.95	167.56	172.68	186.54
10.5	190.96	176.85	170.81	165.60	159.72	164.76	170.47	175.68	189.79
11.5	**192.95**	178.70	172.59	167.33	161.39	166.48	172.25	177.51	191.77
12.5	192.30	178.09	172.01	166.76	160.84	165.92	171.67	176.91	191.12
13.5	192.34	178.13	172.04	166.80	160.87	165.95	171.70	176.95	191.16
14.5	188.48	174.55	168.59	163.45	157.64	162.62	168.25	173.39	187.32
15.5	182.70	169.20	163.42	158.44	152.81	157.63	163.10	168.08	181.58
16.5	175.76	162.77	157.21	152.42	147.01	151.64	156.90	161.69	174.68
17.5	167.76	155.37	150.06	145.48	140.32	144.74	149.76	154.33	166.73
18.5	157.83	146.17	141.17	136.87	132.01	136.18	140.90	145.20	156.86
19.5	147.08	136.22	131.56	127.55	123.02	126.90	131.30	135.31	146.18
20.5	134.68	124.73	120.47	116.80	112.65	116.20	120.23	123.90	133.85
21.5	122.21	113.18	109.31	105.98	102.22	105.44	109.10	112.43	121.46
22.5	110.62	102.45	98.95	95.93	92.52	95.44	98.75	101.77	109.94
23.5	112.67	104.35	100.78	97.71	94.24	97.21	100.58	103.66	111.98
Ax. Avg.	**148.97**	**137.96**	**133.24**	**129.18**	**124.60**	**128.53**	**132.98**	**137.04**	**148.05**

Table A.9. Heat Flux Profile (W/cm^2) in LEU Element at 99 MWd, Equilibrium Xe, Plate 1.

Axial position from top of fuel (inches)	**Meat width**	**1.690**	**inches**			**Meat thickness**		**9**	**mil**
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.760 inches	0.760 to 0.930 inches	0.930 to 1.099 inches	1.099 to 1.296 inches	1.296 to 1.493 inches	1.493 to 1.690 inches
0.5	61.04	59.44	58.78	59.14	56.53	59.14	58.78	59.73	61.34
1.5	62.57	60.92	60.25	60.62	57.94	60.62	60.25	61.23	62.87
2.5	69.64	67.81	67.06	67.47	64.49	67.47	67.06	68.15	69.98
3.5	80.31	78.20	77.34	77.81	74.37	77.81	77.34	78.59	80.70
4.5	85.53	83.28	82.36	82.86	79.20	82.86	82.36	83.69	85.94
5.5	93.76	91.29	90.29	90.84	86.83	90.84	90.29	91.75	94.21
6.5	99.00	96.40	95.34	95.92	91.68	95.92	95.34	96.88	99.48
7.5	105.12	102.36	101.24	101.85	97.35	101.85	101.24	102.87	105.63
8.5	107.47	104.65	103.50	104.12	99.52	104.12	103.50	105.17	107.99
9.5	113.13	110.15	108.94	109.60	104.76	109.60	108.94	110.70	113.68
10.5	114.70	111.68	110.46	111.13	106.22	111.13	110.46	112.24	115.25
11.5	116.01	112.96	111.72	112.40	107.43	112.40	111.72	113.53	116.57
12.5	117.71	114.62	113.36	114.05	109.01	114.05	113.36	115.20	**118.29**
13.5	116.47	113.41	112.16	112.84	107.86	112.84	112.16	113.97	117.03
14.5	115.92	112.88	111.64	112.31	107.35	112.31	111.64	113.44	116.48
15.5	111.27	108.35	107.16	107.81	103.04	107.81	107.16	108.89	111.81
16.5	107.61	104.78	103.63	104.26	99.65	104.26	103.63	105.30	108.13
17.5	100.92	98.27	97.19	97.78	93.46	97.78	97.19	98.76	101.41
18.5	96.48	93.95	92.91	93.48	89.35	93.48	92.91	94.42	96.95
19.5	88.96	86.62	85.67	86.19	82.38	86.19	85.67	87.06	89.39
20.5	82.05	79.90	79.02	79.50	75.99	79.50	79.02	80.30	82.45
21.5	74.61	72.65	71.85	72.28	69.09	72.28	71.85	73.01	74.97
22.5	69.56	67.73	66.99	67.39	64.42	67.39	66.99	68.07	69.90
23.5	70.52	68.67	67.91	68.32	65.31	68.32	67.91	69.01	70.86
Ax. Avg.	**94.18**	**91.71**	**90.70**	**91.25**	**87.22**	**91.25**	**90.70**	**92.17**	**94.64**

Table A.10. Heat Flux Profile (W/cm^2) in LEU Element at 99 MWd, Equilibrium Xe, Plate 4.

Axial position from top of fuel (inches)	Meat width	2.012	inches			Meat thickness		20	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.868 inches	0.868 to 1.144 inches	1.144 to 1.421 inches	1.421 to 1.618 inches	1.618 to 1.815 inches	1.815 to 2.012 inches
0.5	73.83	62.74	60.19	58.44	56.39	58.26	59.50	62.68	74.21
1.5	68.20	57.96	55.60	53.99	52.09	53.81	54.97	57.90	68.55
2.5	78.80	66.97	64.24	62.38	60.18	62.18	63.51	66.90	79.20
3.5	91.14	77.45	74.29	72.14	69.60	71.91	73.45	77.37	91.60
4.5	102.30	86.94	83.40	80.98	78.13	80.72	82.45	86.85	102.82
5.5	112.04	95.21	91.33	88.68	85.56	88.40	90.29	95.11	112.60
6.5	121.11	102.92	98.73	95.87	92.49	95.56	97.60	102.82	121.72
7.5	128.00	108.77	104.34	101.32	97.75	100.99	103.15	108.66	128.64
8.5	133.48	113.43	108.81	105.66	101.94	105.32	107.57	113.32	134.16
9.5	139.72	118.73	113.90	110.60	106.71	110.24	112.60	118.62	140.43
10.5	141.02	119.84	114.96	111.63	107.70	111.27	113.65	119.72	141.74
11.5	143.64	122.07	117.10	113.70	109.70	113.34	115.76	121.95	144.37
12.5	143.71	122.12	117.15	113.75	109.75	113.39	115.81	122.00	144.43
13.5	143.82	122.22	117.24	113.85	109.84	113.48	115.91	122.10	**144.55**
14.5	141.60	120.33	115.43	112.08	108.14	111.73	114.12	120.21	142.32
15.5	137.17	116.56	111.82	108.58	104.76	108.23	110.55	116.45	137.86
16.5	130.39	110.80	106.29	103.21	99.58	102.88	105.08	110.69	131.05
17.5	121.73	103.45	99.23	96.36	92.97	96.05	98.10	103.34	122.35
18.5	115.31	97.99	94.00	91.27	88.06	90.98	92.93	97.89	115.89
19.5	104.54	88.84	85.22	82.75	79.84	82.49	84.25	88.75	105.07
20.5	96.73	82.20	78.85	76.56	73.87	76.32	77.95	82.12	97.22
21.5	86.33	73.36	70.38	68.34	65.93	68.12	69.58	73.29	86.77
22.5	75.08	63.80	61.21	59.43	57.34	59.24	60.51	63.74	75.46
23.5	89.77	76.29	73.18	71.06	68.56	70.83	72.35	76.21	90.22
Ax. Avg.	**113.31**	**96.29**	**92.37**	**89.69**	**86.54**	**89.41**	**91.32**	**96.20**	**113.88**

Table A.11. Heat Flux Profile (W/cm^2) in LEU Element at 99 MWd, Equilibrium Xe, Plate 22.

Axial position from top of fuel (inches)	Meat width	3.938	inches			Meat thickness		20	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.510 inches	1.510 to 2.428 inches	2.428 to 3.347 inches	3.347 to 3.544 inches	3.544 to 3.741 inches	3.741 to 3.938 inches
0.5	37.13	33.14	31.59	31.02	30.29	30.92	31.59	32.73	37.01
1.5	52.28	46.66	44.47	43.67	42.64	43.54	44.47	46.08	52.10
2.5	80.07	71.47	68.12	66.89	65.32	66.68	68.12	70.58	79.80
3.5	99.62	88.91	84.74	83.21	81.26	82.96	84.74	87.80	99.28
4.5	113.84	101.61	96.85	95.10	92.86	94.81	96.85	100.34	113.46
5.5	125.84	112.32	107.05	105.12	102.65	104.80	107.05	110.92	125.42
6.5	135.74	121.15	115.47	113.39	110.72	113.04	115.47	119.64	135.28
7.5	144.83	129.26	123.21	120.98	118.14	120.61	123.21	127.66	144.34
8.5	148.92	132.91	126.68	124.39	121.47	124.01	126.68	131.26	148.41
9.5	154.63	138.01	131.54	129.17	126.13	128.77	131.54	136.29	154.10
10.5	156.88	140.01	133.45	131.04	127.96	130.64	133.45	138.27	156.34
11.5	157.96	140.98	134.38	131.95	128.85	131.55	134.38	139.23	157.43
12.5	**158.01**	141.02	134.42	131.99	128.89	131.59	134.42	139.27	157.47
13.5	157.02	140.13	133.57	131.16	128.08	130.76	133.57	138.39	156.48
14.5	153.21	136.74	130.33	127.98	124.97	127.58	130.33	135.04	152.68
15.5	149.70	133.61	127.35	125.05	122.11	124.67	127.35	131.95	149.19
16.5	143.10	127.71	121.73	119.53	116.73	119.17	121.73	126.13	142.61
17.5	137.11	122.37	116.64	114.53	111.84	114.18	116.64	120.85	136.64
18.5	129.70	115.76	110.33	108.34	105.80	108.01	110.33	114.32	129.26
19.5	118.70	105.94	100.97	99.15	96.82	98.85	100.97	104.62	118.29
20.5	109.75	97.95	93.36	91.68	89.52	91.39	93.36	96.73	109.37
21.5	98.35	87.78	83.66	82.15	80.22	81.90	83.66	86.68	98.01
22.5	88.02	78.55	74.87	73.52	71.79	73.30	74.87	77.58	87.72
23.5	94.27	84.14	80.20	78.75	76.90	78.51	80.20	83.09	93.95
Ax. Avg.	**122.70**	**109.50**	**104.37**	**102.49**	**100.08**	**102.18**	**104.37**	**108.14**	**122.28**

Table A.12. Heat Flux Profile (W/cm^2) in LEU Element at 99 MWd, Equilibrium Xe, Plate 23.

Axial position from top of fuel (inches)	Meat width	4.048	inches			Meat thickness	17	mil	
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.546 inches	1.546 to 2.502 inches	2.502 to 3.457 inches	3.457 to 3.654 inches	3.654 to 3.851 inches	3.851 to 4.048 inches
0.5	32.47	30.67	30.16	29.74	29.05	29.80	30.01	30.64	32.53
1.5	54.75	51.72	50.86	50.15	48.99	50.25	50.61	51.67	54.85
2.5	86.78	81.98	80.61	79.49	77.65	79.65	80.21	81.90	86.94
3.5	111.75	105.56	103.81	102.36	99.99	102.57	103.29	105.46	111.96
4.5	125.74	118.77	116.80	115.17	112.50	115.40	116.22	118.66	125.97
5.5	139.12	131.42	129.23	127.43	124.48	127.69	128.59	131.29	139.38
6.5	146.81	138.68	136.38	134.48	131.36	134.75	135.70	138.55	147.09
7.5	157.26	148.55	146.08	144.04	140.70	144.33	145.35	148.40	157.55
8.5	162.07	153.10	150.55	148.46	145.01	148.76	149.80	152.95	162.37
9.5	166.41	157.19	154.58	152.42	148.89	152.73	153.81	157.03	166.71
10.5	167.87	158.57	155.94	153.76	150.20	154.07	155.16	158.42	168.18
11.5	169.34	159.95	157.30	155.11	151.51	155.42	156.51	159.80	**169.65**
12.5	169.07	159.70	157.05	154.86	151.27	155.17	156.27	159.54	169.38
13.5	166.03	156.84	154.23	152.08	148.56	152.39	153.46	156.68	166.34
14.5	164.10	155.01	152.43	150.31	146.83	150.61	151.67	154.86	164.40
15.5	160.24	151.36	148.85	146.77	143.37	147.07	148.11	151.21	160.53
16.5	153.66	145.14	142.73	140.75	137.48	141.03	142.02	145.00	153.94
17.5	147.70	139.51	137.20	135.29	132.15	135.56	136.51	139.38	147.97
18.5	141.14	133.32	131.11	129.28	126.29	129.55	130.46	133.19	141.40
19.5	130.88	123.62	121.57	119.88	117.10	120.12	120.97	123.50	131.12
20.5	120.82	114.13	112.23	110.67	108.11	110.89	111.68	114.02	121.05
21.5	108.32	102.32	100.62	99.22	96.92	99.42	100.12	102.22	108.52
22.5	99.07	93.59	92.03	90.75	88.65	90.93	91.57	93.49	99.26
23.5	101.68	96.05	94.45	93.14	90.98	93.32	93.98	95.95	101.87
Ax. Avg.	**132.63**	**125.28**	**123.20**	**121.48**	**118.67**	**121.73**	**122.59**	**125.16**	**132.87**

Table A.13. Heat Flux Profile (W/cm^2) in LEU Element at 174 MWd, Equilibrium Xe, Plate 1.

Axial position from top of fuel (inches)	Meat width	1.690	inches		Meat thickness		9	mil	
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.760 inches	0.760 to 0.930 inches	0.930 to 1.099 inches	1.099 to 1.296 inches	1.296 to 1.493 inches	1.493 to 1.690 inches
0.5	56.01	54.81	53.83	54.21	51.76	54.43	54.16	54.32	55.35
1.5	56.45	55.24	54.25	54.64	52.17	54.86	54.58	54.75	55.79
2.5	62.64	61.30	60.21	60.63	57.90	60.88	60.57	60.76	61.91
3.5	72.84	71.29	70.02	70.51	67.33	70.79	70.44	70.65	72.00
4.5	76.04	74.41	73.08	73.60	70.28	73.89	73.53	73.75	75.15
5.5	82.35	80.59	79.15	79.71	76.12	80.03	79.63	79.87	81.39
6.5	84.19	82.39	80.92	81.49	77.81	81.82	81.41	81.66	83.21
7.5	89.82	87.90	86.33	86.94	83.02	87.29	86.86	87.12	88.77
8.5	90.39	88.46	86.88	87.49	83.55	87.85	87.41	87.67	89.34
9.5	96.32	94.27	92.58	93.24	89.03	93.61	93.14	93.42	95.20
10.5	95.60	93.56	91.88	92.53	88.36	92.91	92.44	92.72	94.48
11.5	98.55	96.44	94.72	95.39	91.09	95.77	95.30	95.58	97.40
12.5	**98.81**	96.70	94.97	95.65	91.33	96.03	95.55	95.84	97.66
13.5	96.70	94.64	92.95	93.60	89.38	93.98	93.51	93.79	95.58
14.5	96.86	94.80	93.10	93.76	89.53	94.14	93.67	93.95	95.74
15.5	92.60	90.63	89.01	89.64	85.59	90.00	89.55	89.82	91.53
16.5	91.06	89.11	87.52	88.14	84.16	88.49	88.05	88.32	90.00
17.5	85.34	83.52	82.02	82.60	78.88	82.94	82.52	82.77	84.34
18.5	82.48	80.72	79.28	79.84	76.23	80.16	79.76	80.00	81.52
19.5	75.61	73.99	72.67	73.18	69.88	73.48	73.11	73.33	74.72
20.5	73.50	71.93	70.65	71.15	67.94	71.43	71.08	71.29	72.65
21.5	66.85	65.42	64.25	64.71	61.78	64.97	64.64	64.84	66.07
22.5	62.63	61.29	60.20	60.62	57.89	60.87	60.56	60.74	61.90
23.5	63.39	62.04	60.93	61.36	58.59	61.61	61.30	61.48	62.65
Ax. Avg.	**81.13**	**79.39**	**77.98**	**78.53**	**74.98**	**78.84**	**78.45**	**78.68**	**80.18**

Table A.14. Heat Flux Profile (W/cm^2) in LEU Element at 174 MWd, Equilibrium Xe, Plate 4.

Axial position from top of fuel (inches)	Meat width	2.012	inches			Meat thickness		20	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 0.868 inches	0.868 to 1.144 inches	1.144 to 1.421 inches	1.421 to 1.618 inches	1.618 to 1.815 inches	1.815 to 2.012 inches
0.5	72.22	62.22	58.72	57.80	55.41	58.11	58.72	62.40	71.67
1.5	64.69	55.73	52.60	51.77	49.63	52.05	52.60	55.89	64.19
2.5	75.32	64.89	61.24	60.28	57.79	60.60	61.24	65.08	74.75
3.5	89.36	76.98	72.65	71.52	68.55	71.90	72.65	77.21	88.67
4.5	97.23	83.76	79.05	77.81	74.59	78.23	79.05	84.01	96.48
5.5	107.29	92.43	87.23	85.87	82.31	86.32	87.23	92.70	106.47
6.5	115.39	99.41	93.82	92.35	88.52	92.84	93.82	99.70	114.50
7.5	122.38	105.44	99.51	97.95	93.89	98.47	99.51	105.75	121.45
8.5	127.65	109.98	103.79	102.17	97.94	102.71	103.79	110.30	126.68
9.5	133.07	114.64	108.20	106.50	102.09	107.07	108.20	114.98	132.05
10.5	135.18	116.46	109.91	108.19	103.71	108.76	109.91	116.80	134.15
11.5	138.99	119.74	113.01	111.24	106.63	111.83	113.01	120.09	137.92
12.5	**139.03**	119.78	113.05	111.27	106.67	111.87	113.05	120.13	137.97
13.5	136.72	117.79	111.17	109.42	104.89	110.00	111.17	118.14	135.68
14.5	133.10	114.67	108.22	106.53	102.12	107.09	108.22	115.01	132.09
15.5	127.24	109.62	103.45	101.83	97.62	102.37	103.45	109.94	126.26
16.5	124.00	106.83	100.82	99.24	95.13	99.77	100.82	107.15	123.05
17.5	118.04	101.69	95.97	94.47	90.56	94.97	95.97	101.99	117.13
18.5	109.86	94.64	89.32	87.92	84.28	88.39	89.32	94.92	109.02
19.5	101.68	87.60	82.67	81.38	78.01	81.81	82.67	87.86	100.90
20.5	92.51	79.70	75.22	74.04	70.97	74.43	75.22	79.93	91.80
21.5	84.05	72.41	68.34	67.27	64.48	67.63	68.34	72.63	83.41
22.5	75.61	65.14	61.48	60.51	58.01	60.83	61.48	65.33	75.03
23.5	87.43	75.32	71.09	69.97	67.08	70.35	71.09	75.55	86.76
Ax. Avg.	**108.67**	**93.62**	**88.36**	**86.97**	**83.37**	**87.43**	**88.36**	**93.90**	**107.84**

Table A.15. Heat Flux Profile (W/cm^2) in LEU Element at 174 MWd, Equilibrium Xe, Plate 22.

Axial position from top of fuel (inches)	Meat width	3.938	inches		Meat thickness		20	mil
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.510 inches	1.510 to 2.428 inches	2.428 to 3.347 inches	3.347 to 3.544 inches	3.544 to 3.741 inches	3.741 to 3.938 inches
0.5	36.86	32.85	31.64	31.19	30.68	31.54	32.18	33.53	37.50
1.5	51.42	45.83	44.14	43.51	42.80	44.00	44.90	46.77	52.31
2.5	78.59	70.05	67.46	66.50	65.41	67.25	68.62	71.49	79.95
3.5	97.10	86.55	83.35	82.17	80.82	83.09	84.78	88.32	98.78
4.5	108.18	96.43	92.86	91.55	90.04	92.58	94.46	98.41	110.06
5.5	121.53	108.33	104.32	102.84	101.15	104.00	106.11	110.55	123.64
6.5	128.23	114.30	110.07	108.51	106.73	109.73	111.96	116.64	130.46
7.5	136.56	121.73	117.23	115.56	113.67	116.87	119.24	124.23	138.94
8.5	141.32	125.97	121.31	119.59	117.62	120.94	123.39	128.55	143.78
9.5	147.27	131.28	126.41	124.62	122.58	126.03	128.59	133.96	149.83
10.5	149.07	132.88	127.96	126.15	124.07	127.57	130.16	135.60	151.66
11.5	149.81	133.54	128.60	126.77	124.69	128.21	130.81	136.28	**152.42**
12.5	148.92	132.75	127.83	126.02	123.95	127.45	130.03	135.47	151.51
13.5	146.74	130.80	125.96	124.18	122.14	125.58	128.13	133.48	149.29
14.5	144.61	128.91	124.13	122.37	120.36	123.75	126.27	131.54	147.12
15.5	141.46	126.10	121.43	119.71	117.74	121.06	123.52	128.68	143.92
16.5	137.06	122.17	117.65	115.98	114.08	117.29	119.67	124.67	139.44
17.5	130.80	116.59	112.28	110.69	108.87	111.94	114.21	118.98	133.07
18.5	124.07	110.59	106.50	104.99	103.26	106.17	108.33	112.86	126.22
19.5	113.95	101.58	97.82	96.43	94.85	97.52	99.50	103.66	115.93
20.5	105.27	93.84	90.36	89.08	87.62	90.09	91.91	95.76	107.10
21.5	93.97	83.76	80.66	79.52	78.21	80.42	82.05	85.48	95.60
22.5	84.63	75.44	72.65	71.62	70.44	72.42	73.90	76.98	86.10
23.5	90.81	80.94	77.95	76.84	75.58	77.71	79.29	82.60	92.38
Ax. Avg.	**117.01**	**104.30**	**100.44**	**99.02**	**97.39**	**100.13**	**102.17**	**106.44**	**119.04**

Table A.16. Heat Flux Profile (W/cm^2) in LEU Element at 174 MWd, Equilibrium Xe, Plate 23.

Axial position from top of fuel (inches)	Meat width	4.048	inches			Meat thickness	17	mil	
	0.000 to 0.197 inches	0.197 to 0.394 inches	0.394 to 0.591 inches	0.591 to 1.546 inches	1.546 to 2.502 inches	2.502 to 3.457 inches	3.457 to 3.654 inches	3.654 to 3.851 inches	3.851 to 4.048 inches
0.5	32.24	30.53	30.05	29.72	29.24	29.96	30.23	30.77	32.45
1.5	53.40	50.57	49.77	49.22	48.43	49.62	50.07	50.97	53.75
2.5	83.98	79.52	78.26	77.40	76.15	78.03	78.73	80.14	84.53
3.5	106.61	100.94	99.35	98.26	96.67	99.06	99.95	101.74	107.30
4.5	115.98	109.82	108.09	106.90	105.17	107.77	108.74	110.69	116.74
5.5	130.38	123.45	121.51	120.17	118.23	121.14	122.24	124.42	131.23
6.5	132.69	125.64	123.67	122.31	120.33	123.30	124.41	126.63	133.56
7.5	142.95	135.36	133.22	131.76	129.63	132.82	134.02	136.42	143.88
8.5	146.11	138.35	136.17	134.67	132.50	135.76	136.99	139.44	147.07
9.5	150.82	142.81	140.56	139.01	136.76	140.14	141.40	143.93	151.80
10.5	150.84	142.83	140.58	139.04	136.79	140.16	141.43	143.96	151.83
11.5	152.47	144.37	142.10	140.54	138.26	141.67	142.95	145.51	**153.47**
12.5	150.28	142.30	140.06	138.52	136.28	139.64	140.90	143.42	151.26
13.5	149.54	141.59	139.36	137.83	135.60	138.94	140.20	142.71	150.51
14.5	148.01	140.15	137.94	136.43	134.22	137.53	138.77	141.25	148.98
15.5	142.24	134.68	132.56	131.10	128.98	132.16	133.36	135.74	143.17
16.5	140.81	133.33	131.23	129.79	127.69	130.84	132.02	134.38	141.73
17.5	132.24	125.21	123.24	121.89	119.91	122.87	123.98	126.20	133.10
18.5	129.09	122.23	120.31	118.98	117.06	119.95	121.03	123.20	129.93
19.5	119.51	113.17	111.38	110.16	108.38	111.05	112.05	114.06	120.29
20.5	112.45	106.48	104.80	103.65	101.97	104.48	105.43	107.31	113.18
21.5	100.16	94.84	93.35	92.32	90.83	93.07	93.91	95.59	100.82
22.5	91.52	86.66	85.29	84.35	82.99	85.04	85.80	87.34	92.12
23.5	94.14	89.14	87.73	86.77	85.36	87.47	88.26	89.84	94.75
Ax. Avg.	**121.19**	**114.75**	**112.94**	**111.70**	**109.89**	**112.60**	**113.62**	**115.65**	**121.98**

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