

Startup Test Results and Model Evaluation for the HEU to LEU Conversion of the UMass-Lowell Research Reactor

John R. White, Professor, Chemical and Nuclear Engineering Department
Leo Bobek, Reactor Supervisor, UMass-Lowell Radiation Laboratory

University of Massachusetts Lowell
Lowell, MA 01854

Abstract

The 1 MW UMass-Lowell Research Reactor (UMLRR) switched from high-enriched uranium (HEU) fuel to low-enriched uranium (LEU) fuel in August 2000. Several months prior to conversion, a detailed physics study was undertaken to fully characterize the new LEU core, with focus on providing computational support for the actual startup and on estimating the radiation environment in the various experimental facilities in the new LEU-fueled core.

During startup testing, a series of actual reactivity evaluations and thermal flux magnitude and distribution measurements were made. These startup tests not only established operability of the new core, they also allowed direct evaluation of the computational models and methods used to design and characterize the new LEU core.

This paper highlights this evaluation by summarizing the overall startup test program and the computational methods in use at UMass-Lowell, and by providing a set of comparisons between the measurement results and the computational estimates. Although some differences were observed, it is apparent from the results presented that the overall computational methodology was quite satisfactory -- since the as-built system operates essentially as designed.

Introduction/Historical Overview

The process for converting the UMass-Lowell Research Reactor (UMLRR) from high-enrichment uranium (HEU) fuel to low-enrichment uranium (LEU) fuel began in 1988. Several years of design reviews, computational modeling, and thermal hydraulic analyses resulted in a preliminary reference fuel design and core configuration based on 20 standard, MTR-type, flat-plate, 19.75% enriched, uranium silicide (U_3Si_2) fuel elements.¹⁻³ A final safety analysis for the fuel conversion was submitted to the Nuclear Regulatory Commission (NRC) in 1993.⁴ A sketch of the 1993 LEU core design is given on the left side of Fig. 1.

The NRC made two additional requests for information based on the 1993 design and the appropriate supplements were submitted in 1994 and 1997. In July 1997, the UMLRR was issued an NRC order modifying the reactor license to convert from HEU to LEU fuel. Due to a lack of Department of Energy (DOE) funding, manufacture of the LEU fuel for the UMLRR was not authorized until October 1999. During the interim between the NRC order and the funding authorization, the UMLRR reactor supervisor retired and was replaced. Upon review of the proposed LEU core configuration, the new supervisor initiated a design change to eliminate a modification to the regulating blade that was included as part of the 1993 LEU core design.

With the pending HEU to LEU conversion nearing reality, a major effort was undertaken in the summer of 1999 to update our local modeling and calculational support capabilities at UMass-Lowell, to revive and improve upon the LEU computational models from the early 1990s, and to readdress the proposed movement of the regulating blade from the D9 position to the D8 position. This work produced the proposed new reference core configuration displayed on the right side of Fig. 1 -- that does not require any physical change to the HEU core other than the replacement of the fuel assemblies and the re-configuration of the graphite reflectors and radiation baskets. The study also provided a wealth of computational information to help guide the actual core conversion process and to support the continued use of the experimental facilities within the new LEU core configuration.⁵⁻⁷

The actual conversion process took place during the summer of 2000. The receipt and inspection of the new LEU fuel was completed in late July 2000 and, guided by the pre-analysis of the critical loading from Ref. 6, the LEU reactor core was loaded to a critical configuration on August 4. After achieving a final core configuration (which was slightly different from the proposed 1999 layout in Fig. 1), the process of evaluating the reactor operating characteristics was undertaken. Several weeks of testing and data analyses ensued and the new LEU core was found to operate essentially as designed. This paper highlights the three major startup tests that were performed during the HEU to LEU conversion process -- the LEU critical loading process, the evaluation of blade worth distributions in the final core configuration, and the mapping of the thermal flux within the new LEU core -- and it compares the measured and computed results for the new LEU-fueled UMLRR. This comparison highlights several operating characteristics of the new core and it provides a direct evaluation of the models and methods used to design and characterize the new LEU core.

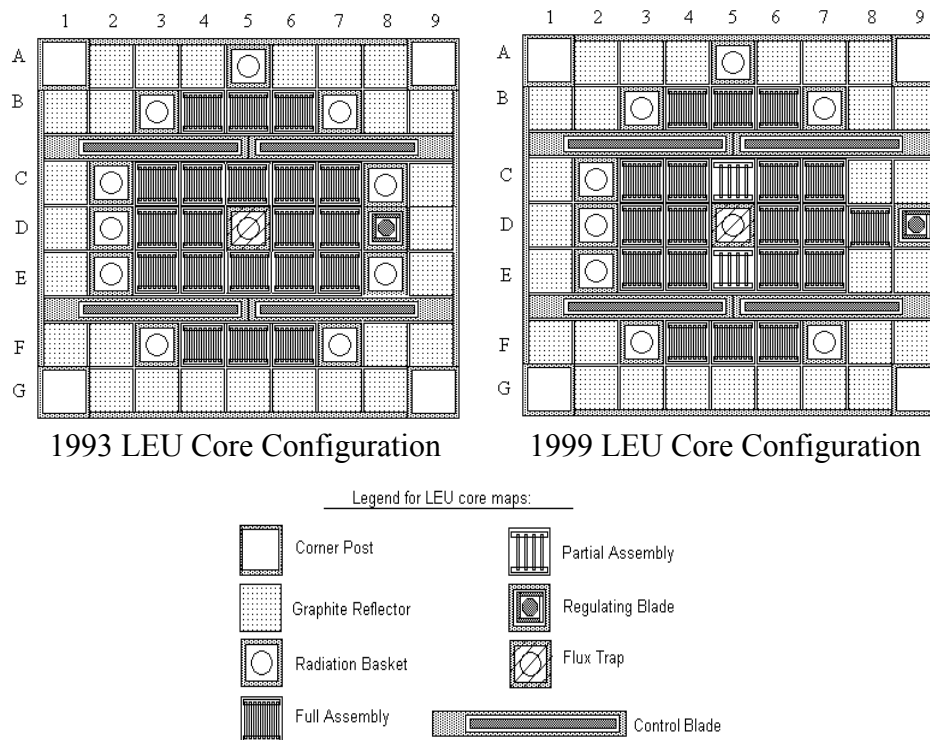


Fig. 1 LEU reference core designs for the UMLRR.

Computational Methodology

The usual approach to deterministic reactor physics modeling at UMass-Lowell involves heavy reliance on the VENTURE and DORT codes.⁸⁻⁹ VENTURE is used to do few-group diffusion theory calculations for the core region and its immediate surroundings, and DORT is utilized to perform multigroup transport computations for the determination of in-core neutron and gamma spectra and for all ex-core radiation transport analyses. The VENTURE and DORT modeling steps are highly-coupled via a series of in-house Matlab codes that assist in the model-building process, in the conversion of the VENTURE-calculated fission source to a DORT input distributed source, and in the post-processing of results from both codes (see Refs. 6 and 7 for further details on the Matlab-based processing codes). In short, VENTURE is used to address core operations (reactivity worths, power distributions, etc.) and DORT is used to quantify the space and spectral distribution of the neutron and gamma radiation environments within the various experimental facilities in the UMLRR.

To support the HEU to LEU conversion work, a significant effort was made to update existing models of the reactor and to generate new LEU-specific cross section libraries for future analyses.⁶⁻⁷ In particular, consistent sets of DORT and VENTURE cross sections were developed specifically for the LEU core using several modules of the SCALE system¹⁰ and the base VITAMIN-B6 library.¹¹ The original 199/42-group energy structure in VITAMIN-B6 was collapsed to 47 neutron groups and to 20 gamma groups for the DORT calculations and to a simple 2-group neutron library for use in the VENTURE eigenvalue calculations.

The bulk of the calculations used to support the startup tests utilized a variety of 2-D XY and 3-D XYZ VENTURE models. The 2-D XY models have a 175x170 mesh grid with material configurations that correspond to the axial mid-plane of the core. They use a simple transverse buckling approximation to account for neutron leakage in the z-direction. These models are used to estimate the planar spatial flux and power distributions and XY peaking factors at the axial midpoint, and to evaluate the excess reactivity, total blade worths, and other large-scale reactivity effects in various LEU core configurations. The 3-D VENTURE models have a 130x121x65 mesh arrangement in the three coordinate directions, with nearly 950 homogeneous zones in the full 3-D configuration to allow for control movement, for fuel burnup studies, and for flexibility in the placement of irradiation samples at different axial locations. The 3-D models have been used to estimate 2-D versus 3-D effects, to develop detailed blade worth curves, and to address small sample worths. In general the XY and XYZ models are quite detailed and they allow full characterization of core operations -- within the normal limitations of a few-group diffusion theory approximation.

The Initial LEU Core -- Simulation vs Measurement

A 21-element core with 19 full fuel elements and 2 partial elements was chosen as the best candidate for the initial startup of the LEU-fueled UMLRR.⁵ As indicated above, both 2-D and 3-D VENTURE models have also been developed and these have been used to predict a variety of neutronic characteristics within the new core. A top view of the material layout for the initial reference core is shown on the right side of Fig. 1 along with a legend to help identify the various components within the system. This figure depicts the final goal of an initial loading procedure.

A set of formal in-house procedures is used by the operations staff when performing a critical loading for a new configuration. The basic idea is to carefully monitor the subcritical multiplication associated with each new configuration as one goes from only a few elements towards a configuration that leads to a critical system. As the number of fuel elements in the core increases, the subcritical multiplication increases, eventually approaching infinity as a critical configuration is reached.

In monitoring a particular critical loading sequence, one often generates the so-called 1/M line for each step in the sequence. The neutron population and detector count rate are roughly proportional to the neutron source strength and inversely related to the degree of subcriticality given by 1-k, where k is the standard neutron multiplication factor. Thus, the initial count rate for some source-detector configuration can be represented as¹²

$$C_0 = \frac{\alpha_0 S}{1 - k_0} \quad (1)$$

where α_0 is a proportionality constant. If the fuel configuration is changed, possibly by adding additional assemblies at the i^{th} step of a critical loading sequence, eqn. (1) becomes

$$C_i = \frac{\alpha_i S}{1 - k_i} \quad (2)$$

where k_i is the multiplication factor associated with the i^{th} core configuration. The subcritical multiplication for this configuration is defined from the ratio of the current count rate and initial count rate, or

$$M_i = \frac{C_i}{C_0} \quad (3)$$

Substituting eqns. (1) and (2) into the “inverse” of this expression gives

$$\frac{1}{M_i} = \frac{\alpha_0}{\alpha_i} \frac{1 - k_i}{1 - k_0} = \beta_i (1 - k_i) \quad (4)$$

where β_i is simply another proportionality constant (β_i is set to unity in the VENTURE simulations). The important feature here is that the inverse subcritical multiplication factor, 1/M, is approximately a linear function of the neutron multiplication factor, k. In particular, a plot of 1/M using two known values can be easily extrapolated to the 1/M = 0 point -- which gives a prediction of when the system will be critical.

The numerical simulation of the initial critical loading experiment for the new LEU core involved the computation of the neutron multiplication factor, k_i , for several different loading configurations. With this information, a standard 1/M plot could be generated; simulating what might be expected during the actual approach to critical for the new LEU core. During actual loading, the detector count rate, C_i , for each configuration is available and this also allows the development of the 1/M plot based on actual reactor measurements.

The resultant 1/M plots for the VENTURE simulation and the actual reactor measurements are given in Fig. 2. The data for the simulated plot were generated with 2-D VENTURE k_{eff} calculations for 14 different assembly configurations. The actual reactor loading approached a

critical configuration with 16 discrete core configurations. Although the core layouts for the simulation and the actual loading were not identical, the trend towards a critical configuration is expected to be quite similar, especially as one approaches the critical state.

The process started by loading the core periphery with an arrangement of graphite reflectors and radiation basket assemblies that is consistent with the proposed final core configuration as shown in Fig. 1. This arrangement leaves 22 centrally located grid positions available for the placement of full and partial fuel assemblies and the central flux trap irradiation facility. Initially, only full fuel elements were loaded into the core, starting in the central core region. New assemblies were then added in a systematic manner, trying to maintain as much symmetry as possible, until the core is nearly critical. At this point, the full fuel assembly in D5 was removed and replaced with the flux trap assembly. In addition, the full fuel elements in C5 and E5 were exchanged with two partial assemblies. Both these moves decrease the multiplication factor, k_{eff} , and increase the inverse subcritical multiplication, $1/M$, in the system. This discontinuity is apparent in Fig. 2 with the start of a new set of $1/M$ lines with 14 assemblies loaded (12 full and 2 partial fuel elements). After this configuration change, the normal systematic loading of full fuel assemblies was continued until a critical core was reached. The final step, of course, was to load all remaining assemblies to achieve the loading pattern given in Fig. 1 to provide some excess reactivity for normal operation of the reactor over an extended period of time.

From Fig. 2, with just full fuel present, we see that VENTURE predicted the LEU core would be critical with 16 elements. However, actual data show that criticality would not be achieved until 17 full fuel elements are loaded. Thus, the VENTURE calculations are somewhat conservative, with a small over-prediction of the fuel reactivity. After replacing the full fuel elements in positions C5, D5, and E5 with the flux trap and two partial fuel elements (with half the U235 loading of a full element), criticality is not reached until 19 and 20 elements were loaded, respectively, for the VENTURE simulations and actual initial loading. Thus, again, the VENTURE data slightly over-predict the core reactivity. The actual initial critical configuration, with 18 full and 2 partial assemblies was designated as the M-1-1 core. As a last step, the final full element was placed in position F6 to give the proposed initial core configuration shown in Fig. 1 (referred to as the M-1-2 configuration).

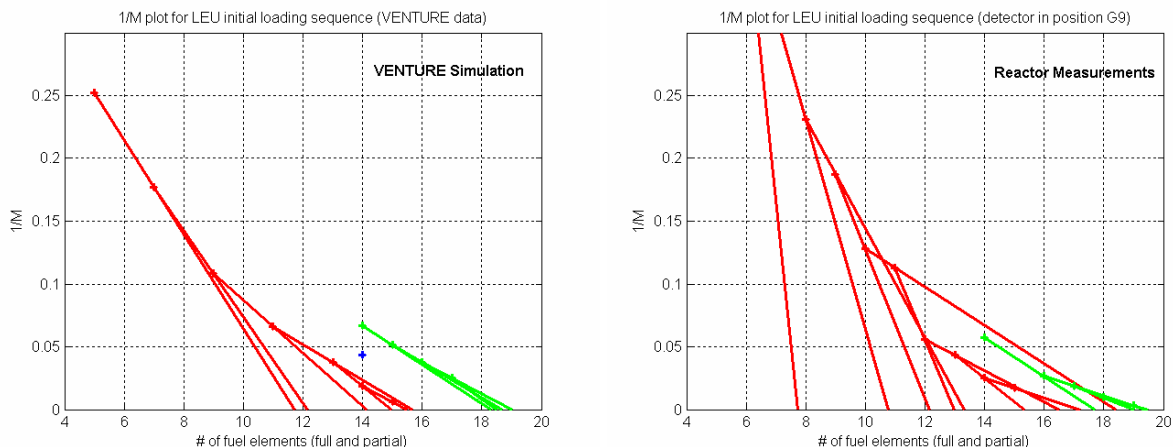


Fig. 2 $1/M$ plots for the initial loading sequence (simulation vs measurement).

The M-1-2 layout was expected to be the startup core for the LEU-fueled UMLRR. However, the banked critical blade height for this configuration was about 17.2 inches withdrawn, with an estimated excess reactivity of 2.3 % $\Delta k/k$. The 3-D VENTURE calculations predicted the critical height for the M-1-2 core would be about 16.0 inches withdrawn with an excess reactivity of 3.2 % $\Delta k/k$. For extended operation of the initial configuration, an excess reactivity of 3 to 4 % $\Delta k/k$ is desired. Thus, to increase reactivity, the four water basket assemblies adjacent to the fuel (see Fig. 1) were replaced by graphite reflector elements, with the water baskets being moved to the core periphery. Anticipating a need for fine reactivity adjustments, prior VENTURE computations indicated that this change would increase reactivity by about 1.2 % $\Delta k/k$, which would put the actual core excess into the desired range. The resultant core configuration, designated as the M-1-3 configuration, is shown in Fig. 3. This core layout was the final startup core for the LEU-fueled UMLRR. The actual banked critical height for this configuration was about 15.1 inches withdrawn, with a VENTURE prediction of 14.6 inches. Thus, the computational model and the actual measurements are quite reasonable, and all the preliminary VENTURE analyses proved to be quite valuable during the actual startup of the new LEU core.

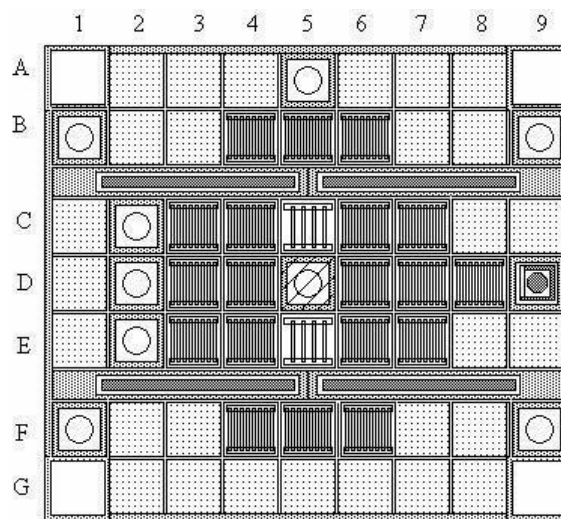


Fig. 3 LEU final startup core configuration (M-1-3).

Blade Worth Evaluations -- Simulation vs Measurement

Differential and integral worths for the four large control blades and for the regulating blade in the UMLRR are generated experimentally in conformance with an in-house special procedure based on the stable positive period method. In this method, the blade to be measured is initially fully inserted into the core, with the remaining blades banked at an axial height that gives a just critical configuration. The blade of interest is then moved out some amount. The associated reactivity change is calculated from the stable reactor period (obtained from data read from the reactor control panel) using the six delayed neutron group reactivity equation. The change in the control blade motion and the reactivity change are recorded, which gives a single experimental value of the differential worth at the midpoint of the blade motion. The reactor is then brought back to critical by moving the remaining blades, and another sequence is initiated to obtain

another dp/dz value at a new z location. This process is repeated until the full axial distance has been traversed.

A mathematical model is then fit to the discrete differential worth data to generate a continuous differential reactivity versus position worth curve for each blade. The continuous differential worth curve is then integrated to form the integral reactivity versus blade position curve. These curves are used during operations to evaluate the reactivity effect of any changes made to the reactor. The procedure outlined above is followed for each of the control blades and the regulating blade in the UMLRR. These “blade calibrations” are required any time a major configuration change is made.

For the full 25-year lifetime of the HEU-fueled UMLRR, a simple theoretical model was used to fit the differential worth data. In particular, this theoretical model, which is derived from a very simple bare homogeneous 1-group diffusion theory model of the system, is given by

$$\frac{d}{dz} \rho(z) = a_1 \left(1 - \cos \left(\frac{2\pi z}{H} \right) \right) \quad (5)$$

where H represents the full range of the blade in inches ($H = 26$ inches for the UMLRR) and z gives the blade position in inches withdrawn. Equation (5) and its integral lead to the familiar symmetric “bell-shaped” differential blade worth curves and to the symmetric “S-shaped” integral blade worth curves that can be seen in most reactor theory texts.¹³ Its biggest drawback is that it gives axially symmetric differential and integral worth curves. In practice, however, this rarely occurs in the UMLRR because the system is operated with the control blades banked at some axial position within the active fuel region. This is required to offset any excess reactivity in the system for operation at a just-critical condition -- as indicated above, the expected critical height for the M-1-3 LEU core configuration is 15.1 inches withdrawn. This situation leads to an axially asymmetric neutron flux distribution, with the peak flux occurring below the axial centerline.

The same situation is also encountered when performing blade worth calibrations, in that the remaining three blades are inserted into the core at some position while the worth of the fourth blade is being measured. This is required to maintain the system near critical and it always leads to differential blade worth data that show a bottom-peaked distribution. The problem, of course, is that eqn. (5) cannot model this asymmetry; so the curve fits are never very good.

Prior to the actual HEU to LEU core conversion, a series of 3-D VENTURE computations for the proposed initial core configuration (the M-1-2 core) were made that simulate the experimental blade calibration procedure described above. This work led to the development of a somewhat better mathematical model for fitting the blade worth data.⁶ The new model combines a cubic polynomial with the theoretical sinusoid shape, as follows:

$$\frac{d}{dz} \rho(z) = c_1 + c_2 z + c_3 z^2 + c_4 z^3 + c_5 \cos \left(\frac{2\pi z}{H} \right) \quad (6)$$

A series of blade worth curve fits using eqns. (5) and (6) were made using the experimental data for the actual startup core (M-1-3) and the VENTURE simulated data for the proposed startup core (M-1-2) (note that the VENTURE data were not re-generated for the M-1-3 configuration because the M-1-2 and M-1-3 cores are so similar). Figure 4 contains an example of the results

from this exercise, with specific discrete data and some curve fits for Blade #1 (the lower left blade in Fig. 3). The discrete VENTURE data and actual measured data are identified as individual points and the continuous lines represent the curve fits using eqns. (5) and (6) for the experimental data (the VENTURE data gives very similar curve fits).

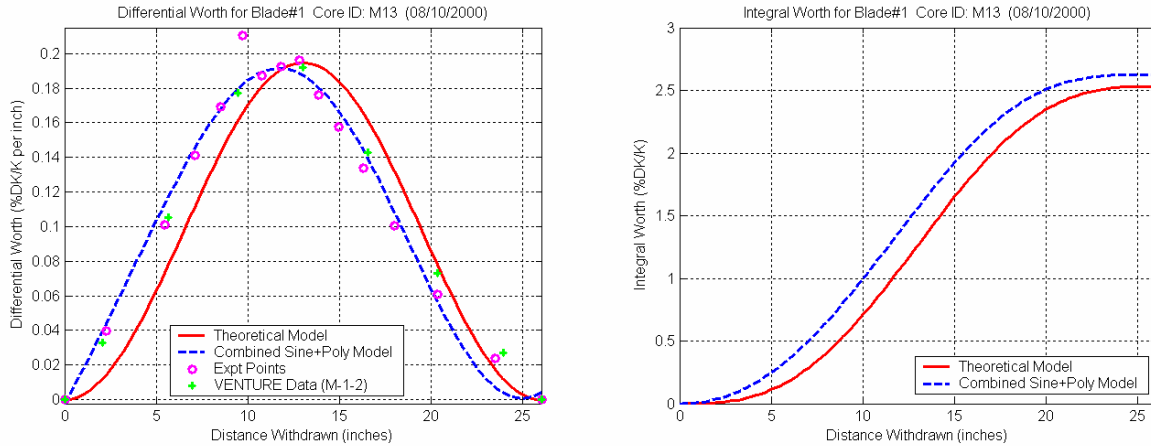


Fig. 4 Differential and integral blade worth results for Blade #1 (M-1-3 core).

Focusing first on the differential curves, we see that the combined model with the cubic polynomial plus sinusoid gives a much better fit to the discrete worth data. Both models have the expected rough “bell-shaped” behavior, but the use of eqn. (6) more accurately represents the slightly “bottom-peaked” nature of the differential worth profile. Although this new mathematical representation is not perfect (note the somewhat awkward behavior at the ends of the blade), a simple visual inspection of the plots clearly indicate that the combined polynomial and sinusoid should be the model of choice for fitting measured blade worth data at the UMLRR. Also, because of the asymmetric behavior that is now modeled reasonably well, the new curve fit model should give a better estimate of the integral blade worth curve and a better prediction of the actual excess reactivity in the system.

Also of interest is the comparison of the VENTURE simulated data and the measured blade worth data. Clearly, from Fig. 4, we see once again that the 3-D VENTURE model does a very nice job of estimating the real behavior of the new LEU core.

Table I contains summary information from all the individual blade worth calibrations for the LEU startup core. Included here are the total blade worths and the estimated core excess reactivity for the two curve fits and for the 3-D VENTURE data versus the actual measured data. The total worths are obtained directly from the $z = 26$ inch point on the appropriate integral worth curves and the excess reactivity is determined by integrating the additional worth above the critical height for the four large control blades (the regulating blade worth is not included here). Notice that the simple theoretical model severely over estimates the core excess reactivity for the M-1-3 core measured data because of the forced axial symmetry that is inherent in this representation. The difference between the symmetric and asymmetric distributions is not nearly as severe for the VENTURE estimates because the M-1-2 core was less reactive and the blades were further out of the core -- resulting in a slightly less bottom-peaked blade worth distribution (this can also be seen in Fig. 4 for the Blade #1 differential worth profiles).

Also note that, except for the regulating blade worth, all the VENTURE results are very comparable to the actual measured results. The rather poor regulating rod comparison was expected because the small physical size and complicated geometry of the regulating blade could not be modeled explicitly in the VENTURE models. Finally, it should be noted that, because of the low worth of the regulating blade, only a few experimental points are usually available. Thus, the use of the polynomial plus sinusoid curve fit model is not appropriate for this blade calibration using actual measured data.

Table I Comparison of measured and calculated blade worths and core excess reactivity.

Parameter	Measured $\% \Delta k/k$ data for the M-1-3 core		VENTURE $\% \Delta k/k$ data for the M-1-2 core	
	Theoretical Model	New Model	Theoretical Model	New Model
Blade 1 Worth	2.53	2.63	2.57	2.71
Blade 2 Worth	2.38	2.47	2.62	2.78
Blade 3 Worth	3.34	3.32	3.22	3.41
Blade 4 Worth	3.19	3.20	3.29	3.49
Excess Reactivity	3.91	2.95	3.25	3.16
Reg. Blade Worth	0.28	--	0.38	0.40

Thermal Flux Mapping -- Simulation vs Measurement

A combination of gold foils and copper wires were used to perform thermal flux mapping in selected locations of the LEU startup core as illustrated in Fig. 5. 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 gold foils and some comparison copper wires were installed near the axial midpoint of two standard sample bayonets and then lowered into the radiation baskets in grid locations C2 and D2. Five long copper flux wires (nearly 3 feet long in some cases) were placed between the fuel plates of un-irradiated fuel elements in positions D6 and E6 and into the D2 and D5 irradiation positions as shown. The irradiations were then performed at an indicated power level of 100 watts for 30 minutes.

After irradiation, the wires and foils were removed and counted on a gamma spectrometer. An inter-calibration between the gold foils and copper wires provided an absolute flux distribution at the five wire locations indicated in Fig. 5. All the measured flux distribution data were then normalized to a nominal power level of 1 MW and compared to the results from the 3-D VENTURE computational model for the M-1-3 core. However, because of the discrete modeling of the axial material distribution in the VENTURE models, the blades were banked at 14.2 inches withdrawn for the VENTURE calculations instead of the actual 15.3 inch level associated with the actual measurements.

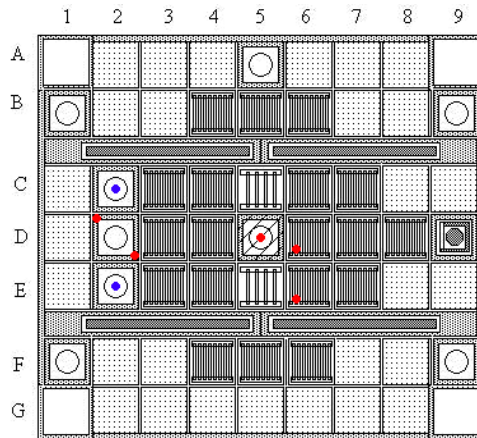


Fig. 5 Location of the gold foils and copper wires for the flux mapping measurements.

Summary results from these comparisons are shown in Fig. 6. The individual points on these curves represent the experimental values of the absolute thermal flux and the continuous lines are associated with the VENTURE results. The top two plots highlight the two copper wires in the D2 position, with relatively good agreement for the wire nearest the fuel and only fair agreement with the wire on the far side of the basket away from the core. Since the modeling here only uses two-group diffusion theory, one would expect less accuracy with distance from the core region. Thus, the results shown here are consistent with expectations.

The results for the wires in the two fuel assemblies are shown in the middle plots in Fig. 6. The particular locations for the wires in the D6 and E6 fuel assemblies were chosen because these were near the locations of the peak power density from the VENTURE calculations. As apparent, the VENTURE results were quite reasonable, with a somewhat better representation of the full axial distribution in the D6 location relative to the E6 position. Again this is consistent with expectations since the copper wire in E6 is very close to Blade #4 which is inserted to a depth of about 18.4 inches above the grid box. The large flux gradient observed in this area is hard to model with two-group diffusion theory. However, even with this inherent limitation, the VENTURE profiles are reasonable. Finally, we note that the LEU fuel assembly height is 30 inches, with 23.5 inches of fuel meat and 3.25 inches of aluminum structure and water just above and below the active fuel region. The VENTURE calculations clearly show the expected thermal flux peak near the fuel/reflector interface (although there are limited experimental data to validate the computed profile).

Finally, the bottom curve in Fig. 6 shows the computed and measured thermal flux profiles in the center of the flux trap assembly in location D5. The agreement here is excellent; probably due to the fact that it is a relatively large homogeneous centrally located region that is easily modeled with few-group diffusion theory. This experimental location has the highest flux magnitude within the UMLRR and it is used whenever high fluence or fluence rates are needed.

Conclusions

The conversion of the UMLRR from HEU to LEU fuel is finally complete. Thorough testing of the startup core and the measurement of several key parameters have yielded sufficient data showing that the new LEU core will operate well within the bounds set forth in the FSAR Supplement⁴ and that the methods and models used to design and characterize the new core

performed quite satisfactorily. The new LEU-fueled facility, with some post-conversion enhancements, has been in routine operation for the last two years since the conversion was complete. We expect that the new LEU core will continue to provide enhanced operational capability to support the education and research mission of the UMLRR for many years into the future.

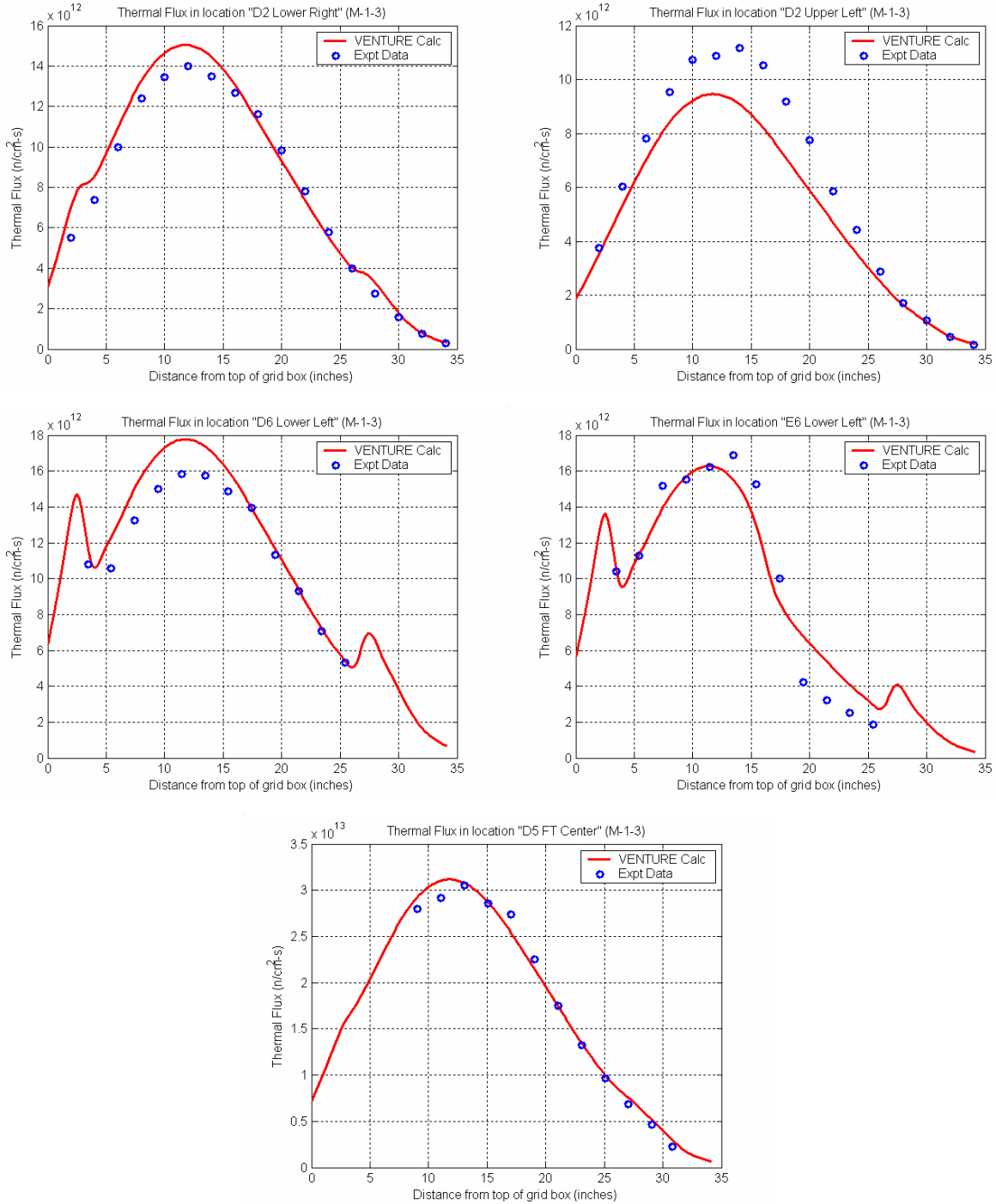


Fig. 6 Axial thermal flux profiles at various locations (M-1-3).

Acknowledgements

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