REACTOR CORE DESIGN AND MODELING OF THE MIT RESEARCH REACTOR FOR CONVERSION TO LEU

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ABSTRACT

Feasibility design studies for conversion of the MIT Research Reactor (MITR) to LEU are described. Because the reactor fuel has a rhombic cross section, a special input processor was created in order to model the reactor in great detail with the REBUS-PC diffusion theory code, in 3D (triangular-z) geometry. Comparisons are made of fuel assembly power distributions and control blade worth vs. axial position, between REBUS-PC results and Monte Carlo predictions from the MCNP code. Results for the original HEU core at zero burnup are also compared with measurement. These two analysis methods showed remarkable agreement. Ongoing fuel cycle studies are summarized. A status report will be given as to results thus far that affect key design decisions. Future work plans and schedules to achieve completion of the conversion are presented.

1. Introduction

The MIT Reactor (MITR-II), currently licensed to operate at 5 MW, contains a hexagonal core that contains twenty-seven fuel positions in three radial rings (A, B, and C), as shown in Figure 1. Typically at least three of these positions 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 standard MITR-II fuel elements. 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 (0.030 in.) and a length of 61 cm (24 inches). The cladding of each fuel plate has 0.25 mm fins to increase heat transfer to the coolant. The fuel has an overall density of 3.7 g/cm^3, with a total loading of 506 g ^{235}U in each element (445 g ^{235}U prior to 1980).

The core is light water moderated and cooled and is surrounded by a D_2O reflector. Boron impregnated stainless steel control blades are present at the periphery of the core at each of the sides of the hexagon. In addition, fixed absorbers of boron-stainless steel can be installed in the upper twelve inches of the core in a hexagonal configuration between the inner and second fuel rings as well as in three radial arms extending to the edge of the core.

Several reentrant thimbles are installed inside the D_2O reflector, delivering greater neutron flux to the beam ports outside the core region. Beyond the D_2O reflector, a secondary reflector

of graphite exists in which several horizontal and vertical thermal neutron irradiation facilities are present. In addition, the MITR Fission Converter Facility is installed outside the D_2O reflector. This facility contains eleven partially spent MITR fuel elements for a delivery of a beam of primarily epithermal neutrons to the medical facility for use in Boron Neutron Capture Therapy (BNCT). Figure 2 shows a larger view of the reactor including the reflector regions and experimental facilities.

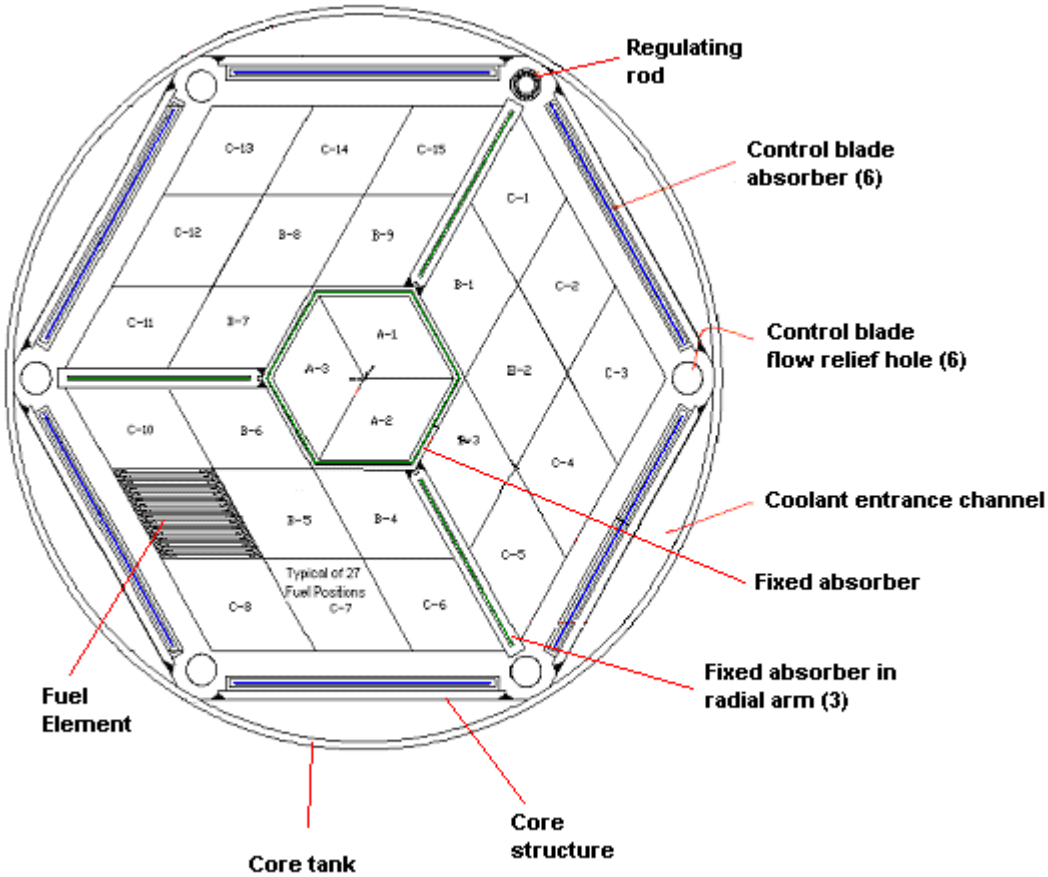

Figure 1. The MITR-II core.

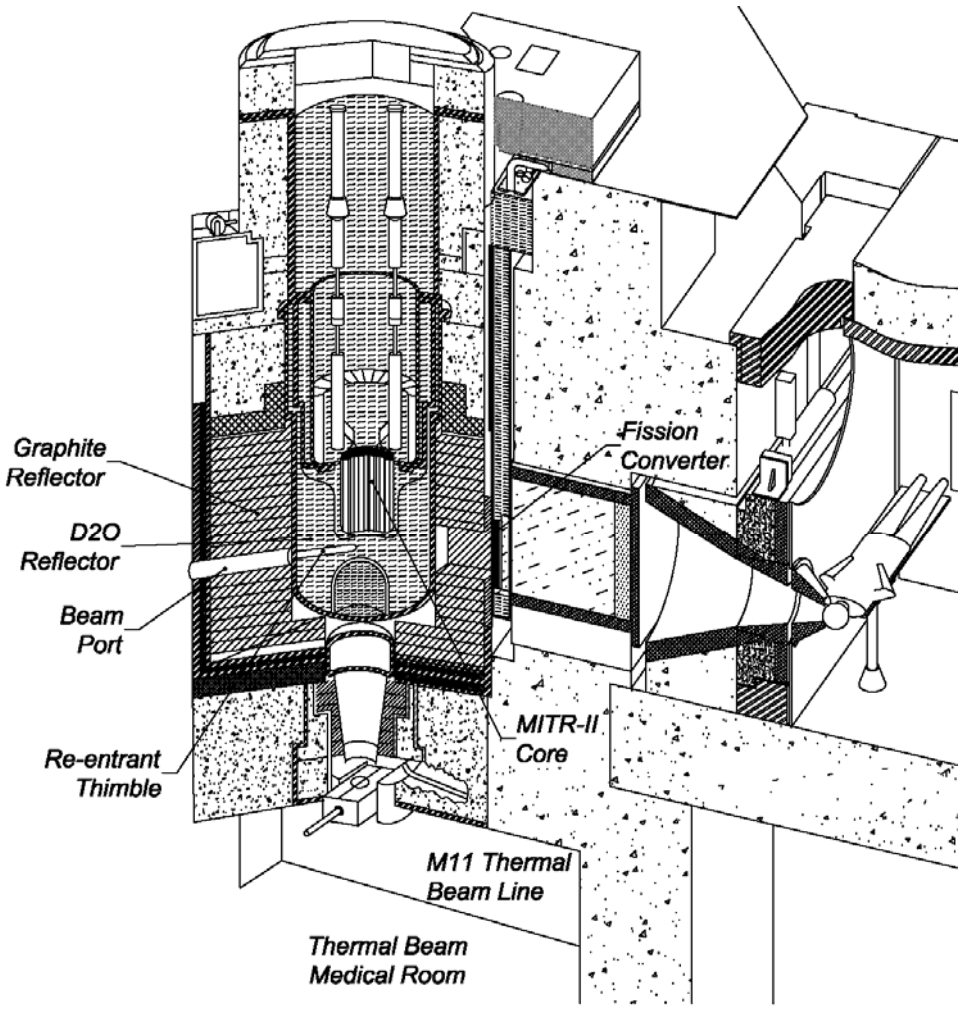

Figure 2. Isometric view of the MIT Reactor

2. Modeling

The Monte-Carlo transport code MCNP has been used for modeling the current HEU configuration as well as for studies of conversion of the MIT reactor to LEU fuel[1]. This model has been fairly well validated using operational data from HEU core #2, which consisted of twenty-two new (445 g ^{235}U) fuel elements and five aluminum dummies in-core with no fixed absorbers.

In order to increase the capabilities of burnup modeling, the WIMS-ANL 1-D transport code [2] was used for generation of seven neutron group cross-section libraries, along with the REBUS-PC code for fuel cycle analysis [3]. Because of the fuel and core design of the MITR-II, a triangular-Z geometry was chosen for REBUS-PC in order to discreetly model the fuel elements. Rhomboidal elements could not be modeled within the existing capabilities of

REBUS-PC. But the DIF3D neutronics processor within REBUS-PC was fully capable of solving triangular-z problems (and had been used for many years in hexagonal geometry). The solution was to create a new extension to the Argonne Reactor Code System input processor GNIP4C that could construct the full core 3D model by building the core from standard geometrical units (rhombus in three orientations, rectangular box in three orientations, circular disk, spherical cap, and hexagon) in the radial plane. The output of this processor consists of standard interface files that define the model geometry in a form directly usable by other modules in REBUS-PC. In fitting the model geometry to the dimensions of the rhomboid-shaped fuel element as well as the absorber spider region separating parts of the core, it was necessary to model the fuel elements as a rhombus consisting of an 8 x 16 triangular mesh. This resulted in the reactor being modeled with a radial mesh of 542 x 312 triangles. Circular boundaries such as the radial graphite and water reflectors are modeled as a "jagged" boundary based on mesh centroid radii. Nodes in the corners of the rectangular mesh, beyond the reflector, are ignored in DIF3D. The hemispherical-shaped vessel bottom is also modeled in 3D. Control blades are also modeled and can be positioned axially as needed. The optical thickness of the aluminum internal core structure surrounding the fuel in ring A, and the three radial webs, is preserved by homogenization. With a 7-zone, 38 node axial model, this full-core model totals 1.2 million mesh points, requiring more than 2 GB of RAM to adequately run the model.

Studies were performed with four-group neutron cross sections, to see the effect of fewer neutron groups. It was concluded that the large spectral variations with position in the core were not well tracked with only 4 groups.

3. Results

New 445 g ^{235}U fuel elements and reactor components were modeled with WIMS. The resulting cross-sections were used with a REBUS model of core configuration #2. The REBUS results were validated by comparison with both measured and MCNP core #2 results.

Figure 3 shows the radial peaking factors (power generated in a fuel element as compared with the average fuel element) of both the MCNP model and the REBUS model. The MCNP peaking factors of each element position are given in boldface above the REBUS peaking factors. Both models show the larger power peaking in the center element (A1), as well as lesser peaking in the outer C-ring elements. Despite the homogenization of the materials in the fuel element regions as well as the use of diffusion theory, the REBUS model shows remarkable agreement with MCNP in all regions of the core.

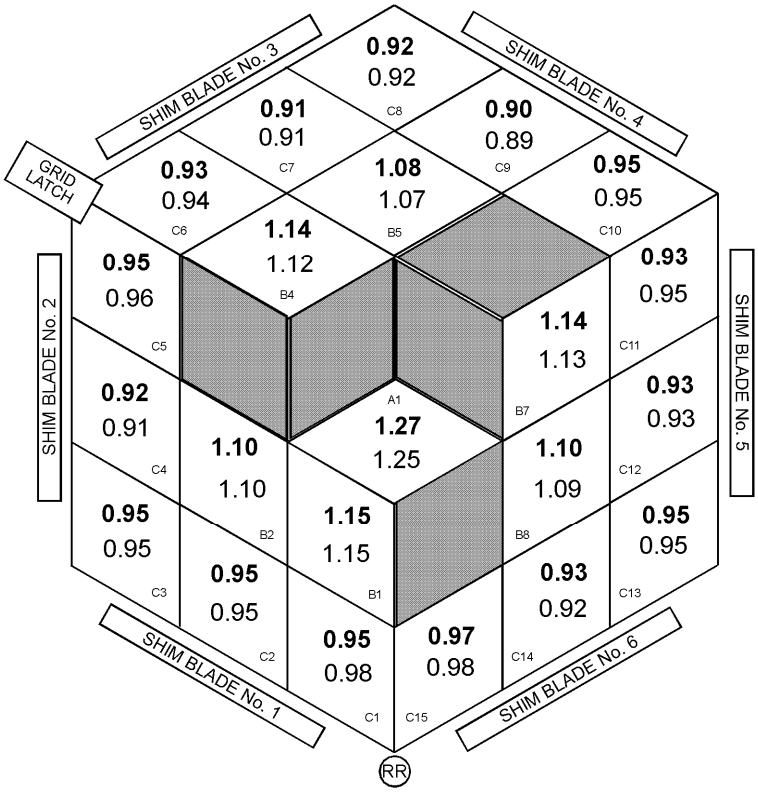

Figure 3. Radial peaking factors in HEU core #2, **MCNP** and REBUS results

Figures 4 through 6 show a comparison of axial peaking factors (power produced in an axial node as compared with the core average node) in elements from both the MCNP and REBUS models in the center A-ring (A-1 element), middle B-ring (B-1 element) and outside C-ring (C-1 element) fuel regions. The difference in the upper area of the A ring element may be due to the homogenization of water and aluminum in the fixed absorber area between the fuel elements. All other areas of the core show very good agreement between the MCNP and REBUS models.

Figure 7 is a plot of the control blade worth as a function of axial blade position. Both the MCNP and REBUS results show criticality occurring very near the actual critical position of 21 cm, as well as very good agreement between the two models in all axial positions. Despite the use of diffusion theory, REBUS still shows good agreement even with blade worths, areas of high neutron absorption.

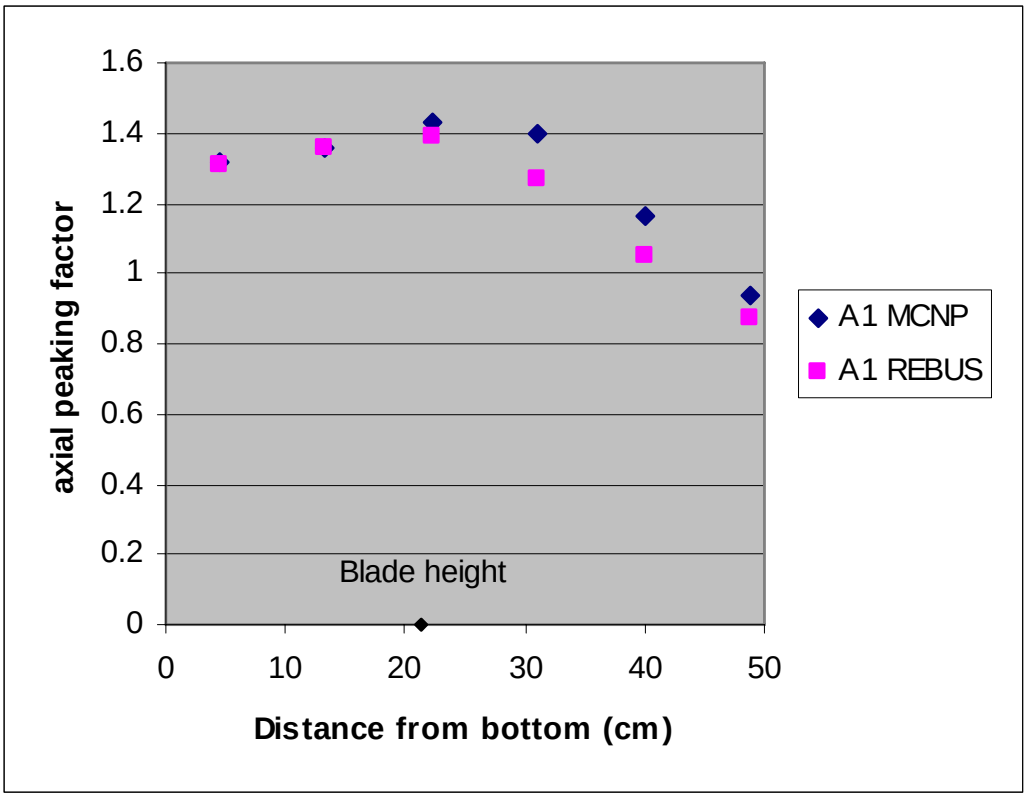

Figure 4. Axial peaking factors in center fuel element

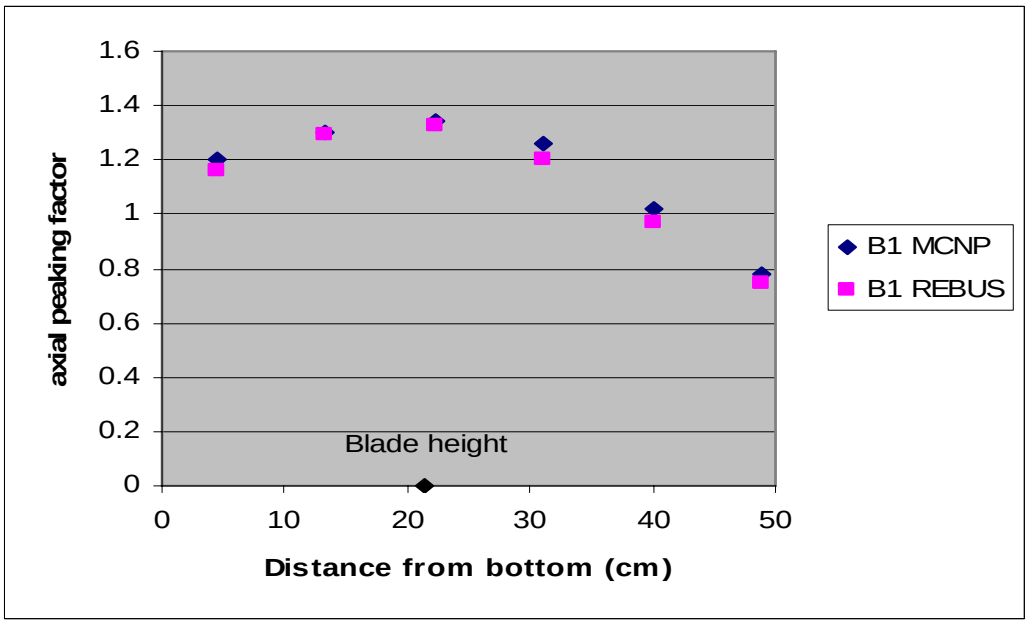

Figure 5. Axial peaking factor in B ring fuel element

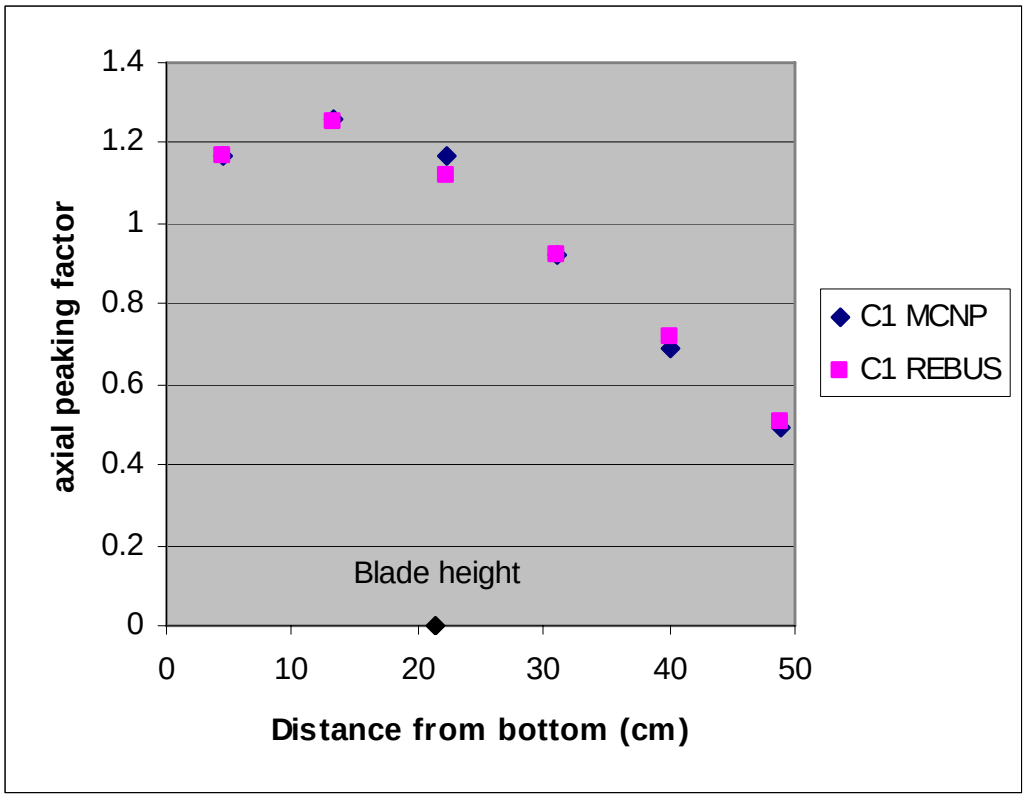

Figure 6. Axial peaking factors in C ring fuel element

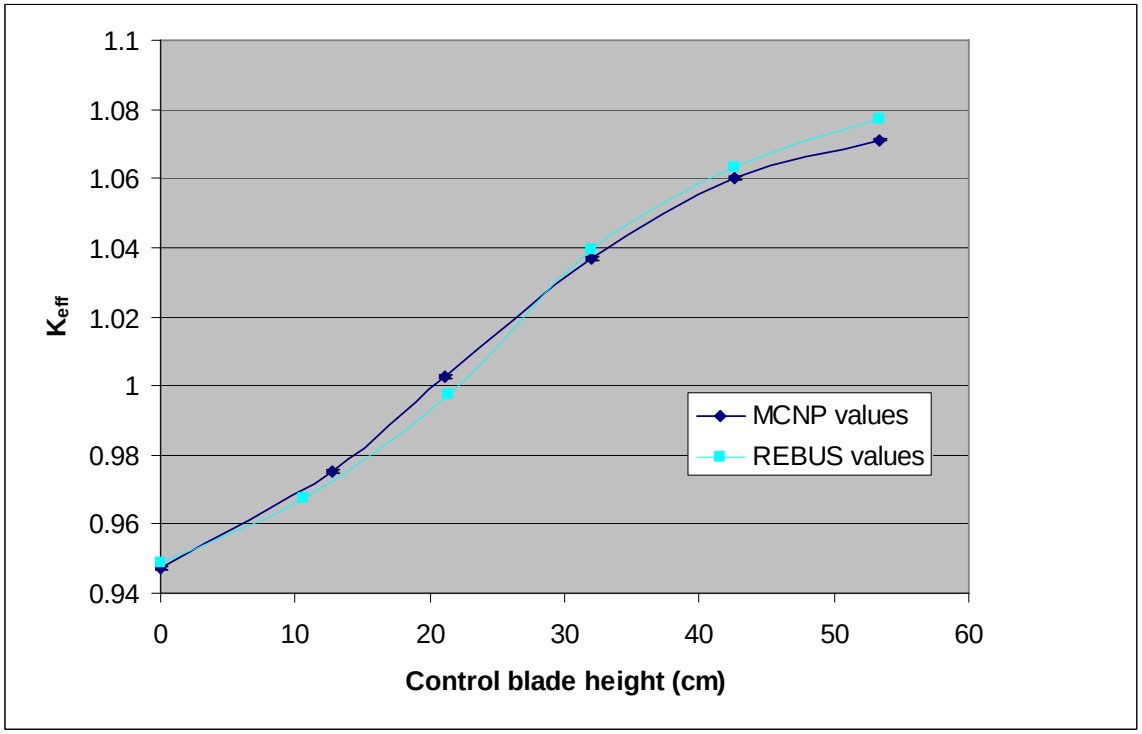

Figure 7. HEU core #2 control blade worth comparisons between MCNP and REBUS-PC

4. Burnup calculations

In order to simulate the burnup in core #2, the REBUS model was used with an approximation of the operating cycle of core #2. During the operating time of this core, the reactor was operated at about 2.5 MW on an approximate 4 day on/ 3 day off cycle over the course of several months. This cycle was assumed in the REBUS model with reactivity results compared with end-of-week measurements of control blade heights at critical position. The end-of-week values were chosen since they are more likely to have been at xenon equilibrium, although this was not always the case. The results of the comparisons of the reactivity change over time between the measured values, REBUS values, and those generated by the MCNP/ORIGEN linkage code MCODE (assuming the reactor at constant power) are shown in Figure 8.

The REBUS values show about 15% more negative reactivity than the measured values at the initial xenon equilibrium points, with the differences reducing with burnup until they become less negative than measured values by up to 10% at the end of the operating period. The MCODE values are closer to the measured values, but also show more negative reactivity initially. Both the MCODE and REBUS models do not include an initial 2.3 MWd/kg generated in core #1 which is reflected in the offset in the initial measured values.

The reasons for the discrepancies are under investigation, with one possibility being reactivity changes with blade height, since the MCODE and REBUS values were made assuming a single blade height, and the reactivity values taken from the variation in K_{eff} with burnup. Another possibility is a difference in power levels in the calculational models, since the actual power levels varied from week to week.

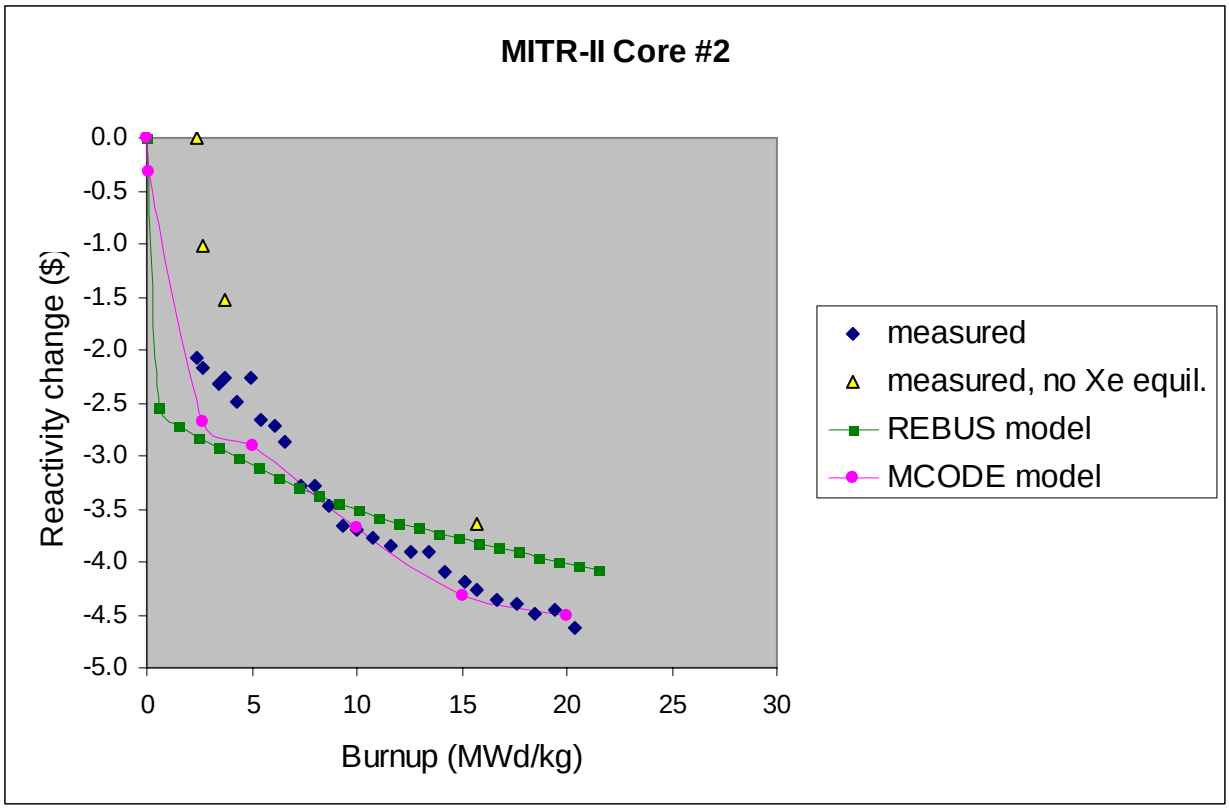

Figure 8. Comparison of measured burnup reactivity changes with REBUS and MCODE models

5. Future Plans

Given the excellent results the WIMS/REBUS model has initially shown for HEU core #2, REBUS will be expanded for further validation. The discrepancies in burnup evaluation will be investigated and the model will be further used in the creation of a quasi-equilibrium HEU core model. Although the MITR-II has no set refueling pattern, it is thought that the establishment of this quasi-equilibrium core model can be used to compare core parameters when evaluating LEU designs.

Although the results above show good agreement of the REBUS model with both measured data and MCNP results, further comparisons will be made using the REBUS model in MCNP in order to determine if the REBUS use of diffusion theory contributes any significant errors in the calculations.

In addition to the LEU evaluations presented above, further LEU fuel and core designs will be evaluated. Assuming that these designs will prove to show adequacy of fuel cycle length, safety parameters, and neutron flux delivery to experimental facilities, it is anticipated that a final proposed LEU core and fuel design will be chosen in 2008. Additional safety evaluations will subsequently be made prior to licensing submittal.

References

[1] T. Newton, X. Zu, E. Pilat, and M. Kazimi, "Modeling the MIT Reactor Neutronics for LEU Conversion Studies, " Proceedings of the PHYSOR-2004 Conference, Chicago, IL, April 2004.

[2] J. Deen, W. Woodruff, C. Costescu, and L. Leopando, "WIMS-ANL User Manual Rev. 6," ANL/TD/TM99-07, Argonne National Laboratory, February 2004.

[3] A. Olson, "A Users Guide for the REBUS-PC Code, Version 1.4," ANL/RERTR/TM-32, Argonne National Laboratory, December, 2001.