RERTR 2008 — 30th INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 5-9, 2008
Hamilton Crowne Plaza Hotel
Washington, D.C. USA

PROGRESS MADE ON THE UNIVERSITY OF MISSOURI RESEARCH REACTOR HEU TO LEU FUEL CONVERSION FEASIBILITY STUDY

J. Charles McKibben, Dr. Kiratadas Kutikkad and Leslie P. Foyto
University of Missouri-Columbia Research Reactor
1513 Research Park Drive, Columbia, Missouri, 65211 – USA

ABSTRACT

The University of Missouri Research Reactor (MURR), the highest-powered (10 MW_{th}) University-operated research reactor in the U.S., is one of five U.S. high performance research reactors that is actively collaborating with the U.S. DOE to find a suitable LEU fuel replacement. A conversion feasibility study, using U-10Mo monolithic LEU fuel, is currently being performed in joint by MURR and ANL. Using broad scoping studies that were completed in 2007 with the transport code MCNP, a proposed optimal LEU core design was selected based on the following calculated parameters: power peaking factors, excess reactivity, and the fast and thermal fluxes available to the experimental facilities. The MURR fuel cycle, which consists of at least 24 fuel assemblies in the cycle at any one time, requires weekly replacement of all eight fuel assemblies in the core. In order to model burn-up calculations for this fuel cycle using the REBUS/DIF3D code, modification to the REBUS code was required and performed by ANL. The results of using the modified REBUS code to model the current HEU fuel cycle benchmark and the proposed LEU fuel cycle are included within this paper.

I. Introduction

This paper is the third in a series of papers discussing the feasibility of converting the facility's current highly-enriched uranium (HEU) fuel to low-enriched uranium (LEU) fuel. Because of its compact core design (33 liters), which requires a much higher loading density of ^{235}U, the University of Missouri Research Reactor (MURR) cannot perform its mission with any currently-qualified LEU densities. A BOLD VENTURE 3-D model, benchmarked against the only MURR destructively analyzed fuel element, was used in 1986 to demonstrate that a silicide LEU core loaded to density of 7.2 gU/cm^3, and with no fission product inventory, would result in a K_{eff} of less than 1.0 [1]. However, the MURR is actively collaborating with the Reduced Enrichment for Research and Test Reactors (RERTR) Program, and four other U.S. high-performance research reactors that use HEU fuel, to find a suitable LEU fuel replacement.

II. Facility Description and Basic Reactor Design

The MURR is a multi-disciplinary research and education facility providing a broad range of analytical and irradiation services. Scientific programs include research in archaeometry, epidemiology, health physics, human and animal nutrition, nuclear medicine, radiation effects, radioisotope studies, radiotherapy, and nuclear engineering; and research techniques including neutron activation analysis, neutron scattering, and neutron interferometry.

The reactor is a pressurized, light-water moderated and cooled, reflected, heterogeneous, open pool-type design, which first achieved criticality on October 13, 1966. The reactor was originally designed for 10 MW operation, but was initially licensed to operate at only 5 MW until reactor utilization and operating experience were sufficient to justify full power operation. In 1974, additional cooling equipment was added and the process instrumentation and reactor safety systems were modified as required to facilitate operation at the current full design power of 10 MW_{th}.

The reactor core assembly is located eccentrically within a cylindrically-shaped, aluminum-lined pool, approximately 10 feet (3.0 m) in diameter and 30 feet (9.1 m) deep. The reactor core consists of three major regions: fuel, control blade, and reflector. Horizontal and 3-D views of the reactor core assembly are shown in Figures 1 and 2, respectively.

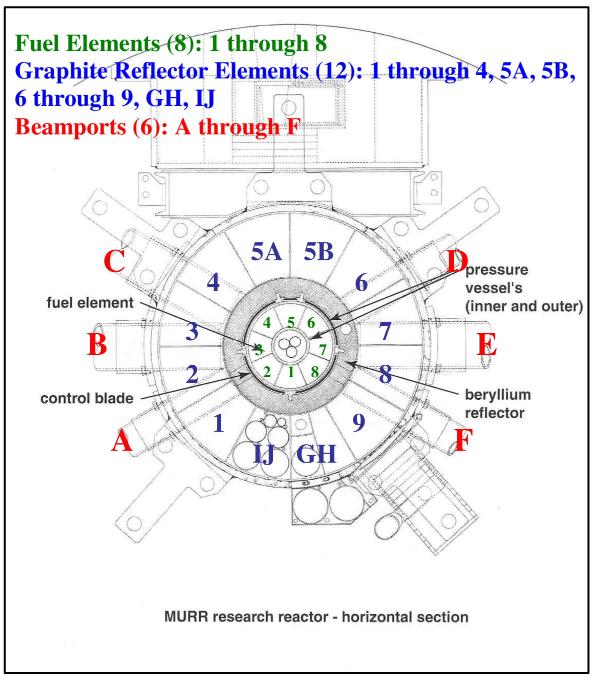

Figure 1
Reactor Core Assembly – Horizontal

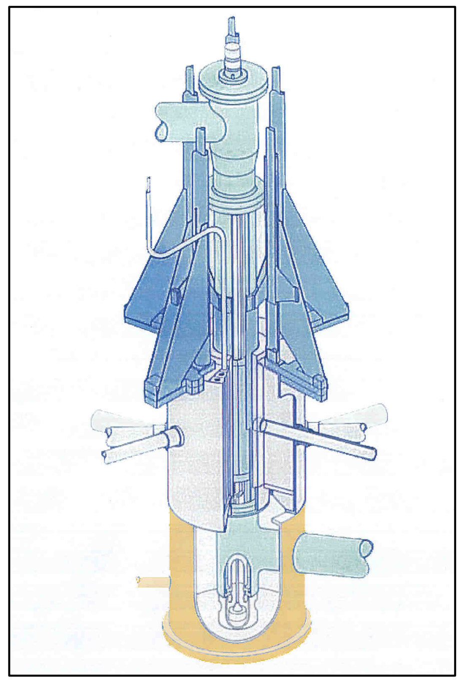

Figure 2
Reactor Core Assembly – 3D

The fuel region has a fixed geometry consisting of eight (8) fuel elements having identical physical dimensions placed vertically around an annulus in between two cylindrical aluminum reactor pressure vessels. Each fuel assembly is comprised of 24 circumferential plates containing uranium enriched to approximately 93% in the isotope ^{235}U as the fuel material. The control blade region is an annular gap between the outer pressure vessel and the inner reflector annulus, so that no penetration of the pressure vessels is required. Five (5) control blades – four (4) boral and one (1) stainless steel – operate vertically within this gap, controlling reactor power by varying neutron reflection. The reflector region consists of two concentric right circular annuluses surrounding the control blade region. The inner reflector annulus is a 2.71-inch (6.9 cm) thick solid sleeve of beryllium metal. The outer reflector annulus consists mostly of vertical elements of graphite canned in aluminum, having a total thickness of 8.89 inches (22.6 cm).

The following six experimental facilities support the facility's service and research programs: the center test hole (flux trap); the pneumatic tube system; the graphite reflector region; the bulk pool; the (six) beamports; and the thermal column. The first four provide areas for the placement of sample holders or carriers in different regions of the reactor assembly for the purposes of material irradiation. The beamports channel neutron radiation from the reactor core to experimental equipment that is used primarily to determine the structure and properties of solids through neutron scattering. The graphite thermal column is designed for the purpose of performing neutron radiographs and large sample irradiations.

III. Current Fuel Design and Operating Cycle

The current MURR 775-gram fuel element is a product of the UAl_x dispersion fuel system that was developed at the Idaho National Engineering Laboratory (INEL) for the high flux, high power Advanced Test Reactor (ATR) and subsequently used at the Materials Test Reactor (MTR) and the Engineering Test Reactor (ETR) prior to its use at the MURR [2] [3].

The fuel elements have an overall length of 32.5 inches (82.55 cm). Each element is longitudinally-symmetrical with 24 fuel bearing plates. The fuel plates are segments of concentric circles 0.050 inches (1.27 mm) thick separated by a coolant channel gap of 0.080 inches (2.03 mm). The fuel meat in each plate is 0.020 inches (0.508 mm) thick with 0.015 inches (0.38 mm) of aluminum cladding on each side. A drawing of the MURR fuel element is shown in Figure 3. Additional fuel element specifications can be found in Table 1, Section IV.

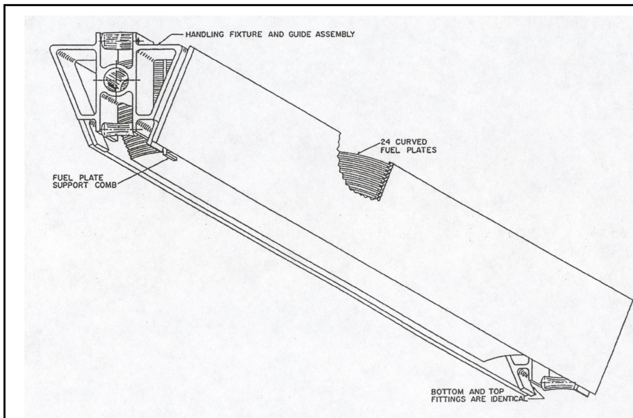

Figure 3
MURR Fuel Element – Pictorial View

The MURR operates continuously with the exception of a weekly scheduled shutdown. Over the past 31 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. The active fuel cycle typically consists of 32 fuel elements; corresponding to sixteen pairs of elements. 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. The compact core volume limits excess reactivity and causes the control blades to be fully withdrawn when the HEU core, with equilibrium xenon, achieves approximately 670 MWDs. This results in an HEU fuel element reaching a maximum burn-up of 150 MWDs, which in turn corresponds to a hot spot burn-up of less than 1.8E+21 fissions/cc. This ensures that the Technical Specification limit of 2.3E+21 fissions/cc is not approached or exceeded. Cores are usually loaded such that the average power history of a fuel element is approximately 75 MWDs. Typically a fuel element will be used in 18 to 20 different core loadings before being retired from the fuel cycle. A core with fuel elements approaching the burn-up limit will also include a corresponding number of elements with very low power history. This maximizes the number of MWDs obtainable per fuel element. This same approach is also planned for the LEU fuel cycle.

IV. Proposed LEU Core Design

To fully explore the possibilities of an LEU core design that could match or exceed current performance capabilities, the MURR tasked the RERTR Program to answer some key questions on the following fuel design/manufacturing limitations: peak burn-up, minimum thickness of the fuel meat and cladding, minimum thickness of the curved plate to ensure sufficient rigidness, and the magnitude of engineering peaking factors due to reducing the thickness of the fuel meat. From discussions over the past two years at the U.S. high-performance research reactor RERTR meetings in creating a proposed LEU core design, the facility used the following assumed answers to those questions:

- What is the peak fuel burn-up limit? ***~7E21 fissions/cc***
- How thin can acceptable U-10Mo foils be fabricated? ***0.005 inches (0.127 mm)***
- What is the minimum acceptable cladding thickness? ***0.010 inches (0.254 mm)***
- How thin can sufficiently rigid curved fuel plates be fabricated? ***0.038 inches (0.965 mm)***
- Magnitude of engineering peaking factors for thin U-10Mo foils? ***≤ UAl_x HEU factors***
- What is the minimum cladding blister temperature? ***850-900 °F (454-482 °C)***

The initial LEU scoping studies that resulted in the current proposed LEU core design were performed in 2006 and 2007 and covered in papers presented at the past two International RERTR meetings [4, 5]. The goal is to design and fabricate an LEU fuel element that will allow the reactor to operate at a power level that provides the same flux for the users as does the current HEU core, while also providing a fuel element with an operational life time as long as feasible to reduce operating costs. Therefore, the heat flux peaking factors for the proposed LEU core design were compared directly to that of the current HEU core. For MURR's HEU fuel with uniform fuel meat thickness, the power and heat flux peaking factors are approximately the same. However, for an LEU fuel element with variable meat thicknesses, the power peaking factors are decreased by the reduction factor of the fuel meat thickness to obtain the heat flux peaking factors. To select a proposed LEU core, various core designs were modeled in MCNP to determine the power and heat flux peaking factors. The fluxes in the center test hole and graphite reflector region irradiation positions were also determined. The proposed LEU core was selected based on comparing K_{eff}, fluxes, and heat flux peaking factors, with only the optimal proposed core included in Table 1.

To appreciate the differences between the HEU and LEU fuel designs, the HEU design will be briefly described. The HEU fuel design of 0.050-inch (1.270 mm) thick plates with 0.015-inch (0.381 mm) thick cladding is based on the initial tests for the ATR performed in the 1960's and early 1970's for improving the original MTR alloy fuel design to the current UAl_x dispersion fuel. With dispersion fuel fabrication methodology, there is more variation in the cladding thickness due to the number of times the plate must be rolled. There is also the concern of stray fuel particles being pressed into the cladding. Consequently, the cladding thickness is nominally 0.015 inches (0.381 mm) to ensure that the required minimal cladding thickness of 0.010 inches (0.254 mm) is achieved and that no stray fuel particles are within 0.008 inches (0.203 mm) of the cladding surface. Table 1 compares the current HEU fuel element with the proposed LEU fuel element design.

Table 1
Summary of MURR Fuel Element Specifications – Current and Proposed

Description	Current HEU Fuel	Proposed LEU Fuel
Fuel		
Material	UAl_x (mostly UAL_3)	U-10Mo
Enrichment	93% ^{235}U	19.75% ^{235}U
Thickness	0.020 inches (0.508 mm)	0.009 inches (0.229 mm) to 0.018 inches (0.457 mm)
Cladding		
Material	Aluminum	
Thickness	0.015 inches (0.381 mm)	0.010 inches (0.254 mm) to 0.020 inches (0.508 mm)
Fuel Assembly		
Number of Fuel Plates	24	
Overall Fuel Assembly Length	32.5 inches (82.550 cm)	
Overall Fuel Plate Length	25.5 inches (64.770 cm)	
Overall Active Fuel Length	24.0 inches (60.960 cm)	
Fuel Plate Thickness	0.050 inches (1.270 mm)	0.038 inches (0.965 mm) or 0.049 inches (1.245 mm)
Distance Between Plates (Coolant Channel)	0.080 inches (2.032 mm)	0.0916 inches (2.327 mm)
Maximum ^{235}U Loading	775 grams	1410 grams
Fuel Density	1.53 grams/cm^3	3.03 grams/cm^3
Weight	~ 6 Kg	~ 11 Kg

To better understand the proposed LEU fuel design, three figures are provided which compare power and heat flux peaking between the HEU and LEU fuel. Figure 4 illustrates the power peaking factors for the proposed LEU core consisting of eight fresh fuel elements with the control blades withdrawn 13 inches (half of the total withdrawal distance). The peaking factors are graphed for each fuel plate, with plate number-1 adjacent to the inner reactor pressure vessel and plate number-24 adjacent to the outer pressure vessel. The graph points correspond to the mid-point of each one-inch vertical segment

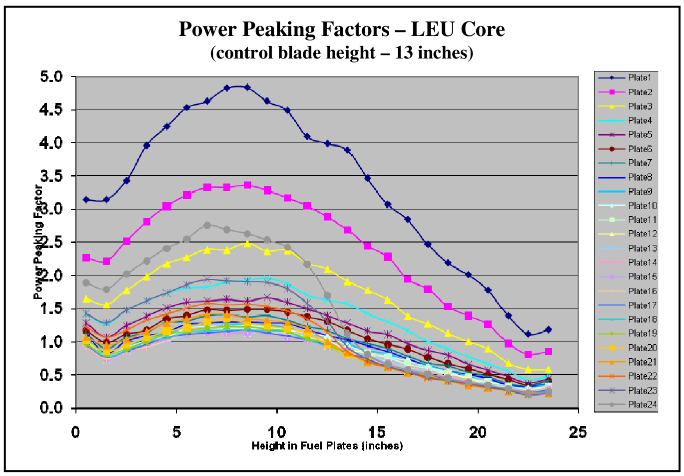

Figure 4
LEU Core Design – Power Peaking Factors

of the 24-inch long fuel meat, starting at 0.5 inches from the bottom to 23.5 inches at the top. The peaking factor is the average fission rate in that fuel volume divided by the average for the total fuel meat volume of that fuel element.

Figure 5 provides the same graphs for the HEU fuel element. In comparing Figures 4 and 5, plate number-1 has the highest power density in both cases, while the power peaking factor is about 1.5 times higher in the LEU fuel element than the HEU element. Plate number-2 has the next highest power peaking factor in both the LEU and HEU fuels. The high peak fuel burn-up limit for LEU fuel means that the high power peaking factors can be managed without needing to decrease the ^{235}U density to avoid limiting fuel element lifetime. However, to avoid the highest hot stripe heat flux peaking from limiting the safe operating power level, the thickness of the fuel meat in plate number-1, -2 and -24 was reduced to lower their hot stripe heat flux. Using this approach, the proposed core design consists of fuel meat thicknesses that vary by a factor of two.

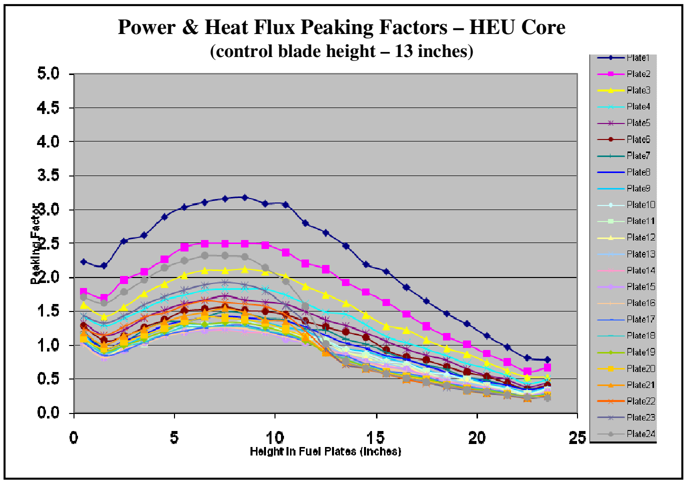

Figure 5
HEU Core Design – Peaking Factors

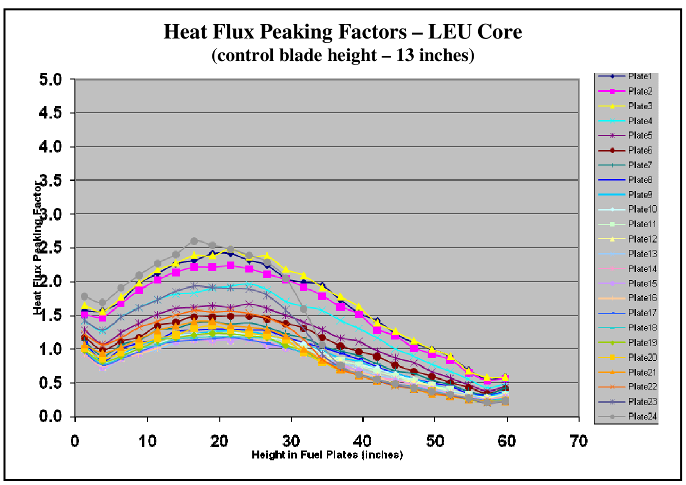

Figure 6
LEU Core Design – Heat Flux Peaking Factors

Figure 6 depicts the heat flux peaking factors for the LEU fuel element. Plate number-1 and -24 are 0.049 inches (1.245 mm) thick for the following two reasons: (1) the cladding on these plates are susceptible to being scratched, dented or bumped during fuel handling, and (2) the plates are located between coolant channels with different widths, thus potentially creating a differential pressure across the fuel plate. Plate number-1 has the thinnest fuel meat of 0.009 inches (0.229 mm) thick. Plate number-2 fuel meat thickness is 0.012 inches (mm) with a corresponding cladding thickness of 0.013 inches (mm). Plate number-24 has a fuel meat thickness of 0.017 inches (0.432 mm). All other plates are 0.038 inches (0.965 mm) thick and have a fuel meat thickness of 0.018 inches (0.457 mm) with corresponding 0.010-inch (0.254-mm) thick cladding, except for plate number-2.

The possible fabrication techniques for the new U-10Mo monolithic fuel plates should require less rolling. Additionally, the monolithic "foil fuel meat" should also substantially reduce or eliminate the chance of fuel particles being pressed into the cladding, thus allowing the 0.010-inch (0.254 mm) nominal cladding thickness. However, the fabrication methodologies must be further developed and tested before the thinnest allowable nominal cladding thickness can be confirmed. Flow validation tests also need to be performed to ensure that the 0.038-inch (0.965 mm) thick plates have sufficient stability and rigidness to fully withstand the hydraulic forces imposed by a primary coolant flow velocity of 25 ft/sec (7.6 m/sec). Plate stability may also vary depending on the relative thicknesses of the fuel meat and cladding, because their contribution to stiffness can differ. These values need to be determined to complete the optimum core design.

In Figures 4, 5 and 6, the control blades are half out (13-inch withdrawn position), which is approximately the critical position of a cold clean new core with 0 MWDs of power history. The LEU core fuel meat thicknesses have been reduced such that the maximum heat flux peaking factors are less than those of the current HEU core. With a desire to maintain current experimental performance and capabilities (i.e., flux levels), the goal is to obtain peaking factors that will allow a power upgrade to 12 MW. Note: The proposed LEU core was designed using only MCNP modeling with no burn-up history to evaluate K_{eff}, power distribution between the fuel plates and changes in flux levels in the experimental facilities.

V. Benchmarking of REBUS-DIF3D and REBUS-MCNP Modeling

To expand the evaluations to include fuel depletion, REBUS-DIF3D and REBUS-MCNP models of both the current HEU core and the proposed LEU core were developed. Beginning in 2007, Dr. John Stillman, Argonne National Laboratory (ANL), lead the work on the REBUS-DIF3D model, whereas Dr. John Stevens, ANL, directed the work on the REBUS-MCNP model. The HEU models are first being benchmarked against the K_{eff}'s of the initial critical tests performed in 1971 on the first MURR UAl_x dispersion core – identical to the current HEU fuel element. Due to security restrictions on the possession of unirradiated HEU, no additional 0 MWD critical measurements have been possible since the early 1980's. The critical benchmarking was coupled with benchmarking the depletion analysis against the burn-up data of fuel element 775-F3 from that first core. After the core had operated for 650 MWDs, fuel element 775-F3 was shipped to INEL for destructive analysis. All 24 plates were then gamma scanned longitudinally along the centerline to profile the burn-up in that element. In addition, five (5) samples were analyzed for burn-up employing the Nd-145, 146, and 148 isotope technique. The linear relationship between gamma activity and burn-up was used to convert the longitudinal scans to values in fissions/cc. It should be noted that all fuel elements in this core were flipped at

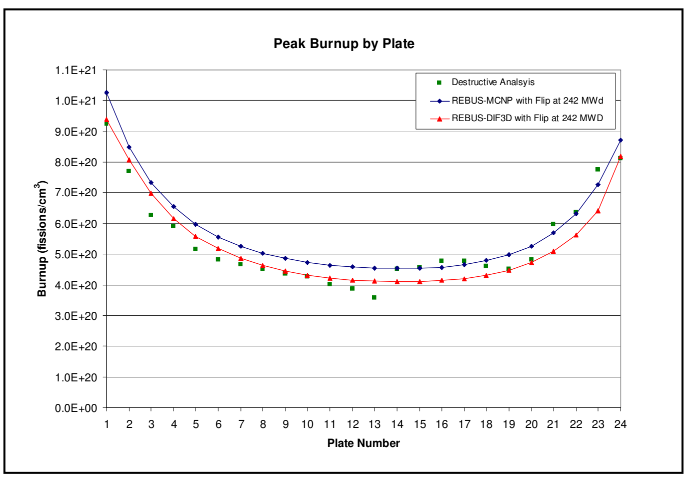

Figure 7
Comparison – Peak Burn-Up by Plate

242 MWDs. This was the only core where fuel elements were ever flipped.

Figure 7 shows the initial results that were used to verify agreement between the models and the measured values. There is close agreement between the predicted peak burn-up on each of the 24 fuel plates and their measured values. However, concerns were raised of the possible differences in the REBUS-DIF3D and REBUS-MCNP models which caused consistent differences for each plate. The need to further refine the models in order to improve this agreement was realized just before Dr. Benoit Dionne joined the RERTR group and started working on the MURR LEU fuel analysis in January 2008. Dr. Dionne took the lead in comparing the two independently developed models and searched for areas where improvements could be made in order to obtain a better agreement between the two. This involved a rather extensive review of the models being used with the WIMS, DIF3D and MCNP codes. Some inconsistencies were found and corrected in the modeling. This clearly identified the need to create a design basis document. Dr. Dionne also identified the need to improve the cross-section generation methodology in WIMS-ANL. This work is covered in a different paper entitled "*Applicability of WIMS-ANL to Generate Cross Sections for Very High Density UMo Fuel in Proposed MURR LEU Assembly,*" written by B. Dionne, J. Stillman and J. Stevens, which was also presented at the 2008 RERTR International meeting. After correcting the modeling inconsistencies and applying the new methodology for generating cross sections in WIMS-ANL, an improved agreement between MCNP and DIF3D was obtained. The results are shown in Table 2.

Table 2
Comparison of K_{eff} Between DIF3D and MCNP

Core	**Case**	**MCNP (K_{eff})**	**DIF3D (K_{eff})**	**Deviation (DIF3D-MCNP) (%ΔK/K)**
HEU	No sample holder/blades out	1.10209 (±11 pcm)	1.10298	+0.073%
LEU	No sample holder/blades out	1.10003 (±11 pcm)	1.09646	-0.296%
HEU	Empty sample holder/blades inserted[1]	0.99313 (±11 pcm)	0.99512	+0.201%
LEU	Empty sample holder/blades inserted[1]	1.00891 (±11 pcm)	1.00598	-0.289%

[1]The control blades are modeled at the recorded heights from the 1971 critical measurements.

VI. Modeling MURR Fuel Cycle - Both HEU and Proposed LEU using REBUS-PC

The highest power peaking factors at MURR occur in a core with all new fuel elements or in a core with a new fuel element adjacent to an element approaching maximum burn-up. For a core with 0 MWDs of power history, the low control blade height at startup suppresses the power distribution down and inward to plate number-1, thus increasing the peaking as shown earlier in Figures 4 and 5. This was easily modeled using MCNP when performing the proposed fuel design in 2007. In order to determine other potentially high power peaking, the ANL/RERTR group recommends the use of REBUS for modeling the fuel cycle. In order to accurately model the proper fuel loading variations between a fresh fuel element that is operating adjacent to an element that is in its final core loading requires modeling the MURR HEU fuel cycle for at least one year of operation or almost two years for the LEU fuel cycle. The task of modeling the HEU fuel cycle commenced in February 2008. It was quickly realized that the team needed to identify every possible way to simplify the modeling and speed up the REBUS-DIF3 and REBUS-MCNP processing rates to avoid the long computational runs.

The first step was to review the REBUS-PC models to see how well the variation in K_{eff} versus core MWDs agreed with the measured values for the HEU core. This was also performed on the LEU core to better estimate what the maximum obtainable MWDs per fuel element might be. Since the U-10Mo fuel irradiation tests conducted at the ATR have so far not indicated any fissions/cc burn-up limit, the limiting factor on how many MWDs can be obtained from a fuel element still remains excess reactivity. To compare the K_{eff} versus MWDs for both the LEU and HEU fuel designs, each was run using REBUS-DIF3D models. The HEU core was modeled with 1200 MWDs of operation at 10 MW with the control blades withdrawn to 23 inches. The LEU core was modeled at the same power level and blade height, however, power history was increased to 2400 MWDs.

Figure 8 provides the REBUS-DIF3D results of these two runs. The HEU fuel cycle with core loadings ranging from 500 to 670 MWDs achieves a maximum burn-up of 150 MWDs per element, which corresponds to 1200 MWDs on a core of eight elements. This graph indicates that approximately 2160 MWDs on an LEU core corresponds to 1200 MWDs on an HEU core. Based on these findings, our initial estimate on the maximum burn-up on an LEU fuel element is 270 MWDs.

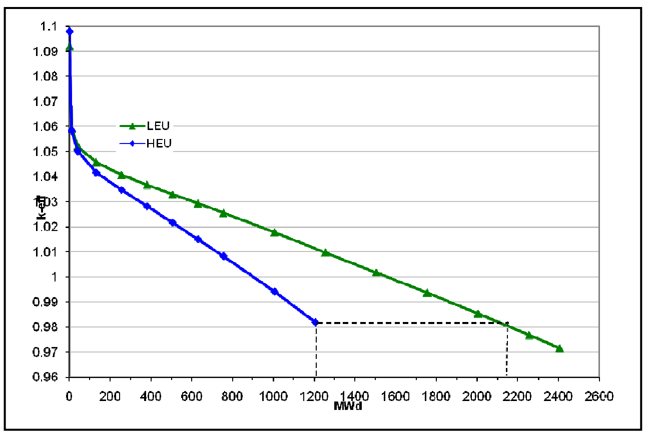

Figure 8
K_{eff} vs. MWDs – HEU and LEU Cores

To obtain the maximum burn-up of each fuel element the MURR fuel cycle involves a weekly change out of all eight elements so that the average burn-up of the elements in the core is about one half of the maximum obtainable burn-up. Table 3 provides a comparison of operating characteristics of the current HEU fuel with the proposed LEU fuel for the following parameters: maximum burn-up, core MWDs with the control blades full out, frequency of core refuelings, and number of fuel elements in the fuel cycle. The challenge in modeling this type of fuel cycle is that each week the new core arrangement consists of eight different fuel elements. This means that spatial burn-up distribution of all the fuel elements in the active fuel cycle need to be tracked until they have reached their maximum burn-up.

It was determined that the key aspects of the MURR fuel cycle could be modeled using 24 fuel elements in the LEU fuel cycle instead of the approximately 32 elements used in the actual HEU cycle. This reduced the number of elements to track by ¼ and the number of weeks of operation needed to model a fuel element from 0 to 150 MWDs. The modeling required 12 pairs of elements with power history per element uniformly distributed from 0 to 143 MWDs. To obtain the 12 pairs of fuel elements with this range of burn-ups to start the fuel cycle simulation required modeling a pre-simulation of nine different core loadings which ranged from 832 MWDs to 67 MWDs for the nine different runs and a total power history of 1,763 MWDs for the set. With these 24 fuel elements in the modeled fuel cycle it takes about 57 core loadings or operating weeks for a new fuel element to reach 150 MWDs. The burn-up distribution on the fuel plates is dependent on the burn-up distribution of the accompanying fuel elements with which it has operated. Starting with the first fuel element that reaches the 150 MWD limit, the distribution of fissions/cc will be compared with successively burned up fuel elements until it is observed that the fissions/cc distribution on the 24 fuel plates has converged on what represents the MURR fuel cycle. The goal is to benchmark the REBUS-DIF3D code with the current HEU fuel cycle and then use it to determine the performance of the proposed LEU fuel cycle.

Table 3
Current and Proposed MURR Fuel Operating Characteristics

Parameter	Current HEU Fuel	Proposed LEU Fuel
Maximum burn-up:	150 MWD/element (1200 MWD/core) due to insufficient excess reactivity – this achieves less than 1.8E+21 fissions/cc burn-up; Technical Specification limit is 2.3E+21 fissions/cc	270 MWD/element (2160 MWD/core) due to insufficient excess reactivity – this achieves less than 4E+21 fissions/cc burn-up
Core MWDs (control blades full out):	~670 MWD core with equilibrium xenon activity (56% of 1200 MWD)	~1200 MWD core with equilibrium xenon activity (56% of 2160 MWD)
Refuelings:	Weekly – replace all eight fuel elements; fuel elements are used in 18 to 20 core loadings to achieve 145 to 150 MWD burn-up (~24% burn-up)	Weekly – replace all eight fuel elements; fuel elements are used in about 35 core loadings to achieve ~270 MWD burn-up (~24% burn-up)
Fuel Cycle:	24 elements used per year; 32 fuel elements in active fuel cycle	15 elements used per year; 32 fuel elements in active fuel cycle

Modeling the fuel shuffling scheme with sufficient accuracy requires the explicit tracking of depletion and out-of-core decay for 12 axial zones of the 24 fuel plates of each fuel element in the fuel cycle. Due to fuel elements reaching the 150 MWD limit and being replaced by new fuel elements, modeling a little more than one year of cores requires tracking this burn-up in 46 different fuel elements. Tracking this explicitly over the one year fuel cycle with 105,984 unique regions requires the entry of several hundred thousands of input cards. To process this large number of input cards in a reasonable amount of time, a new REBUS-PC input processing algorithm was developed that reduces computing time by about a factor of 60. To also speed up the fuel shuffling simulation, the control blades are

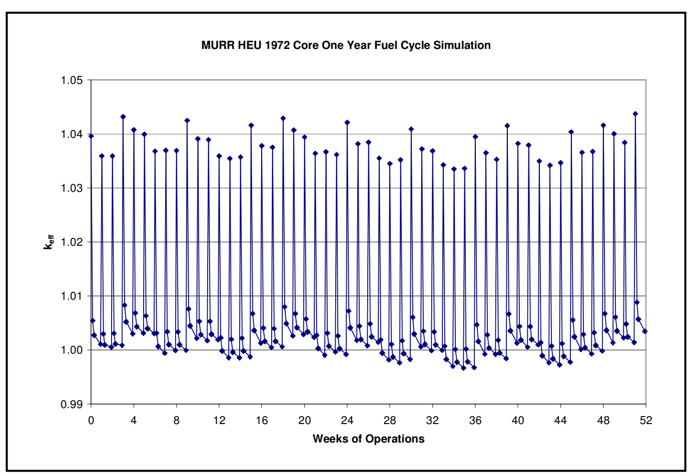

Figure 9
1972 Fuel Cycle – 52 Different Core Loadings

modeled at the 23 inches withdrawn position, the average blade height with equilibrium xenon, and with this no blade movement during the simulation the number of outer iterations required by the code is reduced.

Figure 9 depicts the initial results for a one year fuel cycle involving 52 different core loadings. For each core, the following four K_{eff} values are given: (1) the beginning K_{eff} value of the xenon free core with the control blades at 23 inches withdrawn; (2) the K_{eff} value after 24 hours of operation with corresponding xenon buildup; (3) the K_{eff} value after 48 hours of operation; and (4) the K_{eff} value at the end of the 6.3 day operating period.

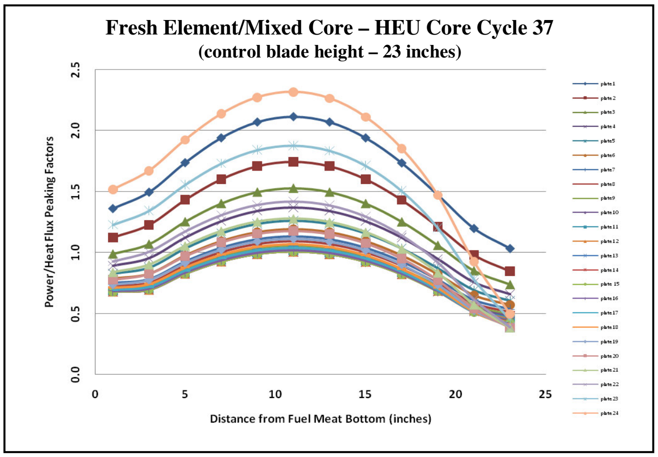

Figure 10
Axial Power Peaking – Fresh Fuel Element

For this fuel cycle simulation, the peak power density occurs in week, or cycle, 37. Figure 10 shows the axial power peaking factor profile for each of the 24 fuel plates of an element with 0 MWDs of power history loaded in core position F-1. Because this is a fresh element, it has the highest power density in the core. The highest power peaking factor of 2.32 occurs on plate number-24. As shown in Figure 5, this value is lower than the peaking factor of 3.18 for plate number-1 of an HEU core with 0 MWDs of power history and no fission product buildup. The peaking factor for the cycle 37 core will be higher at startup because of the lower control blade height and a lack of xenon buildup, but that value has not yet been determined. The control blades at a lower height causes the peak power density in the core to be pressed down and inward. After more complete peaking factors for the various core arrangements are completed, the thermo-hydraulics code PLTEMP will be used to determine which one is the most limiting hot channel.

The corresponding initial simulation of the LEU fuel one year cycle will be completed the week of October 6, 2008. The LEU fuel element outer plates – number-1, -2, -23 and -24 – have higher power peaking factors compared to the HEU outer fuel plates, as previously seen in Figures 4 and 5. The higher power peaking factors combined with the higher targeted MWD burn-up per fuel element should result in a larger difference in the ^{235}U atom densities of the corresponding fuel plates of an element with 0 MWDs of power history to one approaching the maximum MWD limit. The LEU fuel cycle simulation will determine the increase in the highest power peaking factor when comparing the LEU fuel cycle to the current MURR HEU fuel cycle. This may identify a need to further refine the fuel meat thicknesses to obtain the optimal LEU core design.

VIII. Summary and Future Work

The completed broad scoping studies using MCNP indicate that U-10Mo monolithic fuel has the potential to provide an LEU fuel that could be suitable at MURR and potentially reduce the number of fuel elements used per year. Over the past year, necessary improvements have been made in modeling the MURR reactor, in the generation of neutron cross sections, and in the functionality and execution of the REBUS-PC code. Improvements to these tools will help complete the fuel depletion studies of the optimal LEU core design identified in the MCNP broad scoping studies. Safety analyses using worse case power peaking factors that will be determined using REBUS-PC modeling of mixed core loadings of fresh and end-of-life fuel elements will soon be commenced. Additionally, various possible methods of transitioning from HEU to LEU fuel will be evaluated to determine the advantages and disadvantages of each.

There are cladding and fuel plate thickness and other fabrication design limit assumptions that still need to be validated in order to finalize an optimal LEU fuel design.

IX. Acknowledgements

The authors would like to thank Dr. John Stevens, Dr. John Stillman and Dr. Benoit Dionne of the RERTR Program for their expertise and effort in performing the work described in this paper as well as their assistance in helping develop this paper; Dr. Arnie Olson for helping to modify and improve the REBUS-PC code to handle the unique MURR fuel cycle; as well as the U.S. Department of Energy for funding this and any future work.

X. References

[1] Letter Request to USNRC, Application for Unique Purpose Exemption from Conversion from HEU Fuel, Facility License No. R-103, University of Missouri Research Reactor, September 1986; and supplemented by Letter Response to USNRC Request for Additional Information Supporting the Unique Purpose Exemption Request, February 1987.

[2] Gibson, G.W., Graber, M.J., and Francis, W.C., Annual Progress Report on Fuel Element Development for FY-1963, IDO-16934, 1963.

[3] Graber, M.J., et al., Performance Evaluation of Core II and III Advanced Test Reactor Fuel Elements, ANCR-1027, Aerojet Nuclear Company, 1971.

[4] McKibben, J.C., Kutikkad, D., and Foyto, L.P., "Current Status of the Missouri University Research Reactor HEU to LEU Conversion Feasibility Study," Paper for International RERTR Meeting, University of Missouri Research Reactor, October 2006.

[5] McKibben, J.C., Kutikkad, D., and Foyto, L.P., "Current Status of the Missouri University Research Reactor HEU to LEU Conversion Feasibility Study," Paper for International RERTR Meeting, University of Missouri Research Reactor, October 2007.