Preliminary Results and Recommendations for Replacing the Flux Trap Assembly in Location D5 in the M-2-5 UMLRR Core Configuration

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May 26, 2015

Introduction

In preparation for some scheduled maintenance to replace one of the control blades in the UMass-Lowell research reactor (UMLRR), it was discovered that the flux trap element had swollen beyond tolerance and could not be placed back into the core. The exact cause of the swelling is not known at present -- this will be addressed at a later time. The immediate result of the swollen flux trap element was a delay in the scheduled replacement of the control blade and the need for a replacement assembly in the D5 location. The choice for a replacement element was limited to a standard radiation basket or a graphite reflector element, since a change in the fuel assembly configuration would require a re-evaluation of all the core physics parameters along with the re-characterization of several experimental facilities -- and this was to be avoided, if possible. However, replacing the flux trap with a graphite reflector element was not ideal either, since this implies the loss of location D5 as an experimental position. Thus, the remaining initial best choice was to replace the flux trap with a standard radiation basket.

The only difference between the flux trap assembly and a radiation basket is that the space between the inner irradiation hole and the outer Al can contains graphite in the flux trap design instead of water for the standard radiation basket element. This specific design feature was selected nearly 25 years ago when the early calculations to support the conversion of the UMLRR from HEU to LEU fuel were initiated.[1] The goal of the "new" graphite radiation basket element was simply to minimize power peaking in the nearby fuel assemblies -- since graphite gives a lower peak thermal flux in these locations relative to water. Thus, before a radiation basket could be used to replace the existing flux trap element in location D5, the power peaking factors needed to be re-evaluated using our existing models and methods for analyzing the current M-2-5 UMLRR core configuration.

Thus, the purpose of this internal report is to provide documentation for the recent computational studies and to justify why the graphite reflector was selected as the best replacement for the flux trap element at the present time. It also addresses the need for a re-evaluation of the basis for some of the UMLRR Technical Specifications, since we now know that the power peaking factors used in the original safety analysis were lower than can be achieved in normal operation of the facility. Thus, follow-up studies are currently underway to determine the impact of the larger peaking factors, and to determine if a standard radiation basket can be safely used in the center of the core in location D5, since this configuration leads to the highest observed power peaking factors. This configuration is desirable from an operations perspective, since an irradiation facility in this location offers the highest thermal flux available within the UMLRR.

The Computational Tools

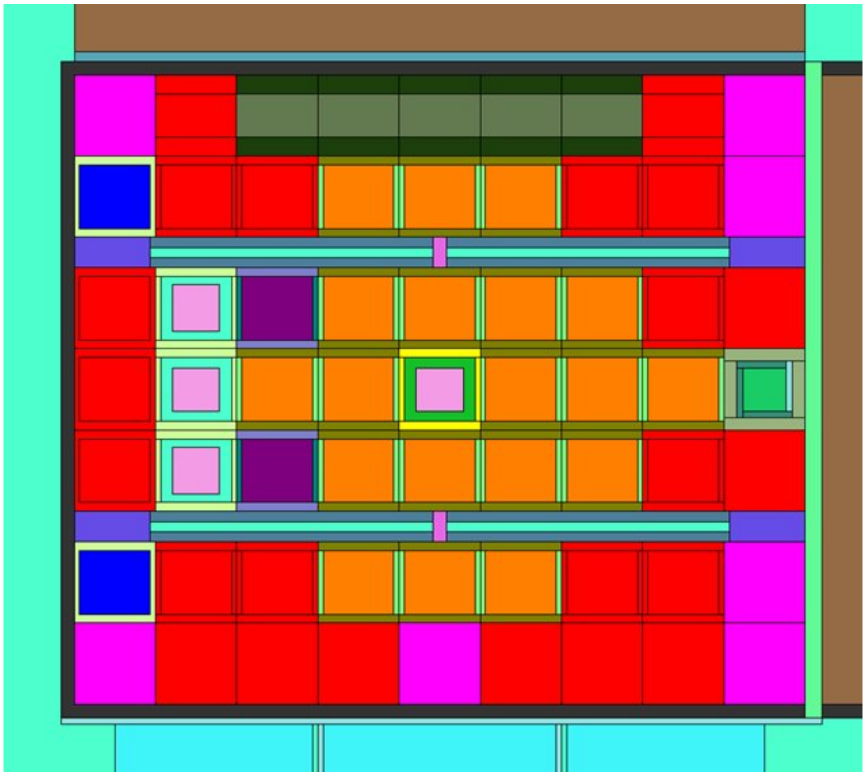
The computational tools and models used for the analysis of the UMLRR have evolved significantly over the last 25 years. In the early 1990s when the HEU to LEU conversion design studies were first performed, we relied heavily on a variety of 2-group 2-D models within the VENTURE code to determine the reactivity parameters and power distribution within the facility.[1] In the 1999-2000 timeframe, the first 3-D VENTURE model was developed along with a series of Matlab-based preprocessing and post-processing tools to help visualize the geometry and material configurations and to analyze the results.[2] Also available at this time were a series of 2-D models within the DORT code -- these were used to get neutron and gamma spectra information within the in-core and ex-core experimental facilities within the UMLRR.[3] In addition, a combination of several 2-D VENTURE and DORT models were used to design and evaluate the fast neutron irradiator (FNI) that was installed within the facility in 2002.[4] Finally, in 2011, the first detailed 3-D MCNP model of the facility was generated, and this model has essentially replaced the use of DORT to obtain detailed neutron information for most of the experimental facilities within the UMLRR (note, however, that the full FNI is still not included within the current MCNP model).[5-6]

Thus, most of the current physics studies within the UMLRR use either the 2-group 3-D VENTURE model or the detailed 3-D MCNP model of the core and its immediate surroundings. Most of the calculations use the beginning of life (BOL) fuel densities and the M-2-5 configuration that has been the actual core layout since the installation of the FNI in 2002. The VENTURE model is used for most preliminary computations since each eigenvalue-flux calculation runs in under 20 minutes on a standard personal computer. The model uses homogenized spatial zones with effective 2-group cross sections generated with the SCALE package. This model, although it has several limitations (including a –2% reactivity bias[6]), has served us well as a design and analysis tool and, even with the MCNP model now available, the 3-D VENTURE model is still very useful as a scoping tool, since preliminary analyses can be performed within just a few days -- whereas it can take a couple of weeks or more for a full MCNP analysis (due to the long run times associated with this code -- often 20 hours or more per calculation). Thus, the usual approach is to get some quick preliminary results with VENTURE and then, if deemed necessary, to follow-up with more detailed MCNP calculations. This was the approach taken in this study.

For reference, Fig. 1 shows the top view of an XY cut through the M-2-5 core geometry just below the core axial centerline for both the VENTURE and MCNP models. Here it is easy to see the homogenized regions within the VENTURE model relative to the explicit detail associated with every assembly that is included in the MCNP geometry. The focus of this study is on the D5 location which is directly in the center of the core layout, and on the adjacent D6 fuel location which is just to the right of D5 -- since this is often the location of the peak power density in the core.

The VENTURE Scoping Study

The initial evaluation for a replacement element for the swollen flux trap assembly focused on the new peaking factors and the reactivity effect associated with the assembly change. As noted above, our first choice was to simply replace the graphite basket element with a standard water-filled radiation basket -- since, with this choice, we would not lose the D5 experimental location. If either the change in peaking factor or the reactivity change was too large, then our



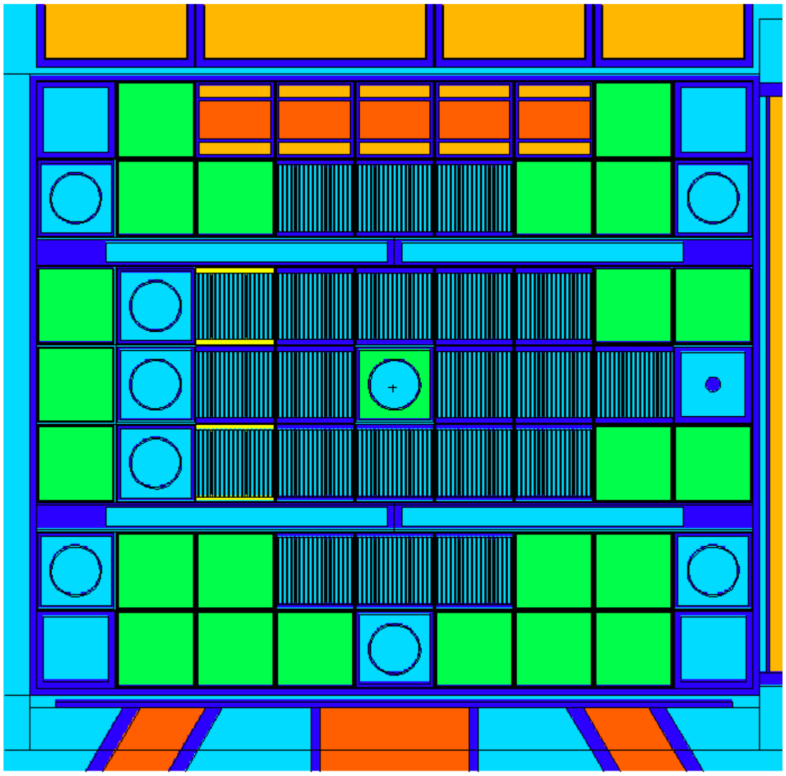


Fig. 1 XY cuts just below the core centerline in the M-2-5 configuration for both the VENTURE (upper sketch) and MCNP (lower figure) models.

second option was to put a graphite reflector in D5, since it was expected to give lower peaking factors and only increase the excess reactivity of the core by a small amount.

Based on this plan, three VENTURE models were run and analyzed:

1. The reference M-2-5 configuration with the flux trap (FT) in location D5.
2. The same as Case 1 with a standard radiation basket (RB) in position D5.
3. The same as Case 1 with a graphite reflector (GR) in location D5.

To facilitate a comparison of the peaking factors for the three cases, a short Matlab code was written to read the VENTURE power density interface file (pwdint) and to generate both radial and axial peaking factors for each configuration. In addition, since each fuel assembly in the current model has an 8×7 array of nodes in the xy plane, we also calculated, for the first time, an intra-assembly peaking factor. Thus, four values are of interest here, as follows (see the Appendix for the detailed equations used to compute these values):

f_a = assembly peaking factor = power generated in assembly a divided by the average assembly power

f_{za} = axial peaking factor in assembly a = peak linear heat rate in assembly a divided by the average linear heat rate in that element

f_{xyza} = total intra-assembly peaking factor in element a = peak power in assembly a divided by the average power in element a

f_{xya} = intra-assembly radial peaking factor = total intra-assembly peaking factor divided by the axial peaking factor in element a

In previous safety evaluations, the overall radial and axial peaking factors, f_{xy} and f_z, were determined from separate xy and yz 2-D VENTURE models. For the radial peaking factor, the value of f_{xy} was determined as the ratio of the peak power density divided by the average power density in the xy control-out model. For the axial profile, a computed axial profile with the blades 15″ withdrawn in the yz model was used to determine f_z. In particular, $f_{xy} = 1.45$ and $f_z = 1.39$ were estimated back in 1991 (see Ref. 1) and these values were used within the FSAR Supplement for Conversion to LEU Fuel and as the basis for the Technical Specifications for the LEU cores.[7-9]

For the current study, the four large control blades were at the BOL critical position (14.9" withdrawn) since this configuration gives rise to the largest axial peaking factors. Table 1 summarizes the 3-D VENTURE results for the three configurations analyzed here. As apparent, these results suggest that putting the radiation basket in D5 will lead to a relatively large reactivity decrease and to an increase in the power generated in the fuel plates near the water-filled radiation basket assembly. Although the values of f_a and f_{za} are not significantly different from the reference M-2-5 values (with the flux trap in D5), there is clearly a larger intra-assembly power tilt, which leads to a larger overall radial peaking factor of nearly 2.0. This behavior is also clearly shown in Fig. 2 which compares the power density profiles along an x-directed line through the D5 location for the three cases of interest here. In fact, these new data imply that even the reference core configuration with the graphite radiation basket gives a value of f_{xy} (the overall radial peaking factor that defines the hot plate in the facility) that is about 20% greater than the value of f_{xy} that was used in previous safety evaluations. This latter result, by itself, implies that a new look at the previous safety evaluations is needed to address the impact of the higher than expected overall peaking factor. And, until this new safety evaluation is complete, any configuration that significantly increases the power generated in the hot plate within the facility cannot be allowed. Thus, the current preliminary analysis says that simply replacing the swollen flux trap element with a standard water-filled radiation basket is not an option until additional studies can be performed to evaluate the impact of the increased peaking factors. And, in addition, it says that a new safety analysis is needed even for the reference core, since the peaking factors here are larger than previously used. An effort is already underway to address these new findings!

Table 1 M-2-5 VENTURE Results with Different Elements in Position D5

Property	**Flux Trap**	**Radiation Basket**	**Graphite Reflector**
%Δk/k	--	-0.68	+0.05
f_a	1.43	1.48	1.39
f_{za}	1.37	1.38	1.37
f_{xya}	1.22	1.34	1.15
$f_{xy} = f_a \times f_{xya}$	1.74	1.98	1.59

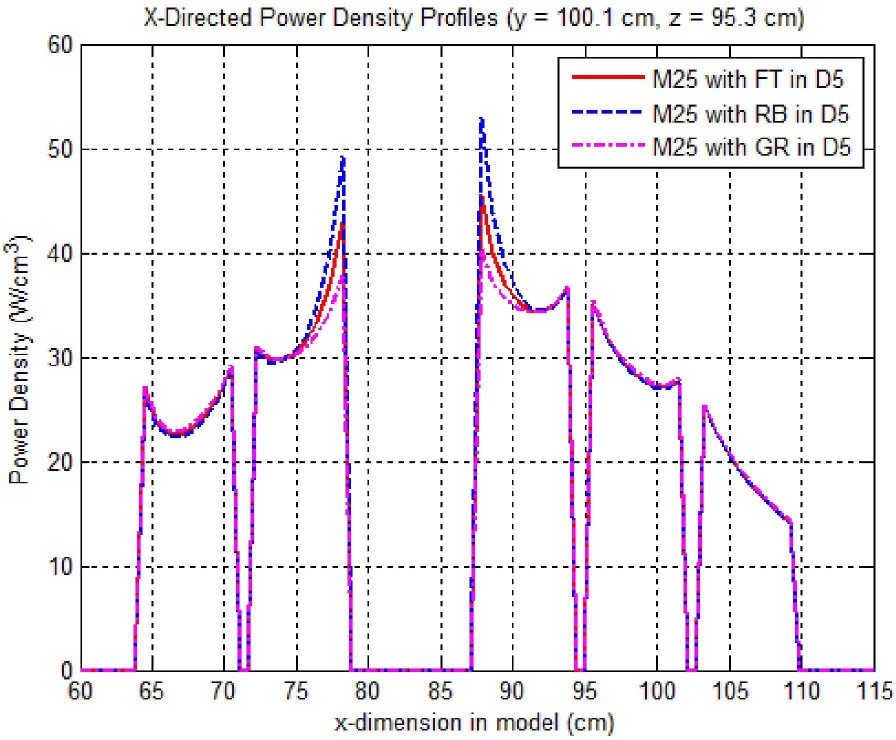


Fig. 2 Power density profile along the x-direction through the D5 location just below the core centerline in the reference and modified M-2-5 configurations.

Thus, for current operation of the UMLRR, we focused our attention on the option that replaces the flux trap element with a graphite reflector. This option is not ideal, of course, since it eliminates the high flux experimental location in the central region of the UMLRR core. However, Table 1 and Fig. 2 show that the peaking factors are even lower than the reference M-2-5 core and that only a small increase in core excess reactivity should be expected. Thus, the configuration with the graphite reflector in position D5, designated as the M-2-7 core, was selected as the new reference.

On May 13, 2015 the M-2-7 core with a graphite reflector (GR) in location D5 was physically constructed and this new configuration went critical with the four large control blades at about 16.2 inches withdrawn with the RegBlade at 8 inches out. This corresponds to a measured increase in reactivity of about 0.45 %Δk/k relative to the previous M-2-5 critical configuration with the blades nearly 16.9 inches withdrawn. Thus, as apparent from Table 1, the VENTURE code under-predicted the expected change in positive reactivity by a relatively large amount -- which clearly indicated that additional modeling with MCNP would be necessary. Although the error in the predicted reactivity increase was greater than expected, the fact that the 2-group diffusion theory estimate from VENTURE has some error is not really a surprise, since previous comparisons between VENTURE and MCNP have shown relatively large differences in prediction capability for material variations made in the central D5 location -- this was discovered when doing some calculations to design a void-worth experiment for use in the D2 and D5 locations.[10] Thus, the next phase of this study was to model and run the same three cases as described in Table 1 within the MCNP code.

The MCNP Results

Similar calculations to those performed with VENTURE have also been completed with MCNP. However, to get a better model prediction of the measured reactivity change associated with the M-2-7 versus M-2-5 core, the BOL MCNP models were run with the four large control blades at the 16.9 inches out level (the current critical height for a xenon-free M-2-5 core). The same three cases as listed above were run with 400 million histories which gives a 1σ standard deviation in the multiplication factor, k, of about 0.00004, which leads to a 3σ uncertainty in the Δk/k estimates less than ± 0.0002 -- thus, the MCNP predictions for the change in reactivity should be quite reasonable.

Summary results for the reactivity evaluations are given below in Table 2, where we see that both cases give a larger reactivity change than the VENTURE predictions. In addition, we see that the predicted $\Delta\rho$ for the M-2-7 core of 0.60 %Δk/k is certainly more consistent with the actual measured result of 0.45 %Δk/k than obtained for the VENTURE calculations -- thus, the very detailed MCNP model gives a more reasonable estimate, as expected.

Table 2 MCNP %Δk/k Results Relative to M-2-5 with Different Elements in Position D5

Radiation Basket	Graphite Reflector
-1.10	+0.60

Concerning additional results beyond the reactivity evaluation, several ***fmesh*** flux tallies were generated as part of the MCNP ***kcode*** calculations. In particular, fast and thermal (E < 0.625 eV) flux profiles were generated along the x, y, and z directions through a spatial point in location D6 close to where the peak power density is often observed (in the M-2-5 model). These flux values were also converted into power profiles using the 2-group macroscopic fission cross sections from the VENTURE cases for fresh fuel -- this allowed the generation of power profiles similar to those given in Fig. 2 using the fluxes from the MCNP calculations (the relative error in the flux values were 2% or less in most of the fuel locations).

The flux and power profile results from the MCNP ***fmesh*** tallies are summarized in several plots of the following few pages. In particular, Figs. 3-5 compare both the fluxes and power profiles in the x, y, and z-directions for the VENTURE and MCNP models of the reference M-2-5 configuration. Clearly the two models give similar results, but there are a number of noticeable differences -- such as the larger fast flux values and the greater fast flux resolution which is related to the additional discrete material regions in the MCNP model, the larger thermal peak in the center of the flux trap region with MCNP, and the dip in the thermal flux at about x = 63 cm in the VENTURE model. This last difference, however, is artificial; it is due the discrete positioning of control in VENTURE versus the continuous placement that is available in the MCNP model. Here, in particular, at the selected z location, VENTURE has the RegBlade inserted and the MCNP model does not. In VENTURE the choice of region boundaries were 8.96″ or 11.3″ to represent the actual 10″ location of the RegBlade -- and we selected the first option since it was a little closer to the desired value. Thus, in VENTURE, the RegBlade is inserted a little further than desired due to modeling limitations.

Concerning the three different configurations, Figs. 6 and 7, respectively, show the summary profiles for the case with a standard water radiation basket in D5 and for the placement of a graphite reflector in this location (i.e. the M-2-7 configuration). Clearly the behavior is as expected with the larger thermal peak with the water basket in D5 relative to the reference M-2-5 core, and the significantly flatter profile when a graphite reflector is in D5. These results simply confirm the VENTURE profiles and peaking factors given earlier, with only slightly different numerical values.

Summary and Conclusions

This study has compared the expected results for two options for replacing the swollen flux trap element in the D5 location of the M-2-5 core configuration. Of the two options, placing a graphite reflector in D5 leads to a lower radial peaking factor and an increase in the calculated core excess reactivity of about 0.60 %Δk/k (actual measured value of 0.45 %Δk/k) -- and both these changes represent improved characteristics. In contrast, putting a water basket into D5 to replace the graphite radiation basket, increases peaking and decreases the core excess considerably -- both of which, for the current fuel configuration, represent negative attributes. Thus, the obvious choice here, based solely on power peaking and excess reactivity considerations, is to select the graphite reflector as the replacement element for the damaged flux trap assembly. However, this choice does eliminate an important experimental facility within the UMLRR, so this should only be considered as an interim option until a better alternative can be found (one that probably includes some fuel element movement or addition).

An additional very important result from this study is that the radial power peaking factors in the UMLRR are really larger than those estimated nearly 25 years ago. In particular, an overall radial peaking factor of 1.45 has been in use for many years, but it appears that values in the range of 1.60 – 1.75 are more appropriate for the recent core configurations and that values as high as 2.0 are possible if a water-filled radiation basket is placed in the central D5 position.

Although not an immediate safety concern because of the large safety margins associated with the UMLRR facility, this new observation dictates that a separate safety evaluation should be performed to address the ramifications of the larger radial peaking factors calculated here. For example, the higher peaking factors will likely modify the power-to-flow map that is used to justify the safety limit settings for the UMLRR. Thus, it is important to establish the impact of the higher peaking factors as soon as possible!

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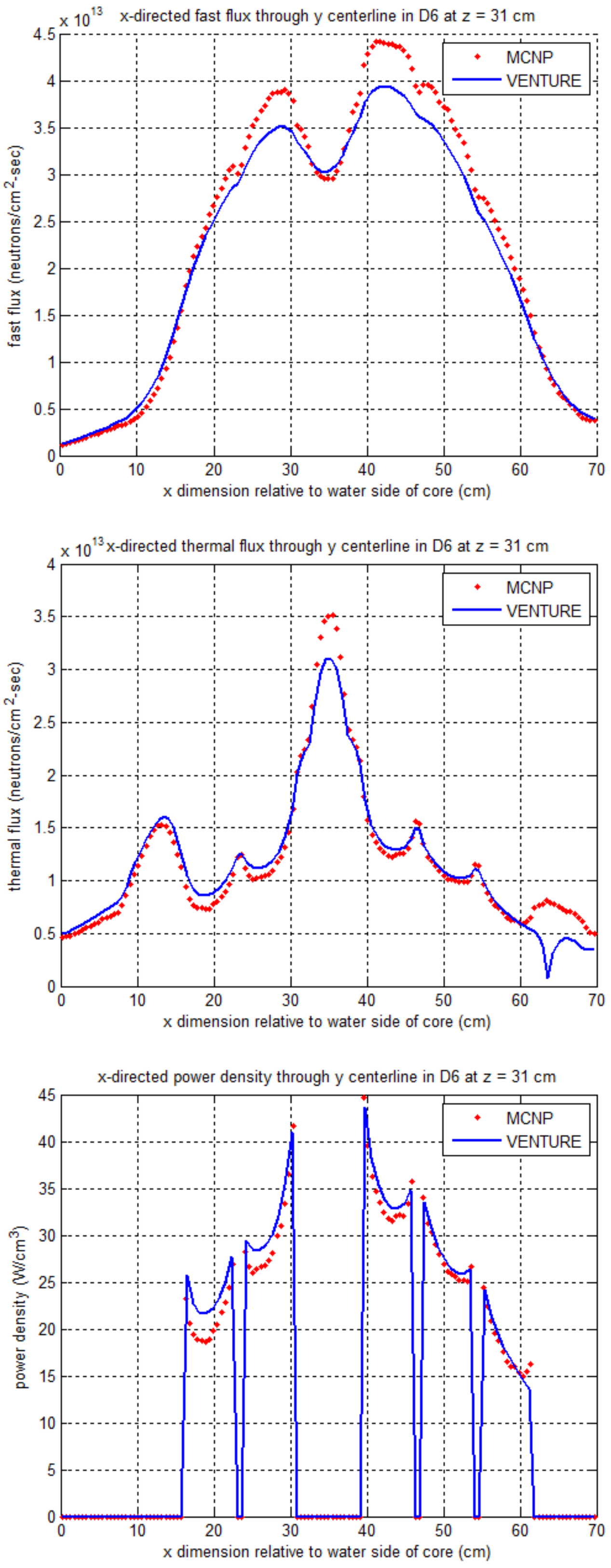


x-directed fast flux through y centerline in D6 at z = 31 cm

x-directed thermal flux through y centerline in D6 at z = 31 cm

x-directed power density through y centerline in D6 at z = 31 cm

Fig. 3 Selected MCNP and VENTURE x-directed flux and power profiles for the reference BOL M-2-5 configuration (blades at 16.9″).

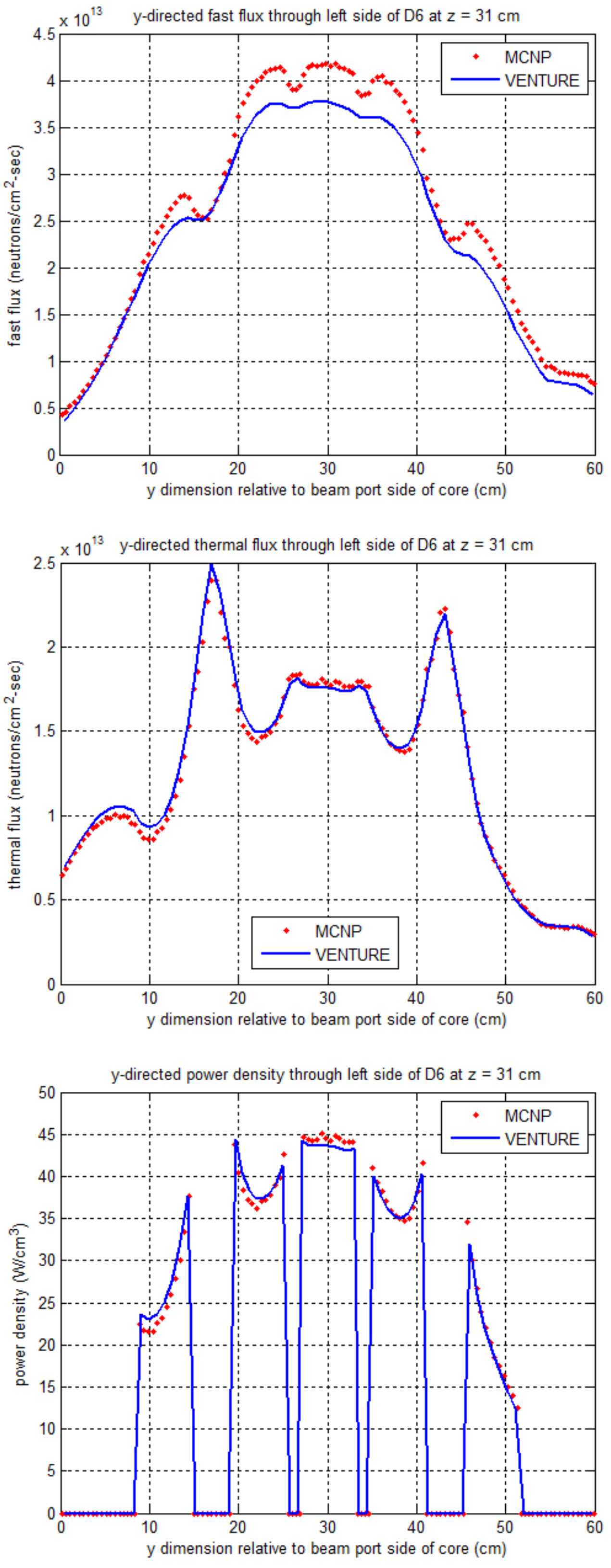
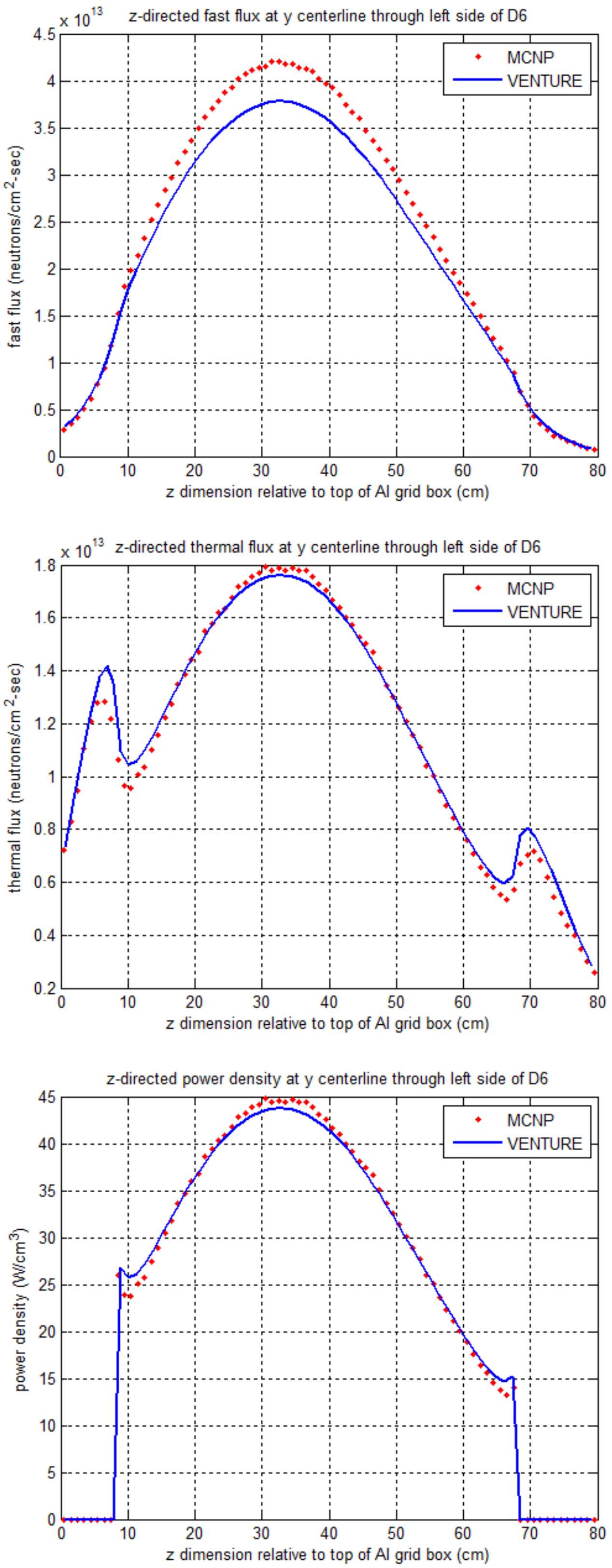


Fig. 4 **Selected MCNP and VENTURE y-directed flux and power profiles for the reference BOL M-2-5 configuration (blades at 16.9″).**


z-directed fast flux at y centerline through left side of D6

z-directed thermal flux at y centerline through left side of D6

z-directed power density at y centerline through left side of D6

Fig. 5 Selected MCNP and VENTURE z-directed flux and power profiles for the reference BOL M-2-5 configuration (blades at 16.9″).

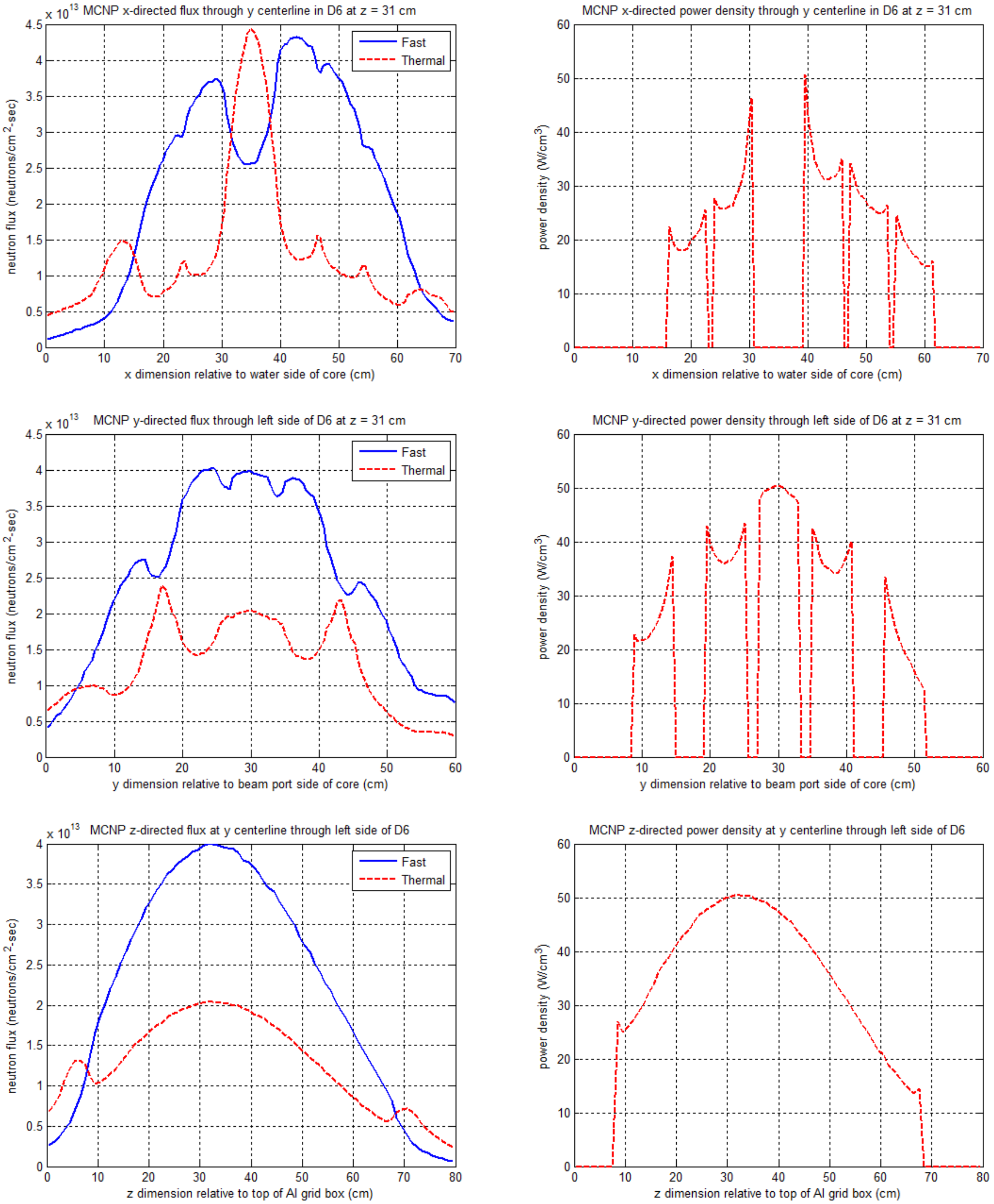


Fig. 6 Selected MCNP flux and power profiles for the BOL M-2-5 configuration with a water-filled radiation basket in D5 (blades at 16.9″).

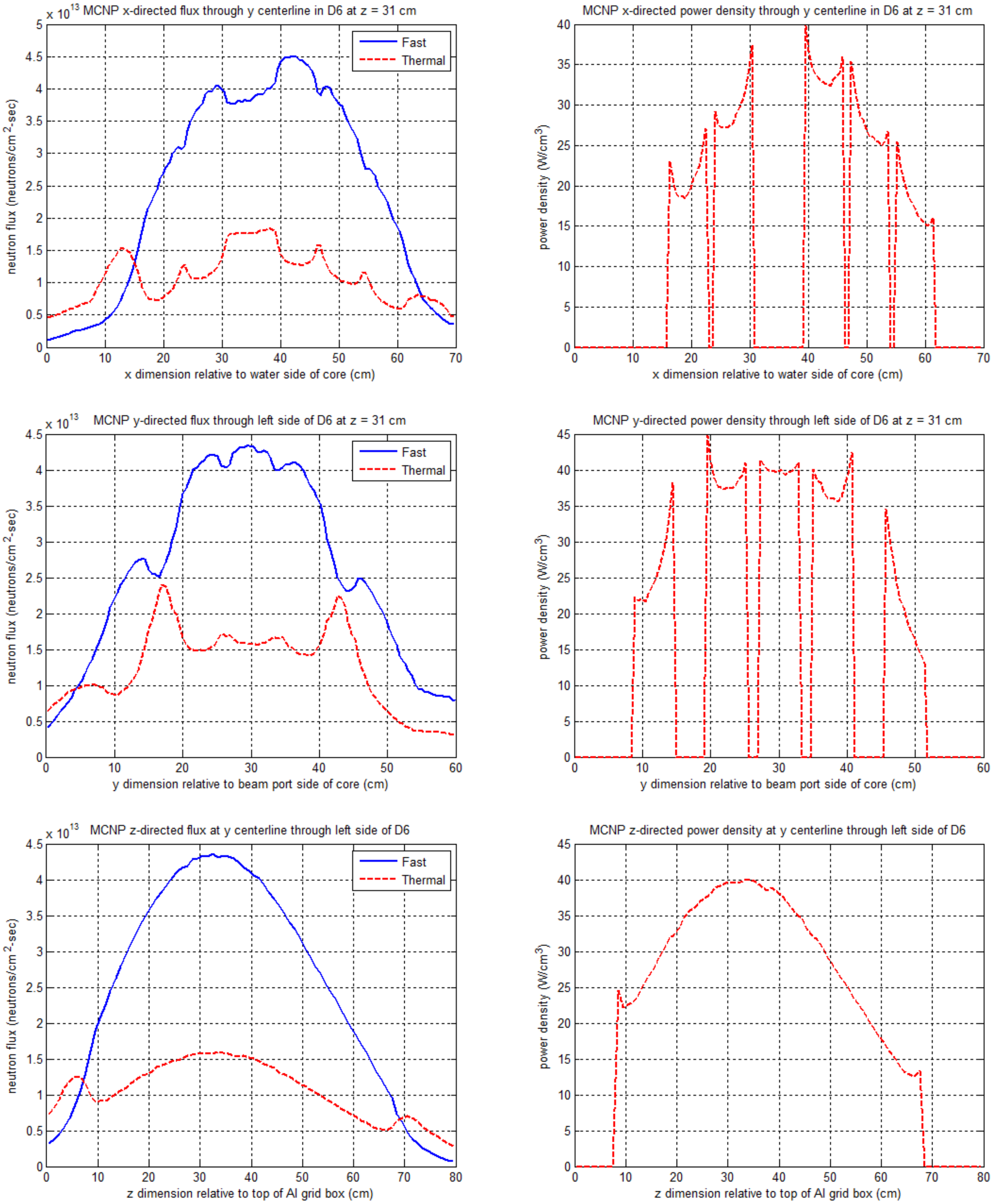


Fig. 7 Selected MCNP flux and power profiles for the BOL M-2-5 configuration with a graphite reflector in D5 (blades at 16.9″).

Appendix -- Definition of Quantities used to Compute the Power Peaking Factors

power in assembly a: $$P_a = \sum_{ijk \in a} P_{ijk} V_{ijk}$$

where P_{ijk} = node power density and V_{ijk} = node volume

assembly peaking factor: $$f_a = \frac{\text{power in assembly}}{\text{average assembly power}} = \frac{P_a}{P_{tot} / (\#\ \text{assy})}$$

linear heat rate in a for axial level k: $$q'_a\big|_k = \frac{1}{\Delta z_k} \sum_{ij \in a} P_{ijk} V_{ijk} \quad \text{(note the sum is only over i \& j)}$$

average linear heat rate in assembly a: $$q'_a\big|_{ave} = \frac{P_a}{H}$$

normalized axial shape function in a: $$\psi_a\big|_k = \frac{q'_a\big|_k}{q'_a\big|_{ave}}$$

Note: $$\langle \psi_a \rangle = \frac{1}{H} \sum_k \psi_a\big|_k \Delta z_k = \frac{1}{H} \frac{H}{P_a} \sum_k \frac{1}{\Delta z_k} \left(\sum_{ij \in a} P_{ijk} V_{ijk} \right) \Delta z_k = 1$$

axial peaking factor in assembly a: $$f_{za} = \max \left\{ \psi_a\big|_k \right\}$$

total intra-assembly peaking factor: $$f_{xyza} = \frac{\max \left\{ P_{ijk \in a} \right\}}{P_a / V_a}$$

intra-assembly radial peaking factor: $$f_{xya} = \frac{f_{xyza}}{f_{za}}$$

axial linear heat rate in hot plate: $$q'_k\big|_{hot} = f_a\, f_{xya}\, \psi_a\big|_k\, q'\big|_{ave}$$

average linear heat rate: $$q'\big|_{ave} = \frac{P_{tot}}{(\#\ \text{plates}) \times H}$$

Note: The hot assembly is defined as the fuel element a that generates the most power (i.e. has the largest f_a value). The overall radial peaking factor is given by $f_{xy} = f_a \times f_{xya}$ for the hot assembly. The power generated in the hot plate is f_{xy} times the average power per fuel plate.