Validation of the 3-D VENTURE and MCNP UMLRR Core Models used in Support of the WPI Fuel Transfer Project

DR. JOHN R. WHITE, RUSSELL GOCHT, MICHAEL PIKE, and JEREMY MARCYONIAK
Nuclear Engineering Program, UMass-Lowell, Lowell, MA 01854

ABSTRACT

This paper overviews recent efforts to validate a set of new 3-D VENTURE and MCNP models of the UMLRR core. Several inter-comparisons of the two models as well as direct comparison to measured data from the reactor at two burn states (BOL and after about 50 MWD of operation) were made. In most cases, good to excellent agreement was achieved with both models -- and, with successful validation, both the VENTURE and MCNP models can now be utilized with confidence within a variety of on-going and future projects.

Introduction

Upon closing of the Worcester Polytechnic Institute (WPI) research reactor, the slightly used WPI fuel elements were transferred to the University of Massachusetts Lowell for use in our on-campus 1 MW pool-type research reactor.[1] Although the WPI and UMass-Lowell research reactor (UMLRR) elements have similar geometries and both contain low enriched uranium (LEU) fuel, the material composition of the fuel meat is different -- the WPI fuel plates contain uranium-aluminide fuel (UAl_x-Al) and the UMLRR plates have uranium-silicide fuel (U_3Si_2-Al). In addition, the U235 loading is 167 g for the WPI element vs. 200 g for the UMLRR assembly and there are also some small differences in meat thickness, plate thickness, water gap thickness, etc. Thus, because of the number of variations to consider, a formal comparison and safety evaluation for combined use of the UMLRR and WPI fuel elements within the reactor is needed before the WPI fuel can be used -- and a series of reactor physics and thermal analysis computations are required to perform the desired comparative analyses.

At UMass-Lowell, the VENTURE code, with few-group cross sections generated by a series of SCALE modules, has traditionally been the primary tool used to do 2-D and 3-D core physics studies, with focus on computing reactivity effects and spatial power distributions within a variety of core configurations. A set of consistent 2-D and 3-D VENTURE models was generated in 1999 for support of the conversion of HEU to LEU fuel in the UMLRR. The actual conversion was successfully completed in August 2000 and the models generated at that time[2-3] have proved to be adequate for predicting the overall core physics behavior within the UMLRR for the last 10+ years.

However, after a detailed review of the existing VENTURE models, it became clear that some updates were needed to support the WPI fuel transfer project and that some additional analytical capabilities that are not available with the deterministic VENTURE models would be highly desirable. In particular, we identified several changes that could be made that would simplify the VENTURE model, make it more useful, and improve upon the overall accuracy of the computational results. In addition, it was decided that a detailed MCNP model of the UMLRR was needed to support a variety of analyses associated with its various experimental facilities (since few-group diffusion theory is not particularly useful for these tasks). Thus, the decision was made to overhaul the existing deterministic VENTURE models and to generate a new detailed 3-D stochastic MCNP model of the UMLRR core and surrounding experimental facilities. Burnup was achieved by coupling MCNP spatial analysis to ORIGEN2 temporal analysis using MCODE so that both the deterministic and stochastic models could simulate the behavior of the system with both fresh and burnt fuel configurations. This paper overviews the various UMLRR configurations that were modeled and addresses the steps taken to validate the new physics models generated as part of this work.

The M-1-3 and M-2-5 UMLRR Core Configurations

The 1 MWth UMass-Lowell Research Reactor (UMLRR) contains a 7x9 grid of fuel assemblies, graphite reflector elements, irradiation baskets, and corner posts. It also has two grid locations reserved for an external neutron source and a low-worth regulating rod for fine reactivity control. Four large control blade assemblies are used for gross reactivity control and for reactor shutdown. The reactor is enclosed on four sides by an aluminum core box and a large pool of water surrounds the system on three sides, with a 3 inch lead shield and large graphite thermal column on the remaining side. The original system also had a set of six beam ports along the axial centerline of the core. A specific arrangement of fuel elements, graphite reflector blocks, and radiation baskets makes up a particular core configuration.

In August 2000 the UMLRR converted from the use of HEU uranium-aluminide fuel to LEU uranium-silicide fuel (see Refs. 2-3). The basic layout for the LEU startup core arrangement, including the six beam ports and thermal column, is sketched in Fig. 1. This reference configuration is referred to as the M-1-3 core and it contains 19 full fuel assemblies and 2 partial assemblies arranged roughly in the center of the 7x9 grid. Directly in the middle of the core is a central irradiation zone known as the flux trap. Note that, when referring to a given location, the row and column indices shown in the sketch are used (e.g. the flux trap is contained in location D5). Also, when referring to the four large control blades, the blades are numbered consecutively starting in the lower left region of Fig. 1 and increasing in a clockwise direction. Thus, Blade 1 is in the lower left, Blade 3 in the upper right, etc., as viewed from the perspective of Fig. 1.

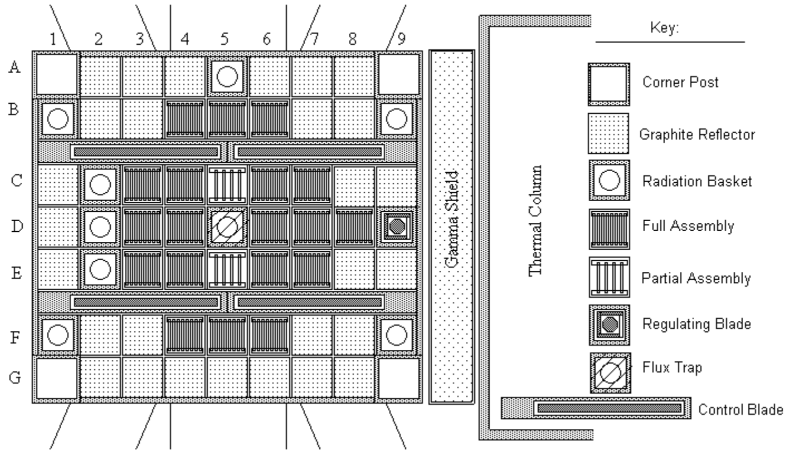


Fig. 1 LEU startup core layout for the UMLRR (M-1-3 core).

During startup testing in Fall 2000, a series of reactivity evaluations and flux profile measurements were taken within the beginning-of-life (BOL) M-1-3 configuration to support routine operation of the new LEU core. Now, 10+ years later, these experimental results are still important since they can be used to help validate any new models that may be developed.

In late 2001, a new ex-core fast neutron irradiation facility[4] was installed within the UMLRR pool. The fast neutron irradiator (FNI) replaced the three beam ports on the side of the core next to row A. The FNI was purposely placed outside the core for relatively easy access to the large experimental location and to minimize any effect on core operation during its use. This new facility required some changes to the actual in-core assembly configuration -- to optimize performance of the FNI and to counter reactivity effects caused by the composite facility changes. The resulting configuration, including the FNI grid and shield blocks, is referred to as the M-2-5 configuration and this is also the current operating layout for the UMLRR (February 2012). This post-FNI configuration is sketched in Fig. 2.

During the approximately 11-year period since startup (Aug. 2000 through June 2011), the LEU core accumulated about 1100 MWhr of total burnup (i.e. equivalent to about 46 full power days at 1 MW operation). Also of note is that the M-1-3 core had less than 4 MWD of burnup when the new M-2-5 configuration was installed. Thus, most of the operating history to date has been associated with a single core layout -- that is, the M-2-5 configuration.

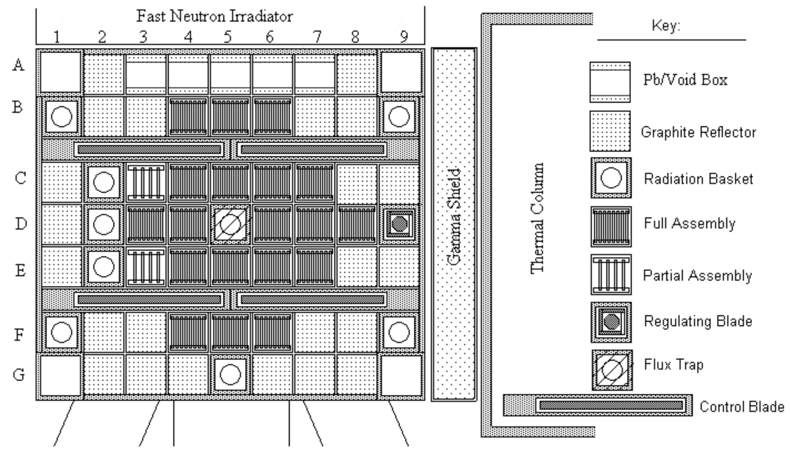


Fig. 2 Post-FNI configuration for the UMLRR (M-2-5 core).

From a model validation perspective, the BOL M-1-3 model represents a fresh core and it has the most measured data available (reactivity evaluations and some thermal flux mappings) to support model evaluation -- thus, this configuration is the easiest and best to use for initial model validation. Also of interest is the initial M-2-5 configuration, but only reactivity evaluations (i.e. measured blade worth curves) are available for this configuration. However, because of the low burnup level (less than 4 MWD), approximating this configuration with fresh fuel densities gives a good representation of reality. In contrast, for the current configuration with its nearly 50 MWD cumulative burnup, fuel depletion calculations are required to achieve a reasonable representation of the core physics. However, since the VENTURE and MCNP models after 50 MWD of burnup essentially represent current operations, this also presented an opportunity to perform additional measurements within the reactor. In particular, selected reactivity worths measurements associated with various bayonet insertions and fuel element interchanges were made in July 2011 and compared to predictions with the new computational models.

Calculational Results and Model Validation

The three configurations noted above have been fully modeled in both codes and comparisons to measured data have been performed. There were four primary comparisons made as part of the validation effort, as follows:

1. Prediction of the "critical" k_{eff} for each of the three critical configurations.
2. Comparison of the computed and measured total worths for each of the five control blades for each configuration. Also of interest here is an estimate of the excess reactivity for each configuration.
3. Comparison of some selected axial thermal flux profiles from the computational models with measured data for the M-1-3 core.
4. Comparison of some selected reactivity worth measurements within the initial M-1-3 startup core and in the current M-2-5 configuration with nearly 50 MWD of burnup.

Each of these comparisons is discussed separately in the following subsections.

Prediction of the "Critical" k_{eff}: The critical configurations for the M-1-3 startup core, the M-2-5 BOL core, and the July 2011 M-2-5 core with nearly 50 MWD of burnup, all give consistent results for the "critical" reactivity level of the system, as summarized in Table 1. As seen here, the VENTURE results have a rather large, but consistent, negative bias of about

2.0-2.5% Δk/k, but the predicted critical MCNP k_{eff} values are very close to unity for all the cases, indicating that these models can predict the absolute reactivity level of the UMLRR with good accuracy (the MCNP calculations used 20×10^6 histories with 1σ = 0.0002 Δk/k). The cause of the large reactivity bias for the VENTURE model is not apparent, but it does not seem to affect the usefulness of the model for a wide range of other parameters (see below).

Table 1 Summary results for several critical configurations within the UMLRR.

Model Description	Blades 1-4 Location (inches out)	Regulating Blade Location (inches out)	VENTURE K_{eff}	MCNP K_{eff}
BOL M-1-3	15.3	8.0	0.980	0.995
BOL M-2-5	14.9	10.0	0.978	0.999
M-2-5 at 50 MWD	16.3	7.7	0.975	0.996

Prediction of Blade Worths: Estimating the reactivity worth associated with each of the four large control blades and the low-worth regulating blade within the UMLRR was another main component of the model evaluation process. Unfortunately, however, the discussion of the blade worth results is somewhat cumbersome for several reasons -- mostly because of the relatively large uncertainty that exists in the resultant "measured or experimental" differential and integral worth curves (e.g. see the discussion in Refs. 2-3). Thus, the comparisons here are not as "clean" as desired and are more qualitative in nature than quantitative -- with focus on obtaining the proper blade worth distribution among the four blades, along with a reasonable estimate of the absolute magnitude of the total worth of each blade.

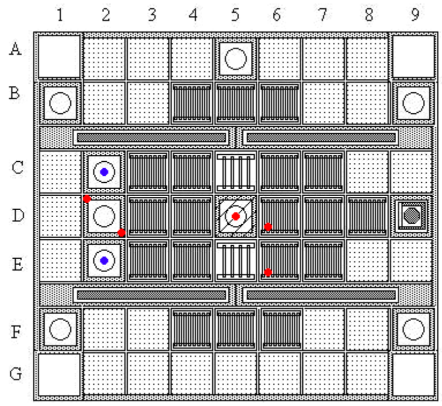
Table 2 Computed vs. measured blade worths for three UMLRR configurations.

	M-1-3 BOL Core Total Worth (% Δk/k)			M-2-5 BOL Core Total Worth (% Δk/k)			M-2-5 at 50 MWD Total Worth (% Δk/k)		
Blade #	**Expt.**	**VENT**	**MCNP**	**Expt.**	**VENT**	**MCNP**	**Expt.**	**VENT**	**MCNP**
Blade 1	2.63	2.95	3.00	2.82	2.91	2.76	2.55	2.86	2.73
Blade 2	2.47	2.80	2.75	2.19	2.35	2.40	2.23	2.29	2.40
Blade 3	3.32	3.32	3.42	3.19	3.16	3.42	3.64	3.06	3.19
Blade 4	3.20	3.43	3.55	3.93	3.72	3.83	4.19	3.74	3.71
Total Blades 1–4	11.6	12.5	12.7	12.1	12.1	12.4	12.6	12.0	12.1
Excess K_{eff} Blades 1–4	2.82	3.22	3.44	3.46	3.45	3.46	2.41	2.71	2.60
Regulating Blade	0.28	0.44	0.38	0.30	0.45	0.38	0.31	0.45	0.38

From the summary data in Table 2, generally good agreement to within 10-15% is apparent for most of the calculated vs. experimental results for the four large control blades -- and, considering the observed uncertainty in the experimental approach, this is actually not bad. In addition, all the expected trends are predicted quite nicely with the various VENTURE and MCNP models. For example, the fuel and graphite/water reflector arrangement suggests that, for the M-1-3 BOL core, there should be a slight tilt in the flux and blade worth distribution in the direction of Blades 1 and 4, with an additional slight shift towards Blade 4 (lower right portion of Fig. 1). Thus, for the BOL M-1-3 core, we would expect the worths for Blades 1 and 2 to be comparable, with Blade 1 worth a little more than Blade 2. Similarly, Blades 3 and 4 should have comparable worths, with Blade 4 having the largest reactivity effect of all the blades. For the M-2-5 configurations, roughly the same worth distribution is expected, but the asymmetry should be magnified significantly because of the movement of the partial assemblies to the left side of the core (Col. 3 instead of Col. 5) and the replacement of five graphite reflectors in Row A with Pb-void elements (i.e. compare Figs. 1 and 2). Thus, for this configuration, Blade 2 is expected to have the lowest worth and Blade 4 the highest, with the difference being much larger than for the M-1-3 layout. These expected trends are exactly as observed in Table 2, which gives good confidence in the ability of the computer models to predict these effects.

Concerning the regulating blade worths, the VENTURE and MCNP values are consistently high relative to the measured values. Here the VENTURE values are 45-55% high and MCNP over predicts the worths by 25-35%. However, it is important to note that the absolute differences are rather small and the uncertainty in the measured value is not negligible.

Axial Thermal Flux Profiles in the M-1-3 Core: A mix of gold foils (blue) and copper wires (red) were used to perform thermal flux mapping in selected locations of the M-1-3 LEU startup core as illustrated in the UMLRR core map shown here. Cadmium-covered and bare gold foils were used to provide an absolute determination of neutron fluence rate, while copper wires provided an axial flux distribution at the chosen locations. The irradiation was performed at a power level of 100 watts for 30 minutes. The wires and foils were then removed and counted on a gamma spectrometer, and the measured flux distribution data were then normalized to a nominal power level of 1 MW and compared to the results from the VENTURE and MCNP computational models for the M-1-3 core with the BOL critical blade configuration.



Summary results from these comparisons are shown in Fig. 3. The individual small circles on these curves represent the experimental values of the absolute thermal flux, the dots with the 1σ error bars are associated with the MCNP results, and the solid lines represent the VENTURE predicted flux profiles. The top two plots highlight the two copper wires in the D2 position, with relatively good agreement in both cases. The results for the wires in the two fuel assemblies are shown in the middle plots and, as apparent, the MCNP simulation over predicts the thermal flux in these regions by as much as 20-25%, whereas the VENTURE results are quite good. Finally, the bottom curve in Fig. 3 shows the computed and measured thermal flux profiles in the center of the flux trap assembly in location D5. The agreement here is also quite reasonable for both cases with a good representation of the axial shape but, again, the MCNP results slightly over predict the flux magnitude by roughly 10-15%.

Finally, we should note that there is not a lot of information available about the uncertainty in the measurements that were taken back in August 2000 (only nominal flux values are available). This is unfortunate, since it is difficult to draw quantitative conclusions about the validity of the computer models without some idea as to the uncertainty in the experimental data. One concern, for example, is that the irradiations were performed at a power level of approximately 100 W and the measured data were then scaled to 1 MW -- thus, even a small error in this “approximate” power level could account for a magnitude difference in the measured and computed results. Overall, however, the five experimental and computed axial profiles for both models show good qualitative agreement, with the VENTURE results giving somewhat better magnitude comparisons to the nominal experimental data.

Selected Reactivity Worth Comparisons: As a final indicator of the general reliability of the UMLRR computational models, a number of measured reactivity worth results were also compared with those computed using the MCNP models for the BOL M-1-3 core and for the M-2-5 configuration after nearly 50 MWD burnup. The majority of the tests involve the insertion of an empty (air-filled) bayonet into one or more specific locations. However, one test in the M-1-3 core also measured the worth of a water-filled bayonet in the flux trap. Finally, the worth associated with the replacement of a burnt fuel element in location D6 with a fresh uranium-silicide assembly was also compared. Table 3 summarizes these reactivity worth comparisons -- where we note that a full set of VENTURE comparisons are not given here, since its homogenized flux trap and radiation basket geometries are not appropriate for these type of calculations (this is one of the main reasons for developing the MCNP model).

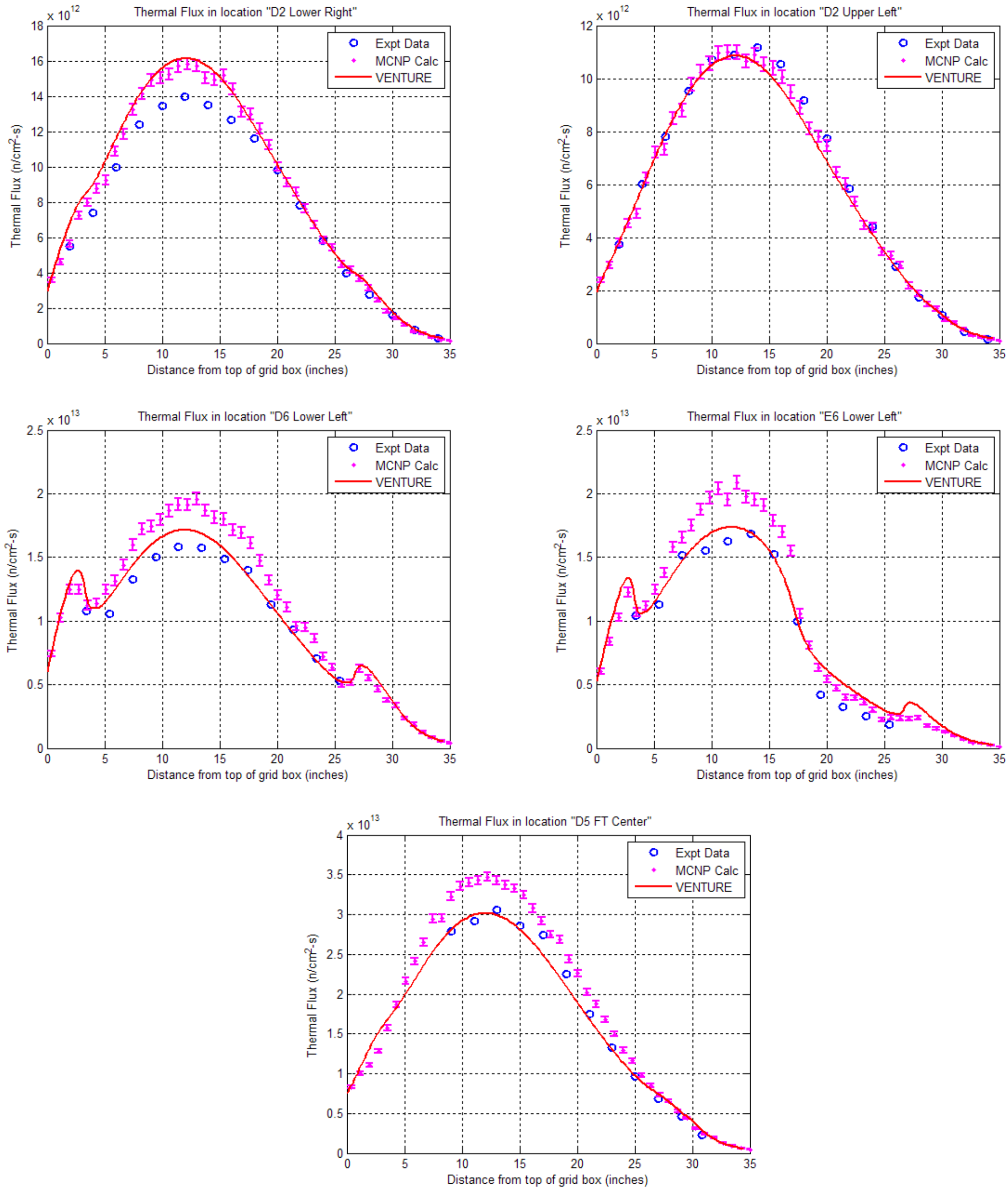


Fig. 3 Calculated vs. measured axial thermal flux profiles at various locations (M-1-3).

In these comparisons, it is important to emphasize that the 1σ uncertainty in the MCNP computations is about 0.02% $\Delta k/k$, and this is a large uncertainty when the absolute actual $\Delta k/k$ is less than 0.10%. In addition, as noted above, there is also a fair amount of uncertainty in the blade worth curves which were used to get the “measured” reactivity worths. Thus, the best we can hope for here with these small worth measurements is to be “in the ballpark” with the correct direction for the reactivity change. For the larger worths, however, a more quantitative comparison is indeed possible.

Table 3 Computed vs. measured reactivity worth results for selected configurations.

Case #	Description of the Experimental Configuration	M-1-3 BOL Core Reactivity Worths (% Δk/k)		M-2-5 at 50 MWD Reactivity Worths (% Δk/k)	
		Measured	MCNP	Measured	MCNP
1	air-filled bayonet in flux trap (D5)	0.25	0.20	0.11	0.14
2	water-filled bayonet in flux trap (D5)	0.03	0.06	--	--
3	air-filled bayonet in radiation basket (D2)	-0.01	-0.07	--	-0.05
4	air-filled bayonet in radiation basket (C2)	--	--	-0.00	-0.02
5	air-filled bayonets in both C2 and D2	--	--	-0.02	-0.08
6	air-filled bayonets in C2, D2, and E2	--	--	-0.02	-0.08
7	interchange fresh fuel assembly with the burnt fuel element in D6	--	--	0.10	0.10

Well, as apparent from Table 3, the measured and calculated reactivity worths are indeed "in the ballpark". In general, small measured reactivities map to small computed values and the correct direction of the change is consistently predicted. For the larger changes, as apparent for Case 1 for example, the magnitude of the change is also well predicted within our uncertainty constraints. In addition, for Case 7, it was estimated that the burnup associated with the fuel element in location D6 was approximately 2.75 MWD, which gives a reduction of slightly over 3 grams of U235 relative to a standard fresh fuel assembly. Thus, by replacing this burnt element with a fresh assembly, one would expect a positive reactivity addition associated with about 3 grams of fissile material near the center of the core. As apparent from Table 5, the reactivity effect was indeed positive and the predicted magnitude was the same as the measured result. For comparison, a VENTURE calculation for this fuel interchange perturbation gives 0.13% Δk/k, which is also in excellent agreement with the measured value.

Summary/Conclusion

The current validation effort has looked at critical blade heights, total blade worths, selected thermal flux profiles, and some reactivity worth measurements in both the M-1-3 and M-2-5 cores. In all cases, the computational results are reasonable and they consistently exhibit the expected behavior of the system. There are some areas that could use improvement (such as the negative reactivity bias in VENTURE and the over-prediction of some of the thermal flux profiles with MCNP), but generally, the comparisons have been quite favorable. Thus, both the VENTURE and MCNP models have successfully passed their first set of validation tests. Of course, model validation is a never-ending process -- so we plan to continually evaluate the real predictive capability of these computer models as they are used to support future operations within the UMLRR facility.

References

1. Decommissioning status for the WPI reactor at URL: http://www.nrc.gov/info-finder/decommissioning/research-test/worcester-polytechnic.html.
2. J. R. White, et. al., "Calculational Support for the Startup of the LEU-Fueled UMass-Lowell Research Reactor," Advances in Reactor Physics and Mathematics and Computation, Pittsburgh, PA (2000).
3. J. R. White and L. Bobek, "Startup Test Results and Model Evaluation for the HEU to LEU Conversion of the UMass-Lowell Research," 24th International Meeting on Reduced Enrichment for Research and Test Reactors, San Carlos de Bariloche, Argentina (2002).
4. J. R. White, et. al., "Design and Initial Testing of an Ex-Core Fast Neutron Irradiator for the UMass-Lowell Research Reactor," ANS Radiation Protection and Shielding Topical Conference, Santa Fe, NM (2002).