Updated Peaking Factors for Use in the UMLRR Safety Analysis

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Introduction

An updated safety analysis study is currently on-going for the UMass-Lowell research reactor (UMLRR). A new safety analysis is needed for several reasons:

1. As part of the on-going re-licensing effort for the UMLRR (the current operating license expires at the end of 2015),
2. To include analyses for the Worcester Polytechnic Institute (WPI) fuel (the UMLRR currently has a possession-only license for the WPI fuel),
3. Because we now know that the radial peaking factors used as part of the safety analysis performed in support of the HEU to LEU conversion were too low, and
4. To justify the use of a standard water radiation basket in the D5 location in the center of the core as a replacement for the damaged flux trap element.

And, of course, the maximum achievable axial and radial peaking factors are key quantities needed by the thermal analysis codes used as part of the safety analysis. Thus, the purpose of the current internal report is to document and justify the value of $f_{xy} = 2.1$ that will be used for the radial peaking factor (1.45 was used previously), and to argue that the bottom-peaked axial heat flux profile associated with a beginning-of-life (BOL) control blade distribution, with an axial peaking factor of about $f_z = 1.4\text{-}1.5$, is still a good choice for a worst case axial distribution. These quantities will be used in the subsequent safety evaluations, and this report simply explains and justifies how these values were derived.

Some Background

To put the current study into perspective, it is appropriate to give a little history concerning our UMLRR modeling and analysis efforts at UMass-Lowell, starting back in 1988 when the analyses for the conversion of the UMLRR from HEU fuel to LEU fuel first began. At that time, we had limited in-house computational capability, so much of our initial effort was focused on developing computer models and benchmarking a set of tools for the physics and safety analysis of plate-type research reactors. This work continued for several years, eventually culminating in a reference LEU uranium silicide fuel element design and core configuration with a symmetric 20-element fuel arrangement that involved moving the regulating blade position from the D9 to the D8 position. Portions of the SCALE package were used to generate 2-group assembly-averaged cross section for the various 2-D VENTURE models in use at that time. In addition, a series of three thermal analysis codes, NATCON, PLTEMP, and PARET, were obtained from Argonne National Laboratory (ANL) to perform the safety studies. With some assistance from the Reduced Enrichment for Research and Test Reactors (RERTR) group at ANL, a final safety analysis for the HEU to LEU fuel conversion was submitted to the Nuclear Regulatory Commission (NRC) in 1993 and approved later that year. However, fuel construction was delayed (due to funding issues with fabricating the fuel elements) and actual conversion of the core did not take place until August 2000. References 1-9 document much of the initial modeling and analysis effort for the UMLRR through 1993.

It is important to note that, in the early safety evaluations, the radial and axial peaking factors, f_{xy} and f_z, were determined from separate xy and yz 2-D VENTURE models and that the mesh spacing and homogenization procedures were relatively coarse compared to the most recent 3-D 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 chopped cosine distribution (to represent the blades fully withdrawn) and a computed axial profile with the blades 15″ withdrawn in the yz model were compared, with the blades at 15″ out being the more limiting case. In particular, $f_{xy} = 1.45$ for the control-out xy model and $f_z = 1.39$ for the 15″ withdrawn yz case were estimated back in 1991 in R. Freeman's M.S. thesis[4], and these values were used in the safety studies[5-7], within the FSAR Supplement for Conversion to LEU Fuel, and as the basis for the Technical Specifications for the LEU cores.[8-9] These specific values have also been used, by reference, in all our thermal analyses since the 1993 FSAR supplement was submitted.

In the summer of 1999, with the pending HEU to LEU conversion nearing reality, a major effort was undertaken to update our local physics modeling and calculational support capabilities at UMass-Lowell, to revive and improve upon the LEU computational models from the early 1990s, and to take a new look at the proposed movement of the regulating blade from the D9 position to the D8 position. This work produced a new reference 21-element design with an asymmetric fuel arrangement, but it retained the regulating blade in its original D9 position. This effort also generated the first 3-D VENTURE model of the UMLRR along with a series of Matlab-based tools to assist in a variety of pre-processing and post-processing tasks. The new 1999 LEU reference core was loaded in Aug. 2000 and, with only a slight modification that involved an interchange of some water baskets and graphite reflectors, this arrangement became the first LEU core in the UMLRR -- this core configuration was designated as the M-1-3 core.

The M-1-3 core was shut down after about 8 months of operation (about 4 MWD of burnup) for major modifications within the control room and to install a new fast neutron irradiator (FNI) on one side of the core. The FNI required some new core elements (i.e. five lead-void elements) and a relocation of the two partial elements in the core. This new configuration, designated as the M-2-5 core, was operated until just recently (May 2015), with a cumulative burnup of about 70 MWD. References 10-14 discuss much of the work done to support and analyze the actual core conversion to LEU fuel, and Refs. 15-16 document the development of the fast neutron irradiator (FNI) and the M-2-5 core configuration.

Again, it should be emphasized that during this time period, the 2-D VENTURE models were still the main analysis tools utilized for most of our UMLRR physics studies, since the new 3-D model was quite computationally intensive relative to the 2-D models (the 3-D model was used primarily for reactivity worth evaluations). In particular, the new FNI was designed exclusively with a combination of xy and yz models in VENTURE and DORT, and the core modifications made here suggested that only a small increase in the radial peaking factor would occur (about 4 %), so a new safety study was not needed to support these changes. A preliminary safety study was conducted in 2002 to address the possibility of operating the UMLRR at 2 MW,[17] but even here, the peaking factors used simply referenced the previous work from the early 1990s.

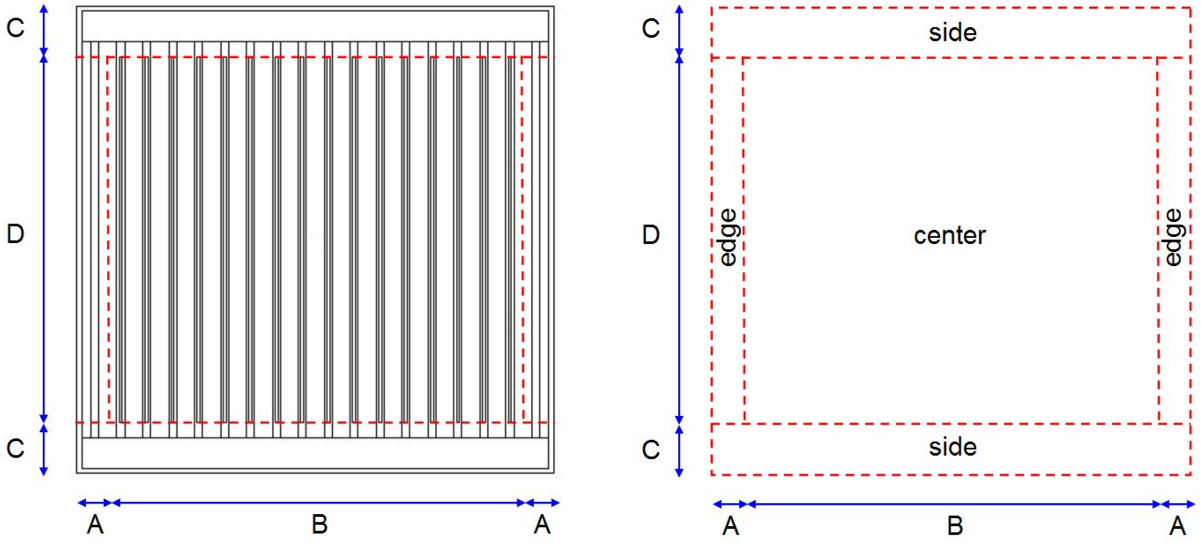
In 2011, UMass-Lowell obtained the slightly used LEU fuel elements from the closed Worcester Polytechnic Institute (WPI) research reactor, along with a possession-only license from the NRC to store the WPI fuel along the pool walls until a formal safety analysis was submitted and approved. The UMLRR and WPI fuel elements have the same general construction and outer dimensions, so both fit nicely in the UMLRR core grid structure -- but there are enough differences in the designs that warrant a formal analysis. Thus, the WPI fuel transfer study was initiated in summer 2010 and continued intermittently until September 2012, after which essentially nothing was done until the current studies in summer 2015. From 2010-2012, the focus of our effort was on validating a series of physics models that included fuel burnup, since up to this time, only beginning-of-life (BOL) models with fresh fuel compositions, were used. In addition, during our work on the WPI fuel transfer project, an MCNP model of the UMLRR was also constructed (as part of another project) -- thus, some inter-comparisons between MCNP and VENTURE were also completed to further validate the VENTURE models. Two internal documents[18-19] and one conference paper[20] were written to partially document the physics studies done during this time. Note, however, that the physics effort was not formally completed and no safety calculations have been performed, as yet, for the WPI Fuel transfer project -- these will be accomplished as part of the on-going analyses to be completed in summer 2015.

To bring this brief history of our UMLRR modeling and analysis efforts up to current times, we need to mention the on-going effort to replace the control blades within the UMLRR and the recent issue with the damaged flux trap element -- see the two recent internal reports in Refs. 21 and 22 for more detail. In particular, during preparation for some scheduled maintenance to replace one of the control blades in the UMLRR, it was discovered that the flux trap element had swollen beyond tolerance and could not be placed back into the core. Two easy options to get the core operational again were to replace the swollen graphite basket element with either a water basket or a graphite reflector element, where the use of a standard water-filled radiation basket was the first choice since this option would retain position D5 as an experimental facility. Detailed analysis of these two options revealed that the peaking factors for the case with the water-filled radiation basket in D5 were quite large and that further study would be needed before this configuration could be used -- thus, a graphite reflector in D5 was the option selected.

Furthermore, in analyzing the peaking factors associated with these proposed configuration changes with the most recent 3-D VENTURE model (with confirmation using MCNP), this study also showed that our original calculation of f_{xy} back in the early 1990s using a simplified control-out 2-D xy model was not conservative. In particular, the value of $f_{xy} = 1.45$ used in our previous safety analyses is too low by as much as 20-25%, and that a value of $f_{xy} =1.80$ is probably much more appropriate. This recent observation dictates that a new safety evaluation to address the higher radial peaking factor is needed as soon as possible (which is one reason for this study/report on peaking factors and our on-going safety evaluations). In addition, if we want to keep open the option of placing a standard water basket element in D5, even higher peaking factors will be observed, with values of f_{xy} approaching 2.0. Thus, for full flexibility, we will need to show that a radial peaking factor as high as 2.0 still gives a significant safety margin under worst-case conditions.

The VENTURE Models

Clearly the above historical perspective suggests that a relatively detailed 3-D model with the control blades inserted to a significant depth into the reactor is needed to properly determine the power generated in the hot plate within the UMLRR -- which is really what is needed for the safety analyses. Unfortunately, an explicit representation of each plate is not available in the 3-zone homogeneous fuel element representation used within the VENTURE model, as illustrated in Fig. 1. However, when the new VENTURE model was generated in 2011-2012, the central fuel region was modeled with an 8×7 array of mesh points in the xy plane for each axial location, giving sufficient detail to determine an intra-assembly power distribution and intra-assembly radial power peaking factor, f_{xya}, in each assembly. In this 3-zone homogeneous model of a fuel element, the radial peaking factor is determined by first identifying the hottest assembly (element with maximum assembly peaking factor, f_a) and then we define $f_{xy} = f_a \times f_{xya}$ in the hot assembly -- this should allow one to obtain a good estimate of the power generated in the hot plate, where $P_{\text{hot plate}} = f_{xy} \times P_{\text{ave plate}}$. In particular, a Matlab code has been written to process the power density file generated within VENTURE and to compute and tabulate the desired peaking factors, and the detailed equations and logic used in the code are summarized in the Appendix to this report.



Region Dimensions (cm)		
A = 0.4995	B = 6.7734	2A+B = 7.7724
C = 0.8437	D = 6.0850	2C+D = 7.7724

Fig. 1 Detailed assembly geometry and simple 3-zone homogeneous representation.

Also it should be noted that the calculations reported below used two slightly different models, as illustrated in Fig. 2. The primary VENTURE model used for much of the WPI fuel transfer study is the so-called 2012 model and this is documented in detail in Ref. 19 -- an xy cut just below the core mid-plane is shown in the top half of Fig. 2. However, in early 2014, the four in-core experimental locations (C2, D2, and E2 near the left side of the figure and the central D5 position) were modified slightly to include three homogeneous zones, instead of the previous

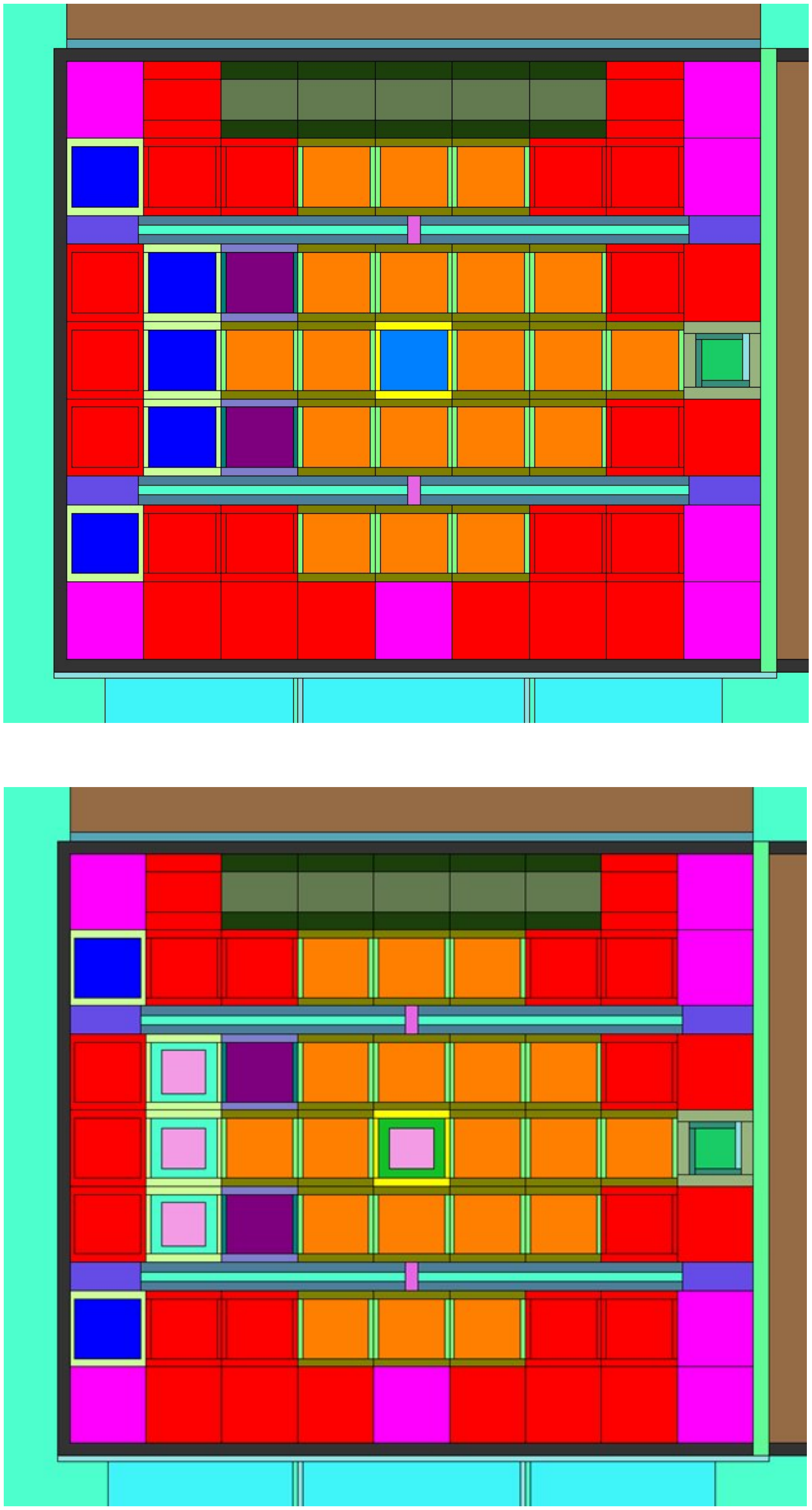


Fig. 2 XY cuts just below the core centerline in the M-2-5 configuration for both the 2012 (upper sketch) and 2014 (lower figure) VENTURE models.

2-zone representation. This latest geometry, as depicted in the lower portion of Fig. 2, is referred to as the 2014 model, and this gives slightly better resolution in the vicinity of these four experimental regions. The 2014 model is now the current reference model, but both the 2012 and 2014 models give similar (but slightly different) results.

From our previous physics studies, we know that the more severe power peaking condition is associated with the blades inserted substantially into the core. Thus, an arrangement with a high excess reactivity which is made nearly critical via blade insertion often gives the desired limiting peaking factors. Note, however, that the excess reactivity in the BOL M-2-5 is slightly over 4 %Δk/k and that the maximum allowable is 4.7 %Δk/k. Thus, the BOL M-2-5 model with the blades at their critical height of about 14.9″ withdrawn represents a good candidate configuration for determining the maximum peaking factors. In addition, it is also sometimes convenient to do some calculations with the blade or blades of interest either fully withdrawn and/or fully inserted, since one can then estimate the blade worths and the core excess reactivity from these calculations. Thus, in the calculations discussed below, a variety of blade positions are used depending on the desired outcome from a particular calculation -- thus, we will be careful to identify the actual blade position in all the cases analyzed here.

Summary Results for Selected Configurations

It should be noted that in addition to the allowed maximum excess reactivity of 4.7 %Δk/k (which limits the maximum number of fuel assemblies allowed in the core), a practical lower limit is somewhere in the range of 1.5-2.0 %Δk/k, since sufficient excess reactivity is needed to override temperature and xenon feedbacks, to allow for additional fuel burnup, and to the counter negative reactivity effects of experiments. In addition, a minimum shutdown margin of 2.7 %Δk/k also limits the asymmetry that can be allowed in the blade worths, since the shutdown margin is computed with the most reactive blade in its least reactive position (i.e. withdrawn). Thus, all these conditions tend to constrain the allowable configurations that can be realized in practice.

Within these constraints, the goal is to evaluate a variety of core configurations containing all UMLRR fuel, all WPI fuel, and a mix of both fuel types. In addition, we want fresh cores and cores with some accumulated burnup, again with the goal of addressing as wide a range as possible of practical configurations.

With this objective in mind, a series of scoping computations were performed with the 2012 VENTURE model for each of the twelve configurations described in Table 1. Reactivity evaluations, including excess reactivity, blade worths, and shutdown margins, were recorded and summarized in Table 2 for each configuration. In addition, for the control-out case, a peaking factor evaluation was performed, with summary results given in Table 3. As apparent, some of the cases addressed here represent very reasonable variations to the reference layout for increasing or decreasing excess reactivity relative to reference (such as in Cases 3, 9, and 10), and others correspond to arrangements were we purposely tried to increase the power peaking factors in the core (such as Cases 5, 7, 11, and 12). For example, adding excess reactivity to a depleted core is often required, so replacing a partial element with a fresh UMLRR or WPI fuel assembly is a logical choice. However, the real goal here was to identify some worst-case scenarios that are feasible, but that give relatively large power tilts, and Cases 5 and 7, for example, are good situations where sizeable power tilts are observed.

Table 1 Description of selected configurations (2012 VENTURE model).

BOL Cases
Case 1: reference BOL M-2-5 UMLRR core with the standard 19/2 configuration (19 full and 2 partial fuel assemblies)
Case 2: same as Case 1 except all 21 fuel assemblies were replaced with WPI fuel
Case 3: same as Case 1 except just the partial fuel assemblies were replaced with WPI fuel
Case 4: combination of 21 UML and WPI fuel assemblies (WPI fuel around the flux trap, with UML full fuel in outer ring)
Case 5: same as Case 4 except assemblies were switched (WPI fuel on the outer ring and UML full fuel in the inner ring)
Case 6: UML full fuel in all 21 locations (partials replaced with full fuel)
Case 7: combination of 21 UML and WPI fuel elements (WPI fuel in Rows B and C and full UML fuel in Rows D, E and F)
50 MWD Cases
Case 8: reference 50 MWD M-2-5 UMLRR core with the standard 19/2 configuration (19 full and 2 partial fuel assemblies)
Case 9: same as Case 8 except the partial fuel assemblies were replaced with fresh full UMLRR assemblies
Case 10: same as Case 8 except the partial fuel assemblies were replaced with fresh WPI fuel assemblies
Case 11: same as Case 8 except the graphite reflector in F7 was replaced with a fresh full UMLRR assembly
Case 12: same as Case 8 except the graphite reflector in F7 was replaced with a fresh WPI fuel assembly

Table 2 Reactivity evaluations for selected configurations (2012 VENTURE model).

Case #	All Out k_{eff}	Blade 1 Worth (%Δk/k)	Blade 2 Worth (%Δk/k)	Blade 3 Worth (%Δk/k)	Blade 4 Worth (%Δk/k)	RegBlade Worth (%Δk/k)	Excess k_{eff} (%Δk/k)	Worth Blades 1-4 (%Δk/k)	Shutdown Margin (%Δk/k)
BOL Cases									
1	1.0429	2.83	2.28	3.19	3.93	0.45	4.29	12.2	4.02
2	1.0193	3.17	2.56	3.19	3.92	0.44	1.93	12.8	6.98
3	1.0495	2.97	2.41	3.08	3.77	0.42	4.95	12.2	3.51
4	1.0330	3.08	2.47	3.14	3.88	0.45	3.30	12.6	5.39
5	1.0384	3.07	2.50	3.08	3.75	0.41	3.84	12.4	4.81
6	1.0510	2.99	2.43	3.04	3.72	0.41	5.10	12.2	3.36
7	1.0408	3.24	2.25	2.84	4.04	0.43	4.08	12.4	4.25
50 MWD Cases									
8	1.0316	2.86	2.31	3.23	3.97	0.46	3.16	12.4	5.24
9	1.0404	3.04	2.47	3.06	3.74	0.42	4.04	12.3	4.52
10	1.0388	3.01	2.45	3.10	3.79	0.42	3.88	12.4	4.68
11	1.0406	2.81	2.08	3.01	4.55	0.48	4.06	12.4	3.84
12	1.0399	2.82	2.10	3.03	4.50	0.48	3.99	12.4	3.96

Table 3 Peaking factor data for selected configurations (2012 VENTURE model).

Case #	location of peak element	f_a	f_{za}	f_{xya}	$f_{xy} = f_a \times f_{xya}$
BOL Control-Out Cases					
1	E5	1.381	1.279	1.181	1.631
2	E5	1.335	1.276	1.172	1.565
3	E5	1.357	1.278	1.174	1.593
4	E5	1.274	1.276	1.169	1.489
5	E5	1.410	1.278	1.173	1.655
6	E5	1.349	1.278	1.172	1.581
7	E5	1.410	1.278	1.166	1.644
50 MWD Control-Out Cases					
8	E5	1.374	1.261	1.180	1.621
9	E5	1.340	1.261	1.170	1.568
10	E5	1.348	1.261	1.172	1.580
11	E5	1.392	1.261	1.192	1.658
12	E5	1.395	1.261	1.190	1.660

Other observations of interest include:

1. The total blade worths are relatively constant, although the worth distribution among the four large control blades can vary somewhat.
2. The regulating blade worth decreases in configurations that shift the flux towards the left side of the core relative to reference, and it increases if the flux distribution is shifted to the right (in all cases, however, the VENTURE model over-predicts the actual RegBlade worth by roughly 50%).
3. For the control-out case, the peak power assembly is consistently in the E5 position (the peak power assembly usually is located in position D6 for the control-in cases).
4. The axial peaking factors are nearly constant for all cases and they tend to decrease with increased burnup (i.e. we see some axial smoothing with fuel depletion). Also, for the control-out case, f_{za} is relatively small relative to cases with the blades at an approximate critical height -- for example, from Ref. 21, the reference BOL M-2-5 critical blade configuration at 14.9″ withdrawn gives $f_{za} = 1.37$.
5. The intra-assembly peaking factor, f_{xya}, is consistently in the 1.17-1.19 range, indicating a relatively large power tilt across the hot assembly for all cases.
6. All these cases have the flux trap element (i.e. graphite basket assembly) in the D5 location.

The last two items are certainly related and, as noted in Ref. 21, the intra-assembly tilts increase when a standard water radiation basket is placed in D5 and, as expected, they decrease if a graphite reflector is placed in this central location. However, until recent events concerning the discovery of the swollen flux trap element, we never considered putting anything in D5 except the flux trap assembly, since this element was specifically designed for this location -- that is, to create a central in-core experimental facility that features a large thermal flux. However, this same goal can be accomplished with a standard radiation basket at the expense of higher peaking factors.

The scoping cases summarized in Tables 1-3 give a good overview of the expected behavior of a variety of possible UMLRR core configurations. However, to estimate the maximum radial peaking factor that can be achieved, we need to look at critically controlled configurations. And, with only one graphite radiation basket (which is currently unavailable), we need to address two situations: the original design with a graphite basket in D5, and the scenario where a water basket element in placed in this central location.

Two representative BOL cases from Tables 1-3 with relatively large f_{xy} values were simulated within the 2014 VENTURE model with the four large control blades at 14.9″ withdrawn to simulate a near-critical axial flux and power distribution (the BOL state was chosen to avoid any axial smoothing due to fuel depletion). Calculations with both graphite and water baskets in D5 were performed, and the resultant peaking factors from these four cases are summarized in Table 4. In addition, Figs. 3 and 4 show the power density profiles along the x-direction through the D5 location just below the core centerline for the four cases -- these clearly show the large gradients that are observed in the fuel near the D5 grid location. In particular, Fig. 3 displays the profiles when the flux trap element is in position D5 and Fig. 4 shows similar profiles when D5 contains a water-filled radiation basket. Also, when viewing these figures, recall that the UMLRR fuel element has 16 fuel plates and two Al end plates (one on each side), but that the WPI fuel assembly has a full complement of 18 fuel plates. Thus, one should expect the Case 5 power profile, where a combination of UMLRR and WPI elements is used, to look somewhat different from the Case 1 distribution, since this core configuration only uses UMLRR fuel.

As apparent from Table 4, all the peaking factors are larger than shown in Table 3 for the control-out configurations (as expected), and the f_{xya} and f_{xy} values for the case with the water basket in position D5 are generally much larger than for the graphite basket in D5 -- where this latter result can also be seen by comparing Figs. 3 and 4. Finally, we see that the Case 5 configuration, with the more reactive UMLRR fuel assemblies surrounding the D5 location, give the largest overall peaking factors, with slightly higher values than for the base Case 1 layout (i.e. the M-2-5 fuel configuration).

Table 4 Peaking factor data for selected BOL near-critical configurations (2014 VENTURE model).

Case Description	**location of peak element**	f_a	f_{za}	f_{xya}	$f_{xy} = f_a \times f_{xya}$
Case 1 with graphite basket in D5	D6	1.429	1.371	1.218	1.741
Case 5 with graphite basket in D5	D6	1.414	1.372	1.240	1.754
Case 1 with water basket in D5	D6	1.479	1.382	1.339	1.980
Case 5 with water basket in D5	D6	1.462	1.383	1.364	1.993

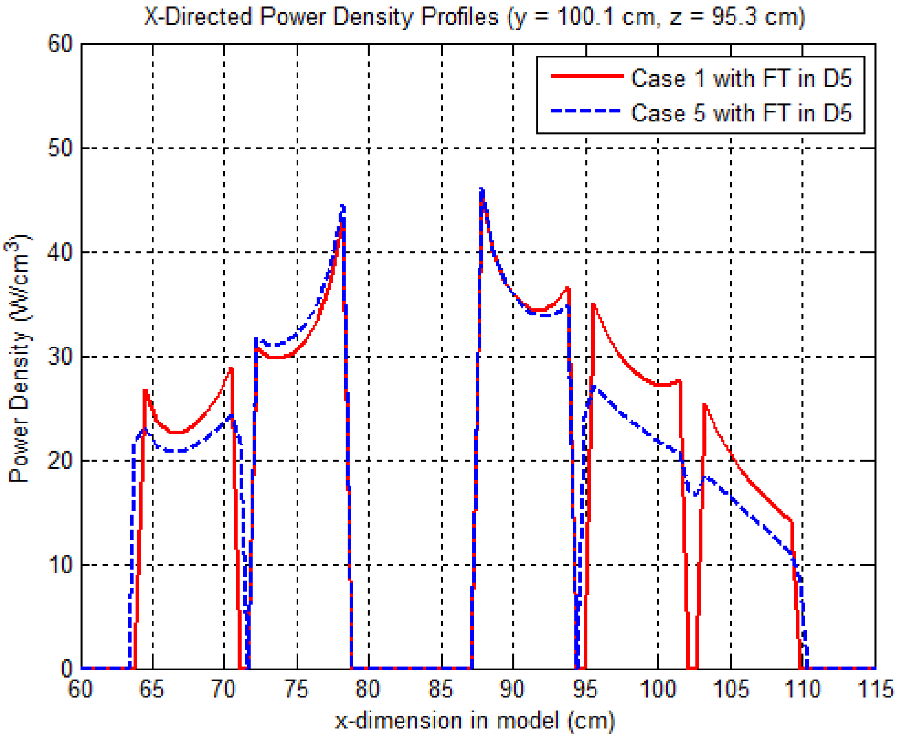


Fig. 3 Selected x-directed power profiles when the flux trap (FT) element is in D5.

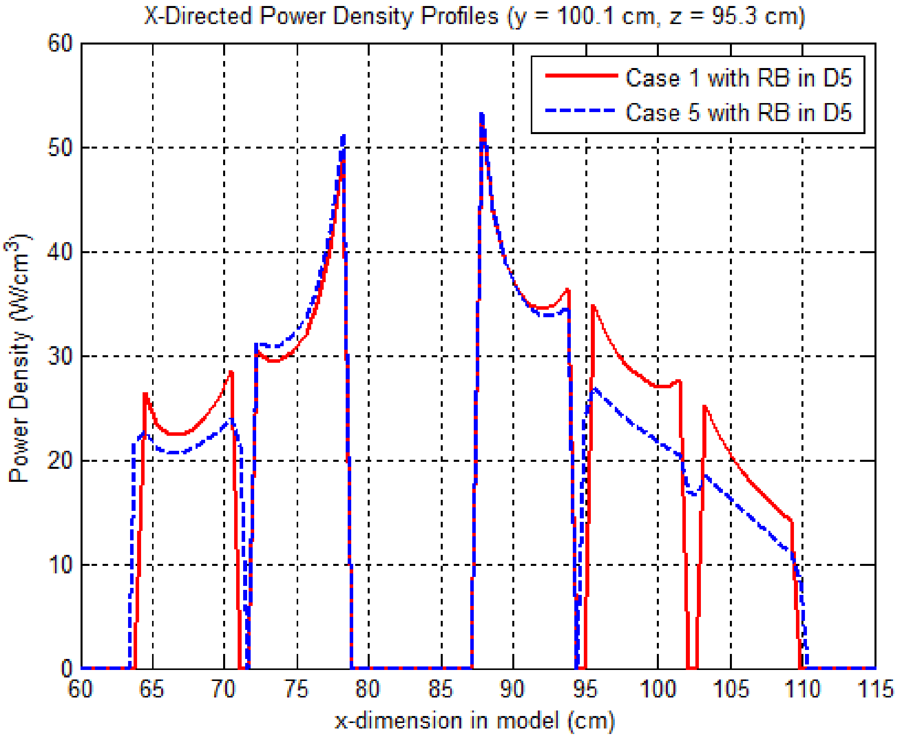


Fig. 4 Selected x-directed power profiles when a standard radiation basket (RB) is in D5.

Conclusions and Recommendations

This study has focused on identifying the maximum value that can be expected for the radial and axial peaking factors within any viable core configuration within the UMLRR. This effort was prompted by a recent study[21] that looked at the possibility of putting a standard radiation basket in position D5 to replace a swollen graphite basket element. Reference 21 indicates, in particular, that the radial peaking factor that had been used in previous safety analyses was not conservative, and that if a water radiation basket is used in the central D5 position, then the radial peaking factor could have a value that approaches as high as 2.0.

In the current work, we looked at a number of core configurations, including the use of both standard UMLRR U_3Si_2-Al fuel assemblies and WPI UAl_x-Al fuel elements, fresh and slightly depleted cores, control-in and control-out configurations, and the use of both the flux trap element and a water basket element in the central experimental D5 core location. It was found that the largest peaking factors occur when the water-filled radiation basket is in D5 within a fuel configuration that has a large excess reactivity so that the blades are inserted substantially into the core to keep the facility near critical. Of the configurations examined, the largest computed power density had a combined radial peaking factor of $f_{xy} = 1.993$ and an axial peaking factor of $f_z = 1.383$. It is recommended that these values both be increased by 5% and rounded up to obtain two significant figures for the quoted values of f_{xy} and f_z. This approach adds some conservatism and gives recommended worst-case peaking factors of about $f_{xy} = 2.1$ and $f_z = 1.5$.

Assuming that a full safety analysis shows that the use of these values do not limit UMLRR operations, then sufficient flexibility for almost any viable core configuration to be used is maintained and, in particular, these values will allow the use of a standard radiation basket in the central D5 location. If the high value of $f_{xy} = 2.1$, on the other hand, limits operational flexibility in some way, then an alternative would be to prohibit the placement of a water basket in the central location, which would greatly reduce power peaking in the nearby fuel elements and reduce f_{xy} considerably. Since maximum flexibility is a desirable goal, the on-going safety analysis will use $f_{xy} = 2.1$ and $f_z = 1.5$, and only address alternative options if absolutely necessary.

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

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

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

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

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

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

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

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

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: $q'\big|_{ave} = \dfrac{P_{tot}}{(\#\ \text{plates}) \times H}$

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, or $P_{hot\ plate} = f_{xy} \times P_{ave\ plate}$.