# Neutronic Analysis Capabilities for Conversion of the MIT Reactor to LEU Fuel

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## ABSTRACT

Neutronics capabilities have been expanded at MITR in support of the conversion to LEU fuel. A fuel management system MCODE-FM has been developed for the MCNP-ORIGEN coupling code MCODE to facilitate flexible shuffling of fuel and experiments. Nodal analyses have optimized appropriate power and depletion region discretization for routine core reload, tracking of fissile inventory, and safety analyses. MITR, which does not have a fixed core reloading pattern, uses flexible fuel management on an ongoing basis. Thus, as a part of these upgraded capabilities, fuel management was partially automated and MCODE updated from ORIGEN-2 to a parallelized ORIGEN-S interface. Transitional LEU-HEU conversion cores have also been modeled while LEU elements are being introduced to the core at each refueling. Analyses with these tools have shown that HEU experimental performance will be maintained with the use of monolithic U-10Mo LEU fuel and an upgrade in operating power from 6 MW to 7 MW. Subsequent thermal hydraulic analyses using peak LEU power distributions results in a limiting safety system setting power based on the onset of nucleate boiling of 7.7 MW.

Alternate LEU designs are also being investigated to improve fabricability. Current HEU plates, and LEU designs to date, have been finned with 10 mil deep grooves along the length of the coolant channel to increase heat transfer. However, plate fabrication may be improved by decreasing the groove depth to allow increased cladding thickness (and tolerances) under the fins. Potential designs are discussed which would optimize power peaking through the use of thinner foils. These would be incorporated in outer plates of elements since, in the designs to date, limiting power peaking has been found in the plate of depleted elements loaded adjacent to the heavy water reflector.

## 1. Introduction

The Massachusetts Institute of Technology Reactor (MITR) is a research reactor in Cambridge, Massachusetts designed primarily for experiments using neutron beam and in-core irradiation facilities.  It delivers a neutron flux comparable to current LWR power reactors in a compact 6 MWth core using Highly Enriched Uranium (HEU) fuel.

In the framework of non-proliferation policies, the international community presently aims to minimize the amount of nuclear material available that could be used for nuclear weapons. In this geopolitical context, most research and test reactors both domestic and international have started a program of conversion to the use of Low Enriched Uranium (LEU) fuel. International efforts conceived during Atoms for Peace in 1955 [1] began as a concerted program for Reduced Enrichment Research and Test Reactors (RERTR) starting in 1978 [2,3]. Fuels allowing higher uranium densities have enabled many reactors to convert to LEU and maintain performance [4,5]. Currently, a new type of LEU fuel based on a high-density alloy of uranium and molybdenum (UMo) is undergoing qualification testing, and is expected to allow the conversion of U.S. domestic high performance reactors like the MITR-II reactor [6].

The MITR core has a hexagonal design that contains twenty-seven fuel positions in three radial rings (A, B, and C), as shown in Figure 1. The core is light water moderated and cooled and is surrounded by a $D_2O$ reflector. Boron impregnated stainless steel control blades are located at the periphery of the core on each of the sides of the hexagon and have a total upward travel of 53 cm. In addition, fixed absorbers can be installed in the upper axial region of the core in a hexagonal configuration between the A and B rings as well as in three radial arms extending to the edge of the core.
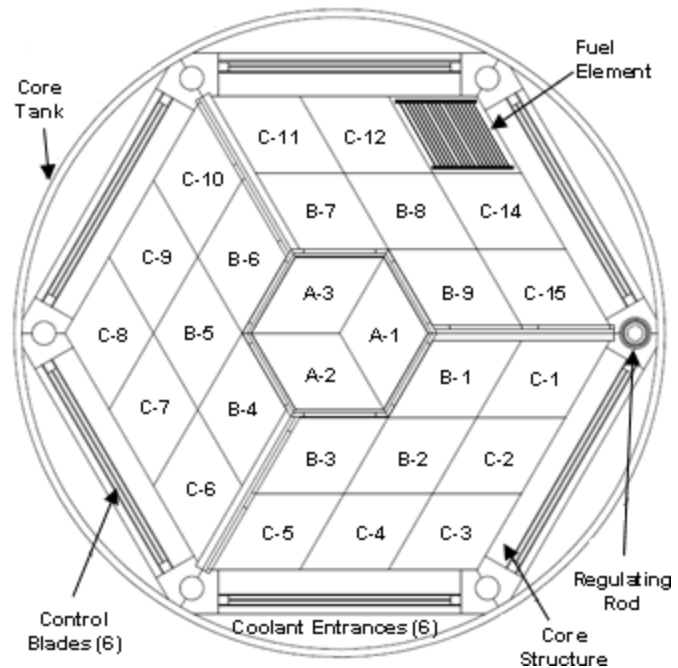


Figure 1. Layout of the MIT Reactor core.

MITR reactor fuel loading is very flexible, and typically at least three of these positions (two in the A-ring) are filled with either an in-core experimental facility or a solid aluminum dummy element to reduce power peaking. The remaining positions are filled with rhomboid-shaped MITR-II fuel elements. Each fuel element can be rotated, flipped, stored and returned to the core as needed over the course of 2-3 years.

## 2. HEU and LEU Fuel Designs

Each rhomboid-shaped fuel element contains fifteen aluminum-clad fuel plates using HEU (93% enriched) in an aluminide cermet matrix with a fuel thickness of 0.76 mm and a fueled length of 57 cm. The cladding of each fuel plate is 0.38 mm thick after machining 0.25 mm x 0.25 mm square fins along the length of the plate to increase heat transfer to the coolant. The fuel has an overall density of 3.8 g/cm$^3$, with a total loading of 508 g $^{235}$U in each element.

An LEU core has been redesigned so that the 15-plate HEU element is replaced by an 18-plate LEU element (see Figure 2) with a 0.51 mm U-10$^{wt}$%Mo 17g/cm$^3$ monolithic (*fuel*
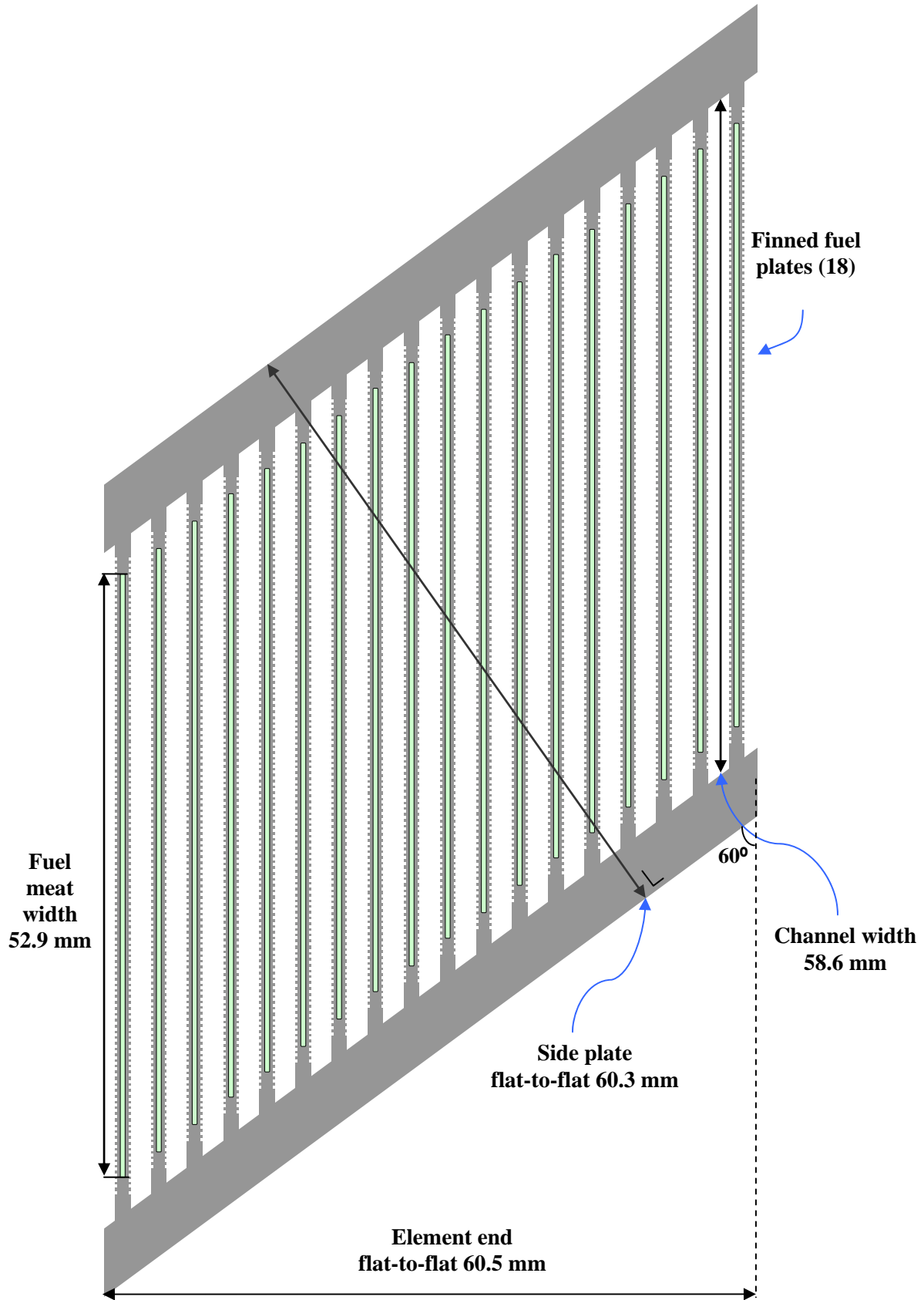
Figure 2. Schematic of MITR LEU fuel element drawn with 18 finned plates.

*formed from a single piece of a uranium alloy casting*) foil in 0.25 mm clad with 0.25 mm aluminum fins.  Heat transfer area provided by the addition of plates is offset by decreasing the water gap between plates from 1.98 mm to 1.83 mm in order that the element and core may remain otherwise unchanged [7].  As will be later discussed, alternate fuel plate designs are also under consideration.  These alternate designs would enhance the manufacturability of the LEU design by providing additional cladding (>0.25 mm) of the monolithic foil.


## 3.  Neutronic Modeling using MCODE

### 3.1 Neutronic Analysis and Verification

A number of neutronic models have been made for the MIT reactor. The Monte Carlo code MCNP has been used for many HEU and LEU core and experiment design studies. The basic reactor design and fuel structure has also been input into the MCNP-ORIGEN linkage code MCODE for fuel management and burnup evaluations [8]. Capabilities to study core and experimental loadings are very important for the MITR reactor since fuel loading is very adaptable.  MITR, which does not have a fixed core reloading pattern, uses flexible fuel management on an ongoing basis.  In addition to the symmetric fuel element which can be rotated and/or flipped for efficient fuel utilization, MITR loads a variable core configuration in which an adjustable number of in-core experimental, dummy and fueled elements are arranged among the 27 core loading positions.  Since there is no fixed core reloading, it is important to have versatile fuel management capabilities integrated with neutronic modeling to evaluate potential LEU, and analogous HEU, cores series as well as for ongoing fuel management.

As part of the LEU conversion of MITR, neutronic models have been developed and benchmarked, with good agreement to experimental data where modeled reactivity was within 1% of predicted critical states across a wide variety of fresh startup core physics testing in 1975-76, and twelve recent cores (BOC to EOC) operated in 2008-2009. Benchmarking of the MCODE model was performed as verification of model accuracy in order to prepare safety analyses and other information appropriate for conversion [9] [10] [11] [12] [13].

### 3.2 Integrated Fuel Management and Nodal Optimization

To allow studies such as these, the graphical user interface (GUI) has been designed and built into the MCODE model in a version called MCODE-FM [14], which includes the ability to model all aspects of fuel management at the MIT reactor, including fuel flipping, rotating and storage for later use. The latter capability includes an ORIGEN calculation of decay and tracking of relevant radioisotopes, including actinides. A criticality search algorithm can also be utilized so that the control blade motion can be modeled. The number of axial burnup nodes as well as fuel plate grouping can also be varied, depending on resolution and computational time needed.

As a part of nodal optimization of reactor analysis, additional capabilities have been added recently into MCODE-FM in order to provide an integrated data analysis management for MCODE-FM output [15]. MCODE-FM includes the ability to track and plot power peaking or number densities of any relevant isotope on a per node, per plate, or per assembly basis. Fuel assembly storage and reorientation have also been integrated have also been

implemented alongside automated nodalization of the MCODE-MCNP models which allows the user to divide plates, or set of plates, into any combination of axial or lateral (stripe) independently depleting regions. The benchmarked model was then used in a detailed study to explore the effect of depletion mesh discretization on simulation accuracy. A wide range of depletion discretizations were analyzed, as summarized in Figure 3 and Table 1. These explored both detailed effects required for safety analyses, as well as to determine a minimal mesh of depletion regions that would allow rapid iterative fuel management.
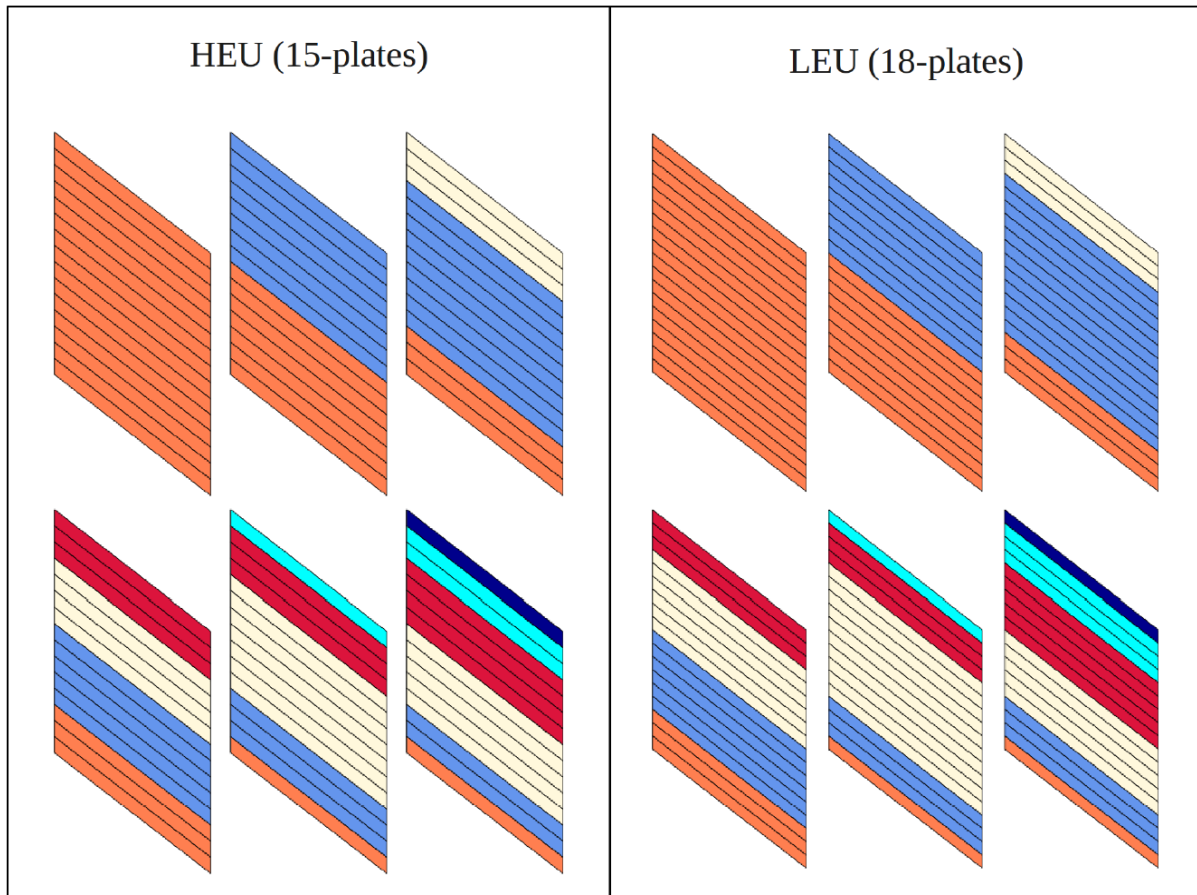


Figure 3. Radial plate depletion groupings studied for HEU and LEU fuel assemblies.

A range of plate groupings from one per element to six were investigated in this study. Independent depletion of plates on opposite ends of the elements (e.g. in the case of 6 radial divisions LEU plates 1 and 18 deplete independently) is important due to rotation, and also flipping whereby plates may be made parallel or transverse to the core center. Axial shape is important in MITR since power is bottom-peaked due to partially withdrawn control blades that separate the core from the heavy water reflector around and below the core. For this reason, elements are commonly flipped in order to evenly distribute burnup, and nodal depletion optimizations incorporated at least 6 axial divisions. For cases with lateral division of the plate, the fuel was divided along the 5.3 cm fuel width into 1.3 cm stripes. The selection of the lateral discretization is important, since power peaks at the edge of the plates. The 1.3 cm stripe was selected in order to account for the effect of lateral heat conduction, which mitigates the impact of power peaking found at the edge of the plate [12].

Discretization showed a negligible impact on total core fissile inventory (<0.1%) over the range of depletion regions. Local variations are however impacted where, as shown in Figure 4, the lateral striping is observed in the 16 axial/16 radial/4 stripe case.

Table 1. Discretization of the depleting zones and power regions to generate whole core 3-D power shapes in MITR HEU and LEU 24 element cores.

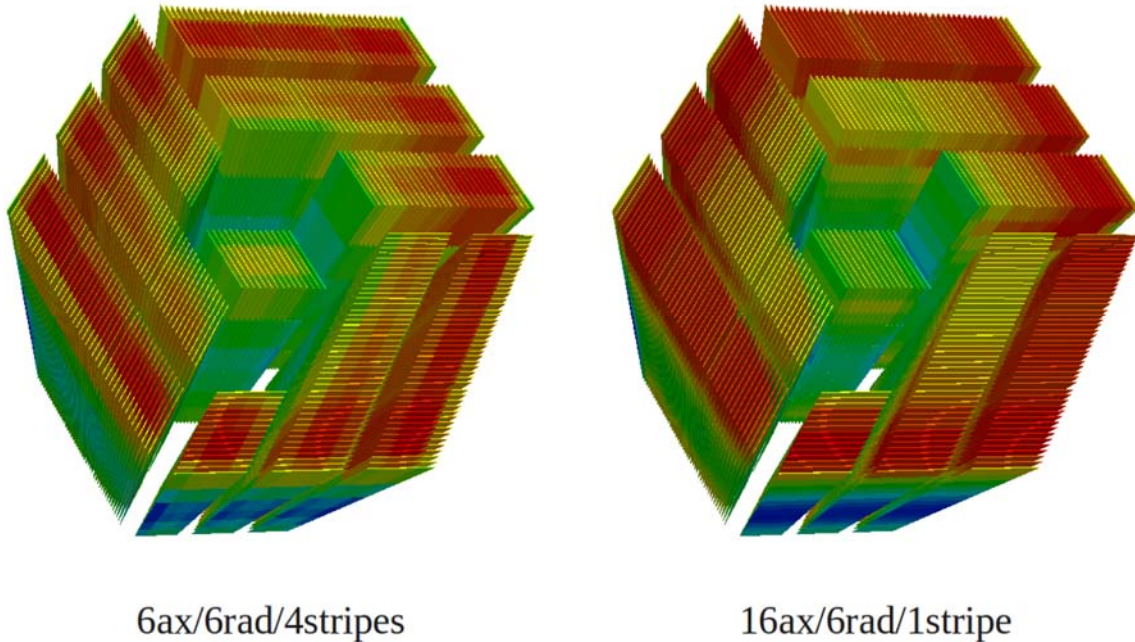| Regions | Geometry | Nodal Optimization of Depletion | Rapid Core Loading Optimization | Current LEU Safety Analyses [12] | |
|---|---|---|---|---|---|
| | | | | Depletion | Power Shape |
| Plate Division | Each plate discrete | 1 to 6 | 3 with independent outer plate | 6 groups | 15 (HEU) 18 (LEU) |
| Fuel Axial Division | Continuous | 6 to 32 | 8 | 6 | 18 |
| Fuel Plate Lateral Division | Continuous | 1 to 4 | 1 | 1 | 4 |
| Total per (LEU) Core | - | 100 ∼ 10000 | 576 | 864 | 31104 |



6ax/6rad/4stripes          16ax/6rad/1stripe

Figure 4. Top-down 3-D views of MITR colored by $^{235}$U density in each depletion region at the end of two HEU blades-out rundowns (red is highest normalized value in each core).

Local variations are more pronounced in each dimension with finer depletion meshes, and can lead to significant impacts on local fissile density. Figures 5-6 show the significant impact on $^{235}$U mass due to radial and lateral (stripe) discretization, respectively.
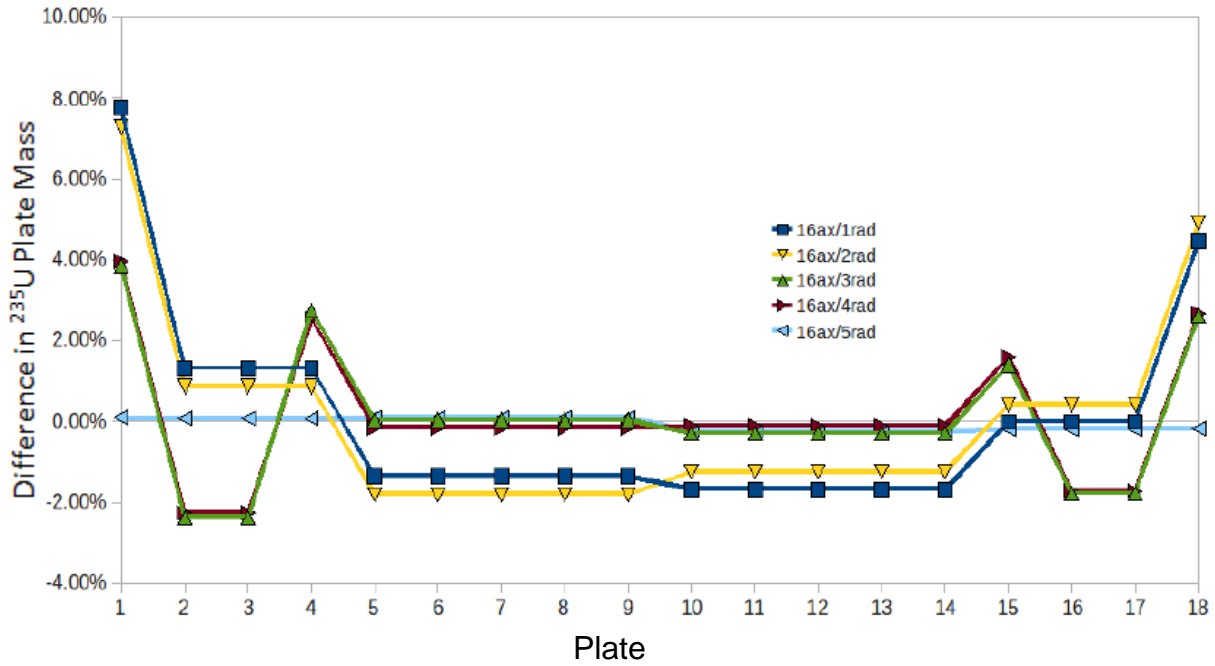


Figure 5. Difference in LEU plate $^{235}$U mass in hot assembly after rundowns with various plate groupings vs. mass from detailed (16 axial/6radial) case.
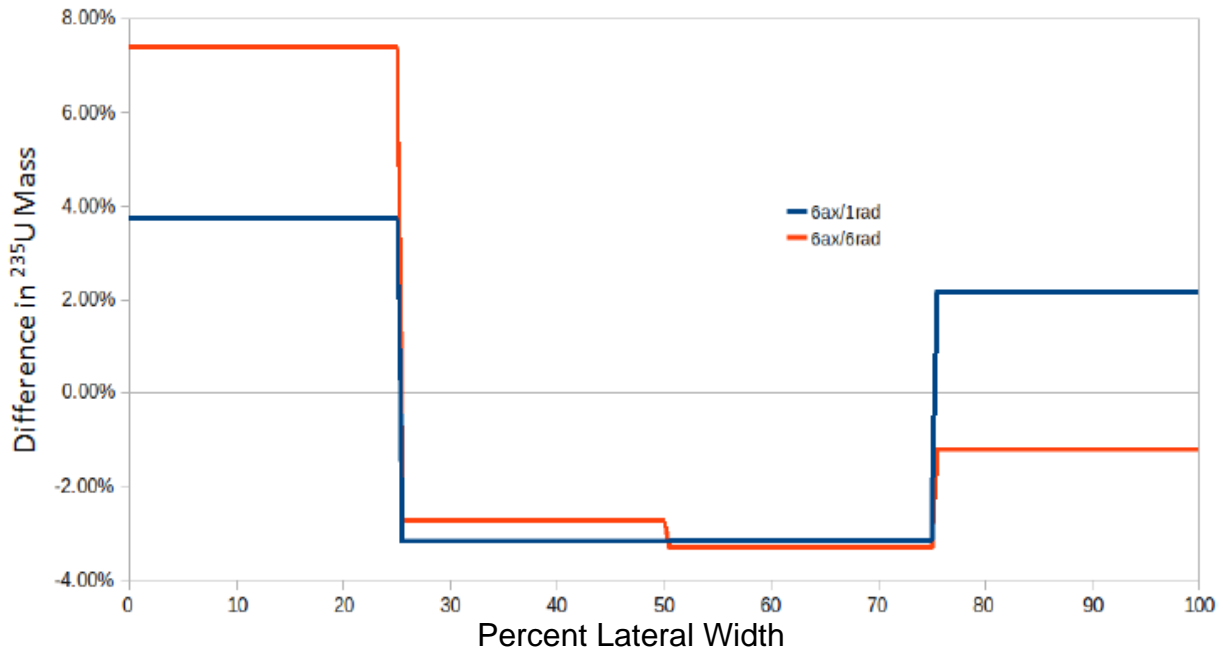


Figure 6. Difference in HEU $^{235}$U mass (at axial mid-plane) without lateral depletion compared to rundown with 4 lateral depleting regions.

Axial fission power shapes are shown in Figures 7-8. Note the similar curves for 1 or 6 radial plate groupings and 6 to 16 axial divisions for HEU and LEU. Since the most detailed depletions are not bounding, this indicates that a fine power distribution, as detailed in Table 1, should be used when detailed comparisons are needed to various coarse meshes.
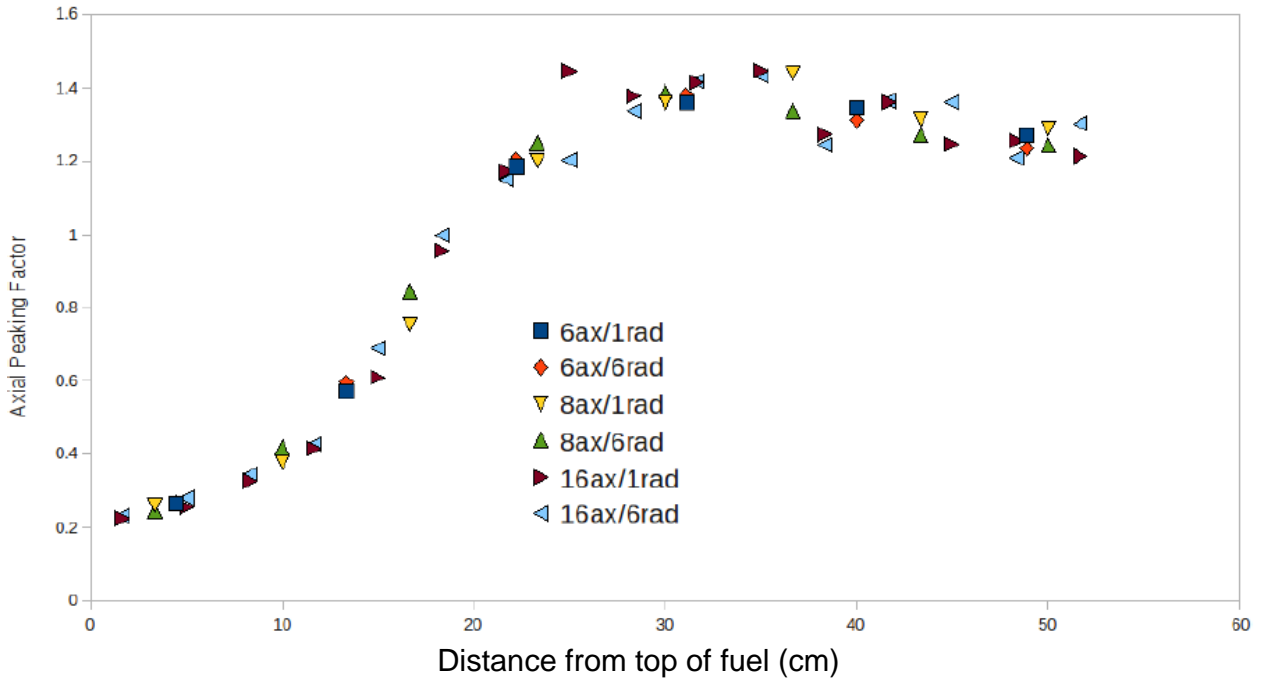


Figure 7. Fission power axial shape for hot plate from HEU cores 178-190, where the peaking factor is plotted at the midpoint of the depletion region.
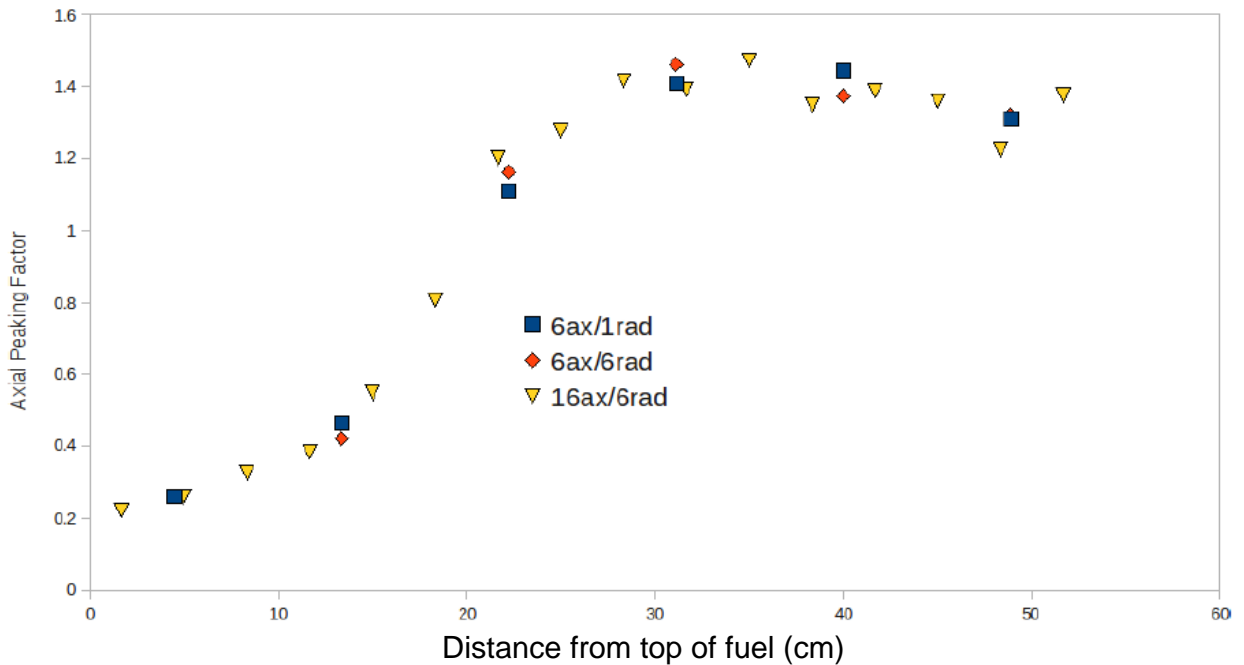


Figure 8. Fission power axial shape for hot plate from LEU cores 178-190, where the peaking factors are plotted at the axial midpoint of the depletion region.

This allows reasonable accuracy with 6-8 axial depletion regions, since for a range of very similar shapes, it is the overall hot stripe (axially-averaged) that has been found to be an important consideration for thermal hydraulic margins [16]. Section 4 will present overall hot stripe power distributions.

### 3.3 Integration of ORIGEN-S into MCODE-3

A new version of MCODE, MCODE-3, has also been created to update from ORIGEN-2 to a fully parallelized ORIGEN-S interface. In addition to the advancements available in ORIGEN-S, the parallelized interface implemented in MCODE-3 reduces the time-consuming ORIGEN calculations of $10^3$ to $10^4$ depletion regions and allowed depletions to proceed up to twice as fast. MCODE-3 depletion results of the MITR reactor are compared in Figure 9 to those of MCODE-2.2, and show that significant actinide densities agree well between the two versions. With the implementation of these enhancements, MCODE is now a capable integrated neutronic modeling system being used at MITR for routine fuel management calculations as well as the LEU power peaking and transitional cores discussed in the following sections.
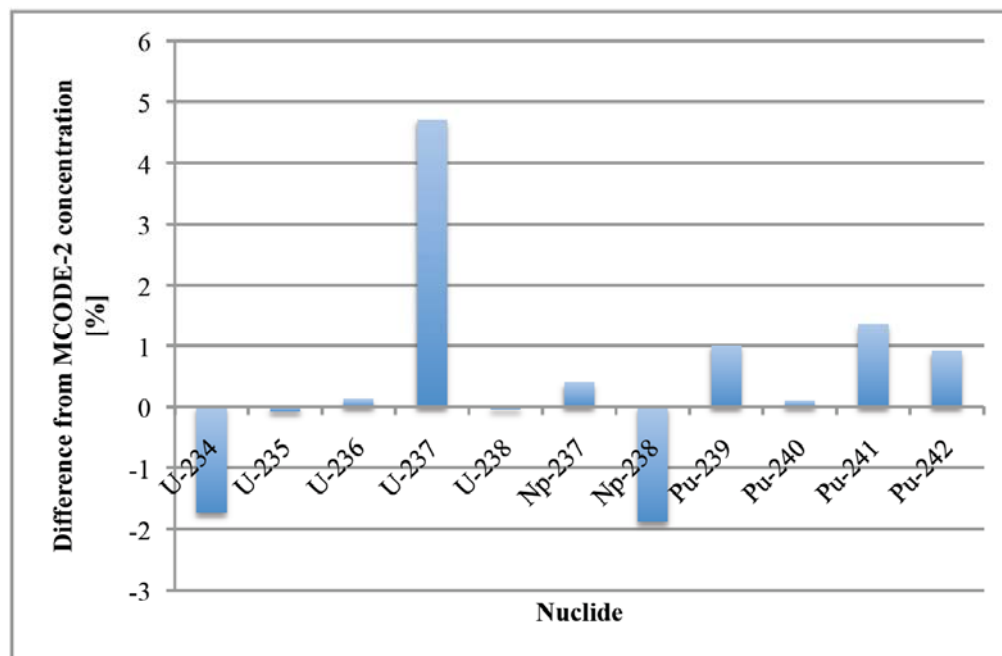


Figure 9. Comparison of MCODE-3 to MCODE-2 results for actinide densities of significant mass.

## 4.  LEU and Transition Core Power Distributions

### 4.1 LEU Core Power Peaking

As was discussed in Section 3.2, the depletion state of outer plates is important for MIT due to the flexible loading and rotation/flipping of elements. Limiting power is found in MITR, as shown in Figures 10-11, in the middle of life, when plates are first loaded into the C-ring alongside the heavy water reflector. The peak stripe factor of 2.12 the core average power is an increase of 63% compared to the same fuel plate when loaded fresh into the B-ring.
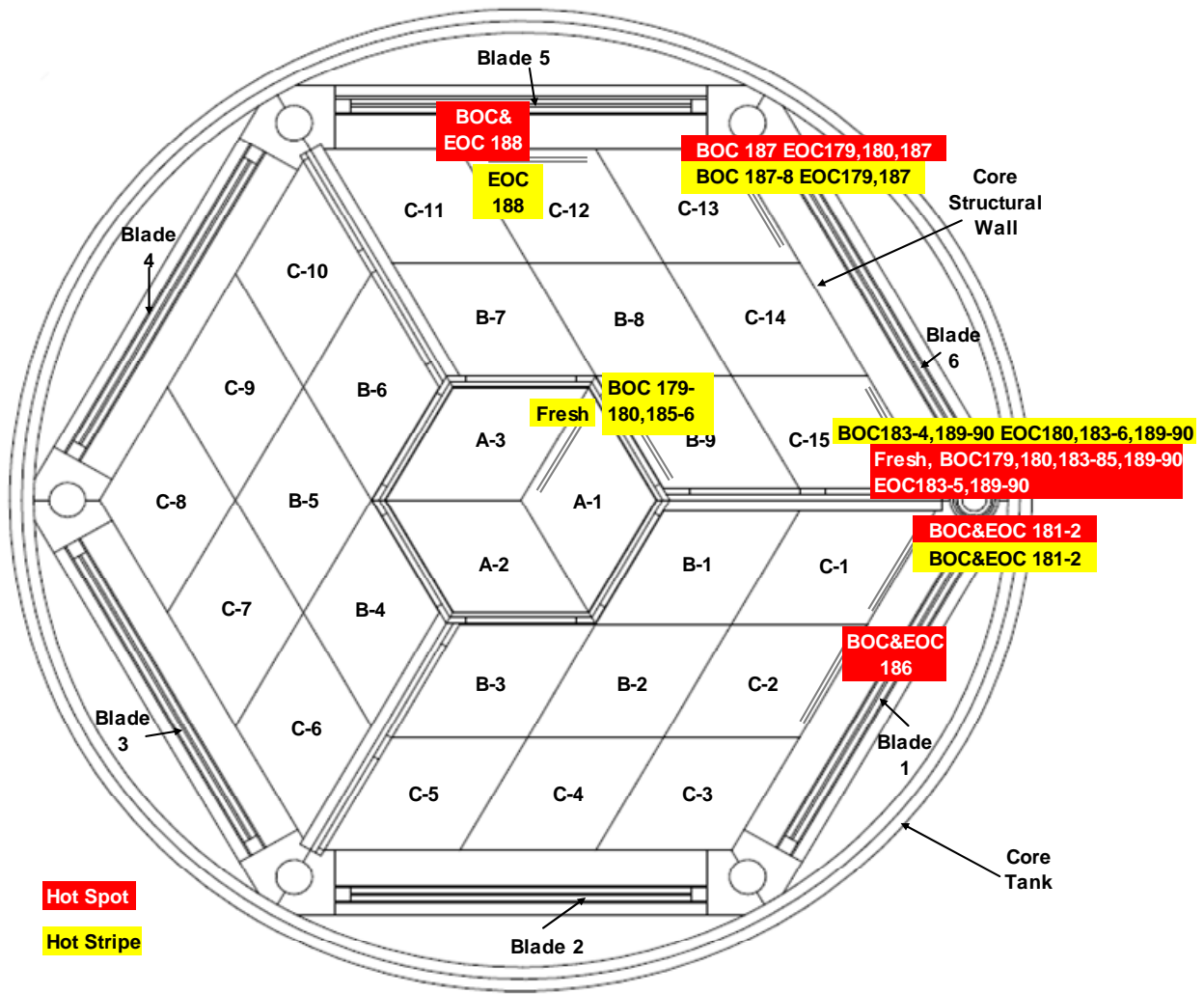
Figure 10. Peak power locations of LEU fresh and depleted Cores 178-190 at BOC and EOC (plate orietation indicated with parrallel lines).
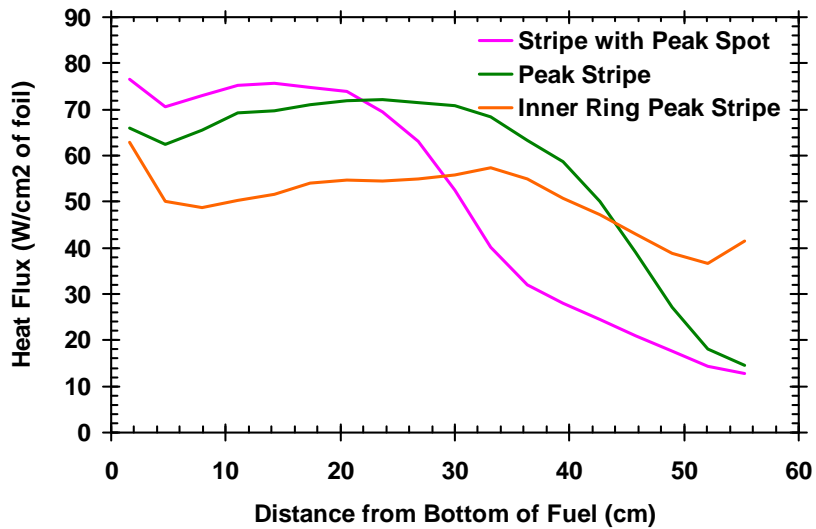


Figure 11. Peak power locations of LEU fresh and depleted cores at BOC and EOC, for peak location, peak stripe (C-ring), and inner ring (A/B-rings) peak stripe.

Analyses with these tools have shown that HEU experimental performance will be maintained with the use of monolithic U 10Mo LEU fuel and an upgrade in operating power from 6 MW to 7 MW. Subsequent thermal hydraulic analyses using peak LEU power distributions results in a limiting safety system setting power based on the onset of nucleate boiling of 7.7 MW [17]. Verification of thermal hydraulic limits is presently being integrated into this fuel management system in order to treat, on a whole core basis, the performance of core loading designs.

### 4.2 LEU Transitional Cores and Automated Fuel Management

The current plan for conversion of the MITR is to transition to an LEU-fueled core by introducing the LEU elements into the HEU-fueled reactor over a series of refuelings. HEU elements will be incrementally replaced with LEU, until the core is fully converted. In support of this approach, a series of transition core loading schemes were simulated, from three to eight new LEU elements being introduced at each cycle.

It was found that, in general, increasing burnup up to 830 MWD per cycle when possible reduced power peaking for most transition cores. Fortunately, with the introduction of a larger number of new LEU fuel elements and reuse of less burned HEU fuel, there is sufficient excess reactivity to sustain such an operation, which is roughly a factor of two higher in burnup than currently practiced with HEU fuel.

The ability to optimize fuel moves for a particular refueling has been added to the suite of MCODE features. A PYTHON program has been written that takes MCODE fuel data for in-core and stored elements and uses MITR fuel management correlations to optimize fuel movements to meet user inputs [18]. These user inputs include proposed cycle length, in-core experiments present, new fuel availability, and target maximum power peaking. This program gives the proposed fuel movements as well as approximate final control blade height and maximum power peaking within a few seconds. The user may then run MCODE to get final, accurate results for the proposed core. This capability currently exists for proposed LEU cores, but the inclusion of HEU fuel is planned.


## 5.    Future Work:  Improved LEU Design

Alternate LEU designs are also being investigated to improve manufacturability. Current HEU plates, and LEU designs to date, have 0.25 mm fins along the length of the coolant channel to increase heat transfer. However, the plate fabrication process may be improved by decreasing the fin height to allow increased cladding thickness under the fins. As discussed in Section 2, the proposed 0.25 mm LEU cladding is thinner than the 0.38 mm HEU cladding. In order to provide additional tolerances that may benefit the manufacturing process, an alternate design is being studied which would increasing the cladding thickness to 0.3 mm by decreasing the grooved fin depth while preserving the overall plate thickness from fin tip-tip.

The decreased fin size would result in a loss of heat transfer area, and adversely impact the thermal hydraulic margins, and so designs are under consideration to reduce power peaking through the use of thinner fuel foils. These would be incorporated in outer plates of elements since, in the designs to date, limiting power peaking has been found in the plate of depleted elements loaded adjacent to the heavy water reflector. Initial scoping studies of fresh cores have

incorporated thinner fuel foils in the outer fuel plates to compensate for heat transfer area lost by reducing the fin size. The 10% reductions in power peaking are anticipated to offset impact of lower heat transfer area. Optimization of these designs with series of depleted cores is underway.

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