November 2010 Progress Report on

MCNP Modeling for the UMLRR

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Introduction/Summary

This goal of this project is to develop and validate a detailed MCNP model of the UMass-Lowell Research Reactor (UMLRR) to support the analysis of subsequent experiments that make use of the mixed neutron and gamma radiation fields generated by the reactor. For many years, the facility has used a combination of the VENTURE and DORT deterministic 3-D diffusion theory and 2-D transport theory codes to support a variety of physics-related analysis projects for the UMLRR. However, these deterministic modeling tools require a variety of spatial homogenization procedures and the generation of properly averaged multigroup cross sections in order to obtain a reasonable representation of the real system -- and this process is as much of an art as it is a science, so the results obtained can sometimes be a strong function of the experience level and skill of the model architect.

The use of Monte Carlo methods (such as the MCNP code), on the other hand, can eliminate much of the uncertainty and bias that is often associated with the homogenization and cross section generation methodologies used with the deterministic codes. Although model development using Monte Carlo techniques is often much more time intensive than for the deterministic codes, the gain in accuracy and confidence associated with the results obtained from a well-designed and appropriately-validated Monte Carlo model is well worth the additional initial effort needed to develop and benchmark the overall computational model. Thus, it is with this perspective that we set out to put together a detailed and validated MCNP model of the UMLRR.

The project got officially started in summer 2010 and this document represents the first formal progress report on the work accomplished thus far. To date (November 2010), a preliminary version of the UMLRR core without any ex-core experimental facilities has been completed. This first model represents a significant overall effort -- that is, for gathering together the appropriate material and geometry data, extracting the pertinent modeling information, putting this together in a consistent fashion into MCNP format, and for designing, building, and debugging the full MCNP geometry.

The current preliminary UMLRR core model represents our first major milestone for the project and this model is now available for preliminary evaluation/use. However, potential users need to be cautioned that, to be really useful as a modeling/analysis tool that is representative of the real system, some aspects of the ex-core facilities definitely need to be added to the model (at least in some simple form). Thus, this task -- a first model of the ex-core experimental facilities -- is now the focus of this project, with the goal of first generating a relatively simple ex-core model that adequately accounts for how these facilities affect the neutron balance within the core. Indeed, over the next several months, these ex-core facilities (beam ports, thermal column, and eventually the fast neutron irradiator) will be added to the full core model, first with a simple representation, and then with more complete facility descriptions as the project moves forward. At present, it is expected that a preliminary version of the complete reactor facility (with a relatively simple treatment of the ex-core components) will be available in late January 2011. Then, after some initial validation tests have been completed (with comparison to some experimental data that were obtained during the startup of the LEU core in Fall 2000), a new version of the model will be released and a new Progress Report that documents the additional models and the validation tests will be issued.

Concerning the current Progress Report, the remainder of this document will first give an overview description of the UMLRR geometry and core layout and then briefly describe, via a set of 2-D geometry figures from the MCNP Visual Editor, the basic MCNP representation of the UMLRR that we have constructed. There are really no MNCP results to describe and discuss as yet (except possibly for some preliminary k_{eff} values), since our work to date has focused on the geometry development. Thus, highlighted here in the remainder of this report is an overview of the real system and the MCNP geometries that have evolved to represent this system since the beginning of this project.

Description of the UMLRR

The UMass-Lowell Research Reactor (UMLRR) is a 1 MW light-water moderated and cooled, graphite-reflected, open-pool type research reactor that has been in operation since January 1975. The primary use of the reactor is to serve a neutron and gamma source for various nuclear-related education and research activities and as a training tool for the Nuclear Engineering and Health Physics Programs at UMass-Lowell.

The reactor core consists of a seven by nine array of fuel elements, reflector elements, control blades, the regulating rod, the startup source, nuclear instrumentation, and a set of radiation baskets for holding experimental samples, all suspended about 24 feet below the surface of the pool by the movable reactor bridge and core support structure. The core itself is rather small and it is surrounded on three sides by various experimental facilities [beam ports, graphite column, and a fast neutron irradiator (FNI)]. The remaining side of the core is open to the 76,000 gallon pool, allowing for the reactor to be moved to the bulk side of the pool, as needed (a gate can be placed in the center of the pool to isolate the two halves to allow for draining and maintenance if needed). Figure 1 shows a sketch of the overall facility prior to the installation of the fast neutron irradiator in 2002. This diagram highlights many of the systems just mentioned -- including the pool, reactor bridge, structural support system, reactor core just below the support structure, and some experimental facilities (note, however, that the in-pool portions of the three beam ports shown in the figure were removed and replaced with the FNI facility in 2002).

A close-up view of the aluminum grid plate and thin aluminum core box which holds the various core assemblies are pictured in Fig. 2. As apparent, the four corners are occupied by the corner posts, which make up the physical supports suspending the core from the reactor bridge. The remaining grid locations are filled with a variety of fuel, reflector, and irradiation basket assemblies, and the arrangement of these elements can be changed as needed to give a particular

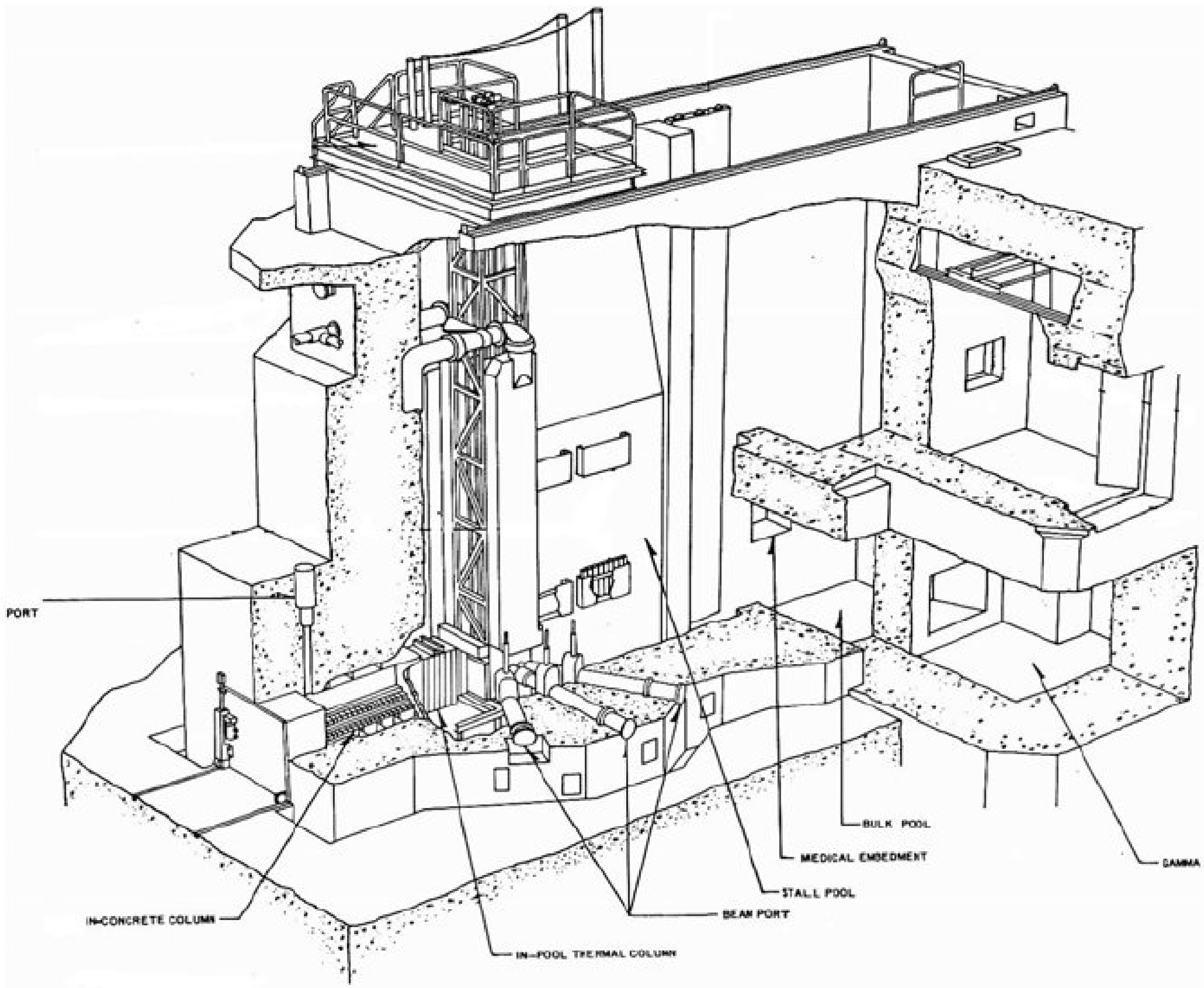

Fig. 1 Sketch of full UMLRR facility showing the pool, reactor bridge, support system, reactor core (just below the support structure), and some experimental facilities prior to installation of the fast neutron irradiator.

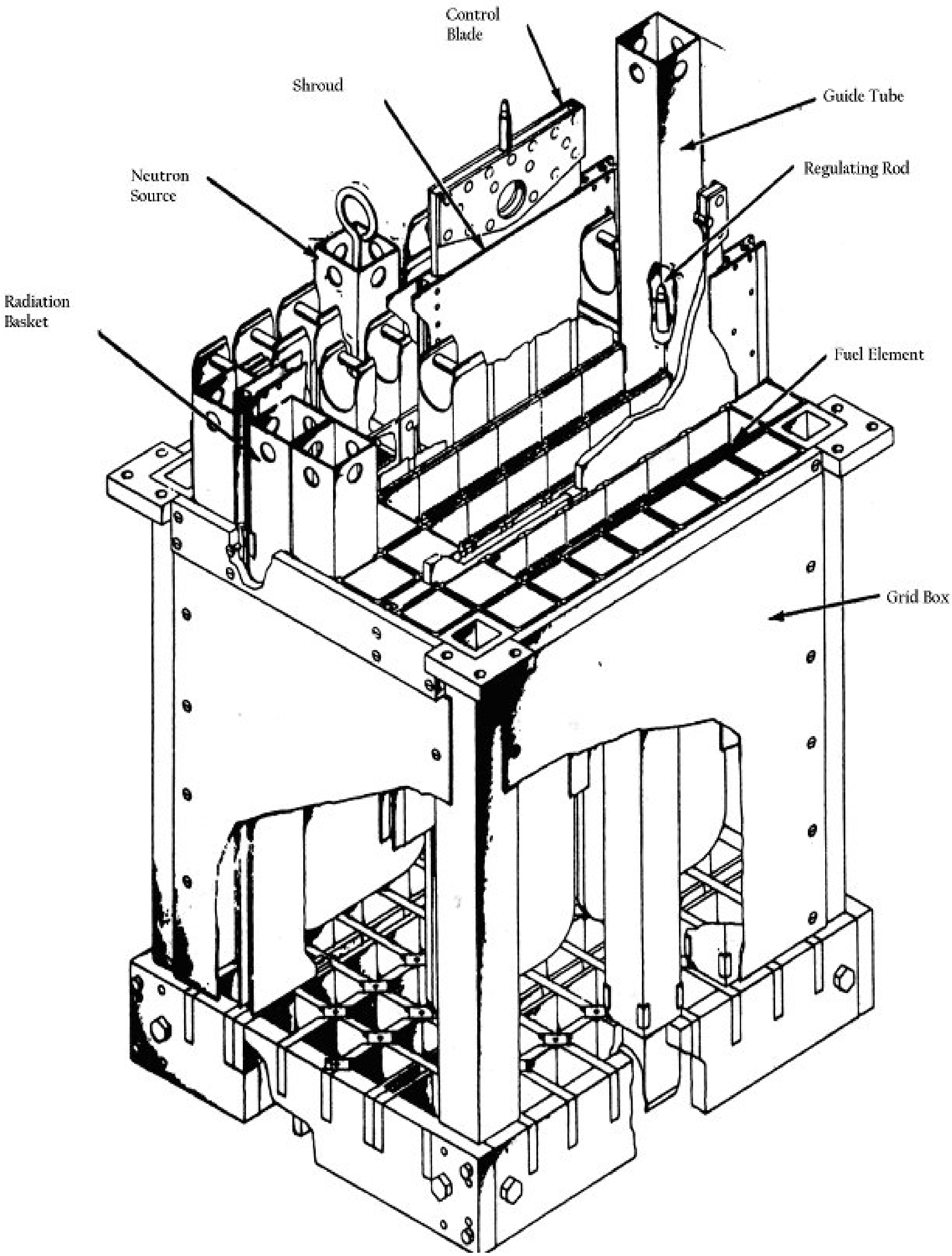

Fig. 2 Grid plate and core box geometry showing the placement of various core elements.

core configuration. The current core operates with 19 full LEU fuel assemblies and 2 partial assemblies (see discussion below on the specific startup and current core configurations).

Each fuel element is roughly a 3″×3″ can that is about 39″ long. An isometric view of a typical element is given in Fig. 3 and a detailed XY cut through a full fuel element, along with appropriate dimensions (in centimeters), is given in Fig. 4. The fuel is of the standard flat plate MTR type. Each LEU assembly has 16 low enriched uranium silicide fuel plates, with the two additional end plates containing pure aluminum. The meat within each LEU fuel plate is an U_3Si_2-Al alloy. The U_3Si_2 contribution is about 67 w/o and the uranium in the LEU fuel is enriched to about 19.75 w/o U235. Each full fuel plate contains 12.5 g of U235 and a partial fuel plate simply contains half this amount with half the meat thickness of a full fuel plate.

The fuel region is surrounded by a combination of graphite reflector elements and irradiation baskets. The reflector elements simply consist of a block of graphite within an aluminum can. The radiation baskets, in contrast, have an outer Al can and an inner Al cylindrical shell, which can hold a bayonet containing samples to be irradiated. Both the space between the Al shells and inner region inside the irradiation tube are filled with pool water when there is no bayonet inserted within the assembly. In addition, a central irradiation zone, referred to as the flux trap element, is also available, and this assembly is identical to a radiation basket except that graphite fills the space between the Al can and the inner Al shell.

For reactivity control, four large control blades and a single regulating rod or blade are used to adjust core reactivity (see Fig. 2). Large reactivity adjustments are made by moving the four large motor-driven Boral control blades -- these are used primarily for startup and shutdown operations and are usually held fixed during normal operation. In contrast, the single low-worth Boral regulating rod is used for fine reactivity control, and this can be used in either auto or manual mode, as desired, to make small reactivity adjustments to modify the power level or to compensate for inherent temperature and/or xenon reactivity effects.

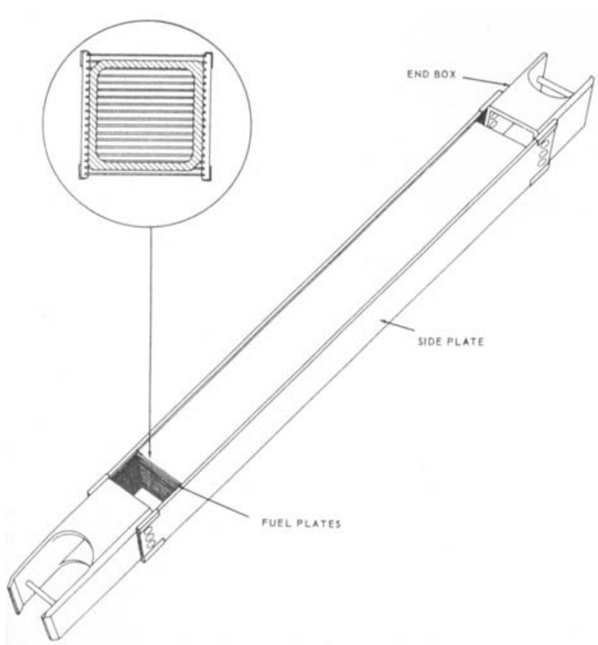

Fig. 3 Isometric view of a typical MTR-type fuel assembly.

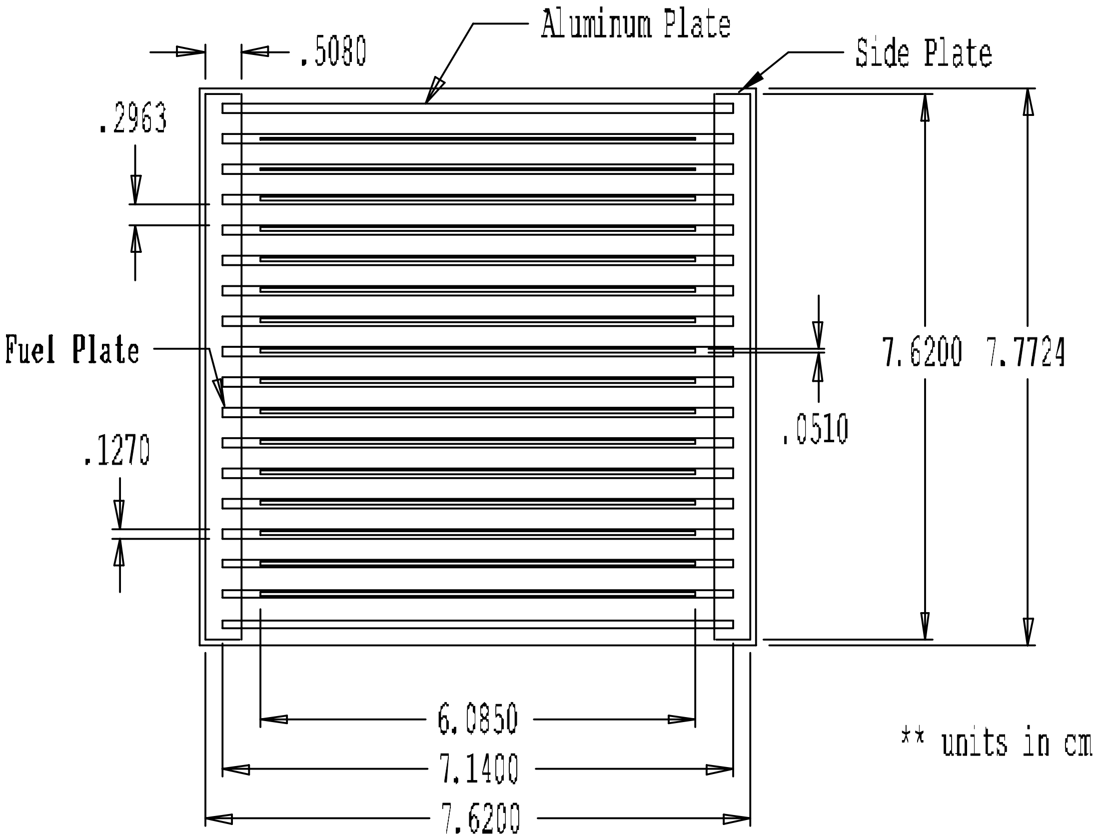

Fig. 4 Standard LEU fuel assembly geometry.

(This sketch is rotated 90^o relative to the assembly arrangement in the core as shown below)

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

All the core components mentioned above, when put together in a specific arrangement, comprise a particular UMLRR core configuration. When the conversion from HEU to LEU fuel was made back in August 2000, the new LEU startup core was designated as the M-1-3 configuration. This fresh core load had 19 full fuel and 2 partial fuel assemblies in the arrangement shown in Fig. 5. This core configuration was studied experimentally in some detail, including a full set of blade worth measurements, as well as the irradiation of a set of gold foils and copper wires that allowed measurement of the axial thermal flux profiles in several core locations. Thus, because of the available experimental data and the fact that this is a fresh core, the M-1-3 configuration will serve as a major test configuration for initial validation of the MCNP models developed as part of this work. Therefore, as will be seen below, all the MCNP models to date refer explicitly to the M-1-3 configuration.

In addition to the specific in-core configuration (i.e. the grid plate, core box, and the particular placement of the in-core assemblies as shown, for example, in Fig. 2), the ex-core experimental facilities also play an important role on the overall core neutron balance. In particular, the three beam ports on two sides of the core and the lead shield and thermal column on the right side as sketched symbolically in Fig. 5, can have a significant impact on the neutron leakage properties near the core boundaries. However, although we recognize that these facilities are important in the overall core model, the focus of the MCNP modeling to date has been on the in-core configuration (i.e. everything contained in Fig. 2). The addition of the ex-core components within the existing model is, in fact, the next step in the overall model development process.

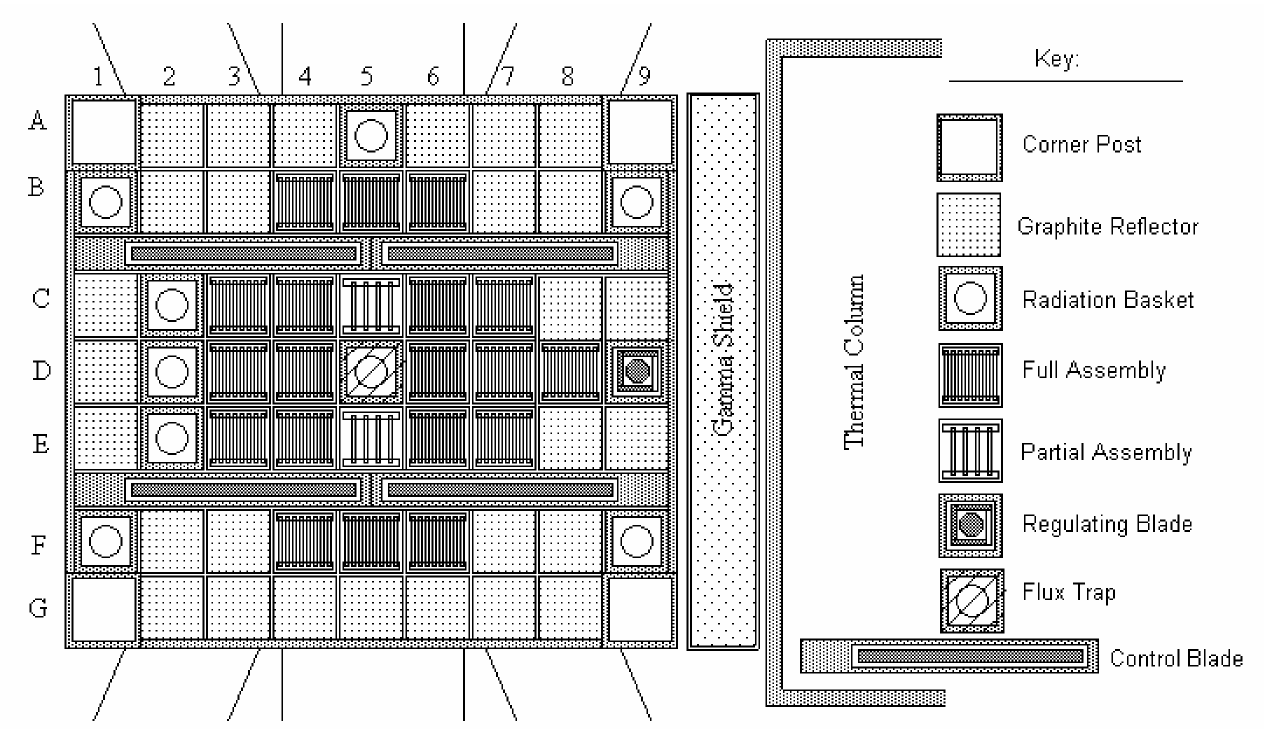

Fig. 5 Core layout for the LEU startup configuration (M-1-3 configuration).

In addition, another feature that affects both the in-core and ex-core models is the fast neutron irradiation (FNI) facility that was installed back in 2002. This experimental facility replaced the three beam ports on one side of the core and it consists of a modular arrangement, including the large dry sample canister, several shield elements, four aluminum blocks, a large Al guide collar, and a single flux-shaping element, all fitting within a large grid structure just to the side of the core (see sketch in Fig. 6).

The installation of the new ex-core experimental FNI facility also required a number of changes to be made to the in-core configuration. In particular, a new in-core element was designed that contains about 0.5 inches of lead on either side of an air space. This new in-core element is referred to as a lead-void box. It is about 29″ long

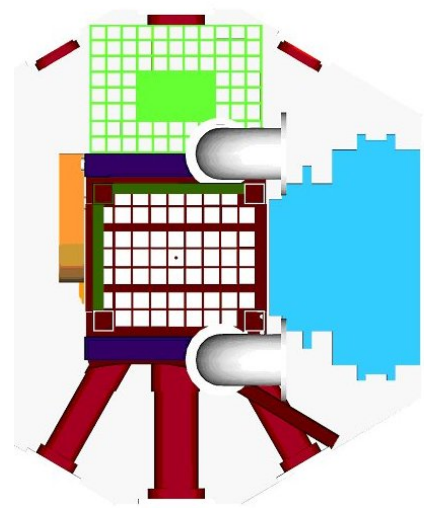

Fig. 6 Top view of the UMLRR with the FNI grid present.

with a 3″×3″ square base so that it fits into a standard core grid position. Five of these elements (see Fig. 7) were fabricated and inserted into the central five positions of row A within the core grid (note that the core grid has seven rows (A, B, ··· G) and nine columns (1, 2, ··· 9). This design feature provides about 1" of primary gamma shielding and it also tends to neutronically de-couple the core region from the remainder of the FNI facility. More importantly from the FNI perspective, however, is that these elements do not significantly decrease the fast flux.

The replacement of five graphite reflectors with Pb-void boxes also caused a fairly substantial decrease in core reactivity. This was offset by interchanging the two partial fuel elements in positions C5 and E5 in the M-1-3 core with the full fuel assemblies in C3 and E3. Moving these two full assemblies into a higher-worth region was just enough to counter the negative reactivity introduced by the five Pb-void boxes. These composite changes also cause a shift in the in-core flux distribution and control blade worth distribution towards the lower right part of the core (relative to the diagrams in Figs. 5-7).

The result of the in-core modifications identified above is shown in Fig. 7. This core configuration, denoted as the M-2-5 core, represents the post-FNI layout, and this is the core configuration now being used in routine operation of the UMLRR. It is this M-2-5 arrangement, including the burnup associated with about 40-50 MWD of operation over the last 8-10 years, that is the ultimate goal of this modeling project -- since this is the current configuration in use within the UMLRR facility.

However, before we get to this point, we first plan to model and formally validate the full M-1-3 core configuration against experimental measurements and our existing deterministic models of the UMLRR M-1-3 core. Then, with a validated base MCNP model, the ex-core FNI facility and

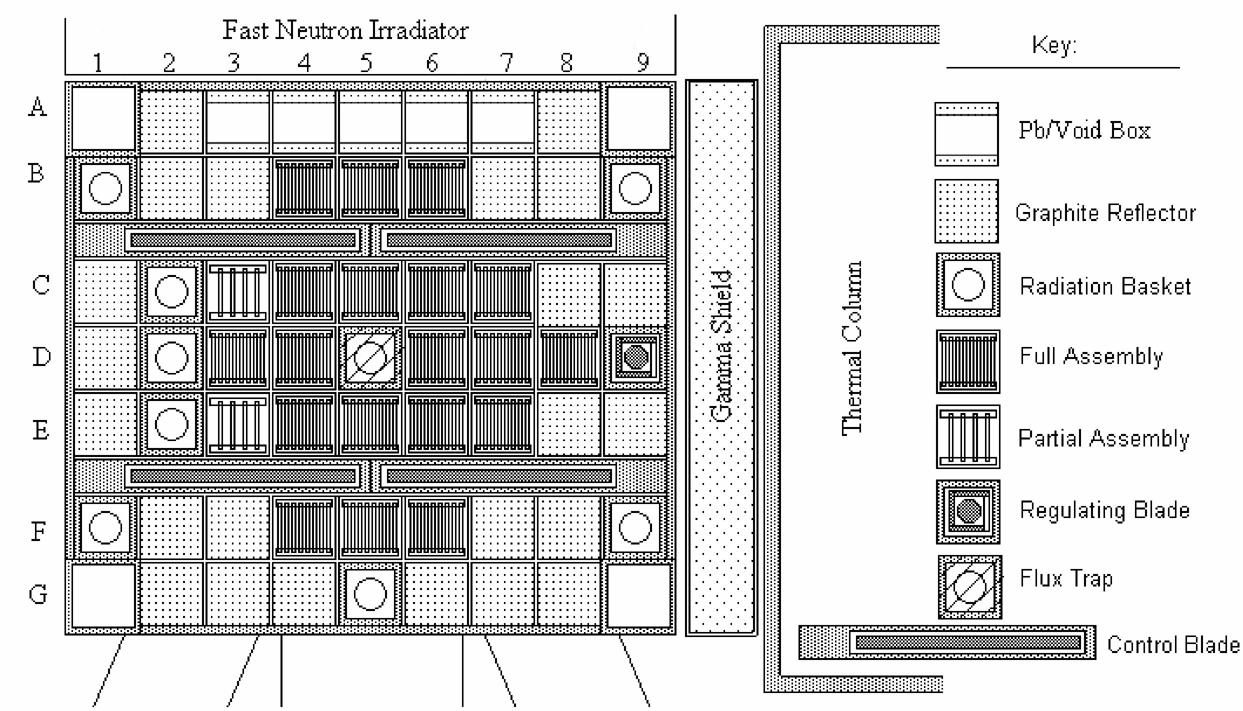

Fig. 7 Core layout with the FNI facility installed (M-2-5 configuration).

the appropriate in-core configuration changes will be modeled to get to the M-2-5 configuration. Some further testing will be done here, with fresh fuel material compositions, since the burnup was still quite low when the FNI was first installed. Finally, including fuel depletion effects for operation over the last 8-10 years will bring the MCNP model in line with current operations and we will finally have a model that can be used for predictive analyses of the physics behavior of the current system…

The MCNP Model

As noted above, the focus of the MCNP modeling to date has been on developing the geometry details for the grid plate, core box, and all the in-core elements associated with the M-1-3 configuration within the UMass-Lowell research reactor (UMLRR). The geometry setup has made extensive use of the macrobody specification within MCNP (especially the RPP → rectangular parallelepiped and RCC → right circular cylinder bodies). With the many RPP and RCC specifications used (and a few distinct surfaces), the various cells and universes needed for the complete model could be constructed without the use of the union and complement operators and without any specific lattice structures (avoiding the use of unions and lattices was requested by the project sponsor). In particular, several key building blocks (i.e. unit cells) were generated, including a ***full fuel plate*** (u = 2), a ***full fuel assembly*** (u = 5), a ***partial fuel plate*** (u = 7), a ***partial fuel assembly*** (u = 8), a ***radiation basket*** (u = 13), a ***flux trap*** (u = 15), a ***graphite reflector*** (u = 19), a ***corner post*** l (u = 23), a ***full control blade*** cell for each of the four large blades (u = 26, 27, 28, and 29), and a ***regulating blade*** (u = 37). These unit cells were placed in a specific reference location and then repeated with the "like n but trcl (···)" structure, as needed, to fill out the 7×9 grid layout for the M-1-3 configuration. A core box and large water reflector was then placed around the core to complete the current model.

Note that, in the current setup, the four control blades are located at their critical height of 15.3″ withdrawn (17.3″ from the top of the grid plate) and the regulating blade is in the fully inserted position (2″ above the grid plate). Here we emphasize that the top of the grid plate represents the z = 0 level in the MCNP model, and that the control blades have a total traverse of 26″, where fully inserted is 2″ above the grid plate. However, from an operator's perspective, fully inserted is z = 0 when discussing the position of the blades, and they can be moved 26″ out relative to this location (but this corresponds to 2″ < z < 28″ within the MCNP model). Thus, the user will have to be careful to properly treat this 2″ difference in axial location (depending on perspective).

Although we plan to fully document all the details of the full geometry model as part of the Final Report for this project, for the current Progress Report we will simply provide some overview documentation of the MCNP geometry via a set of 2-D geometry figures generated by the MCNP Visual Editor. These drawings, along with some summary descriptive comments, are given in Figs. 8 – 13, and they provide a pretty good summary of the currently available MCNP model. In particular, careful study of these geometry sketches shows that all of the key in-core features within the UMLRR have been treated, and that we indeed have a fairly rigorous representation of the real physical system -- and this was the goal of the first part of this modeling project.

Thus, we have met our first major milestone with the development of a detailed in-core model and, clearly, the next step is to add the appropriate ex-core components to the existing model. This new task is now underway, and we hope to have this next step completed, along with some validation of the M-1-3 MCNP model, in late January 2011. This is the plan anyway…

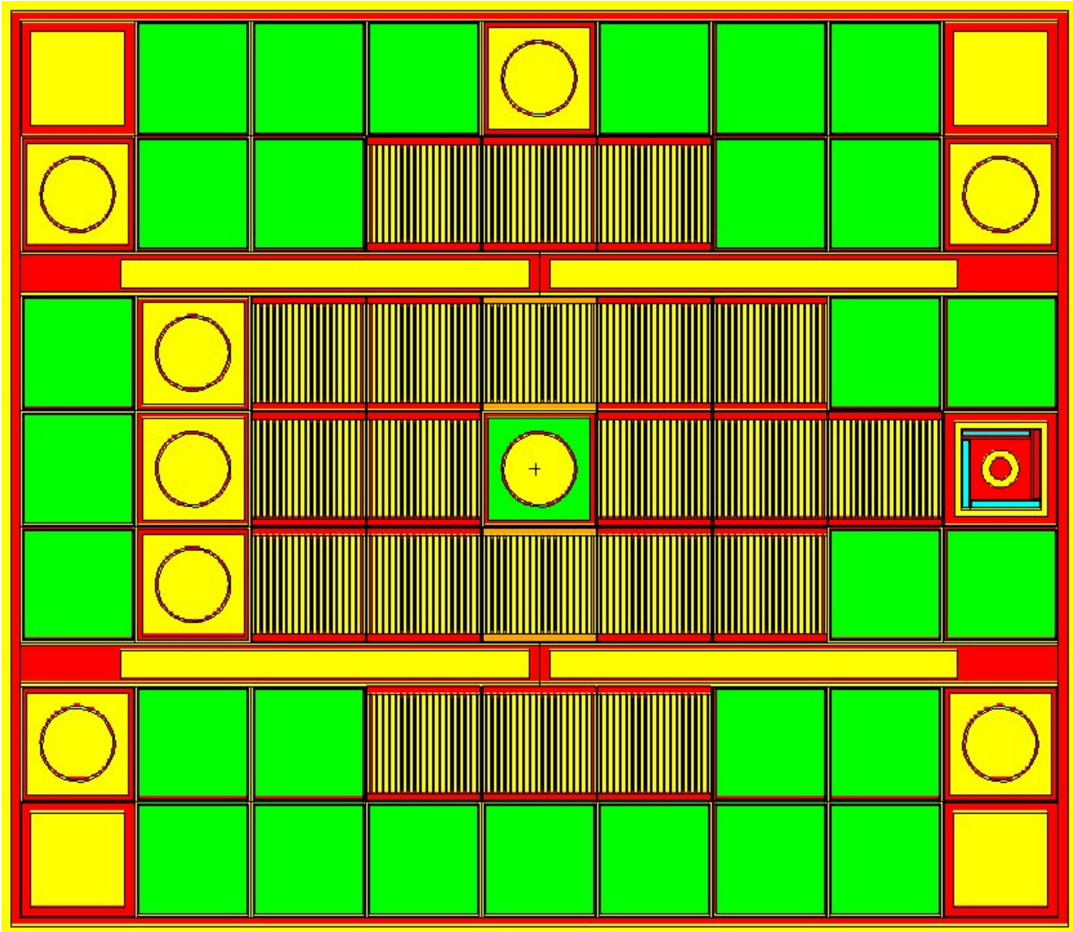

Fig. 8 Full XY view of UMLRR M-1-3 core model (z = 30 cm).

Comments:

This figure represents an XY cut near the axial centerline of the active fuel region for the UMLRR M-1-3 core configuration. One can easily see the 21 fuel elements (19 full and 2 partial assemblies), several graphite reflector elements (i.e. the solid green boxes), several radiation basket or water basket assemblies which have a central water-filled cylindrical Al shell (some of these hold material samples for irradiation purposes), and a single central flux trap element, which is similar in construction to the radiation basket except that it has graphite in the region between the inner cylinder and the outer Al can.

In addition, the four large control blade shrouds are apparent where, at this axial level, the actual control blades are not present, since they are positioned at their critical height of 15.3 inches withdrawn. On the other hand, the regulating blade in location D9 is visible, where the three sides closest to the fuel contain Boral as the control material (i.e. the light blue material).

Finally, the four hollow Al corner posts and the Al core box (i.e. the red Al structure material) fill out and surround the core grid to complete the current model. Note that, in the present (incomplete) model, the actual beam ports, thermal column, and the fast neutron irradiator regions are simply replaced with a large water reflector (the yellow regions represent water in the current MCNP model). Later models will correct this deficiency and include proper representations of these ex-core irradiation facilities.

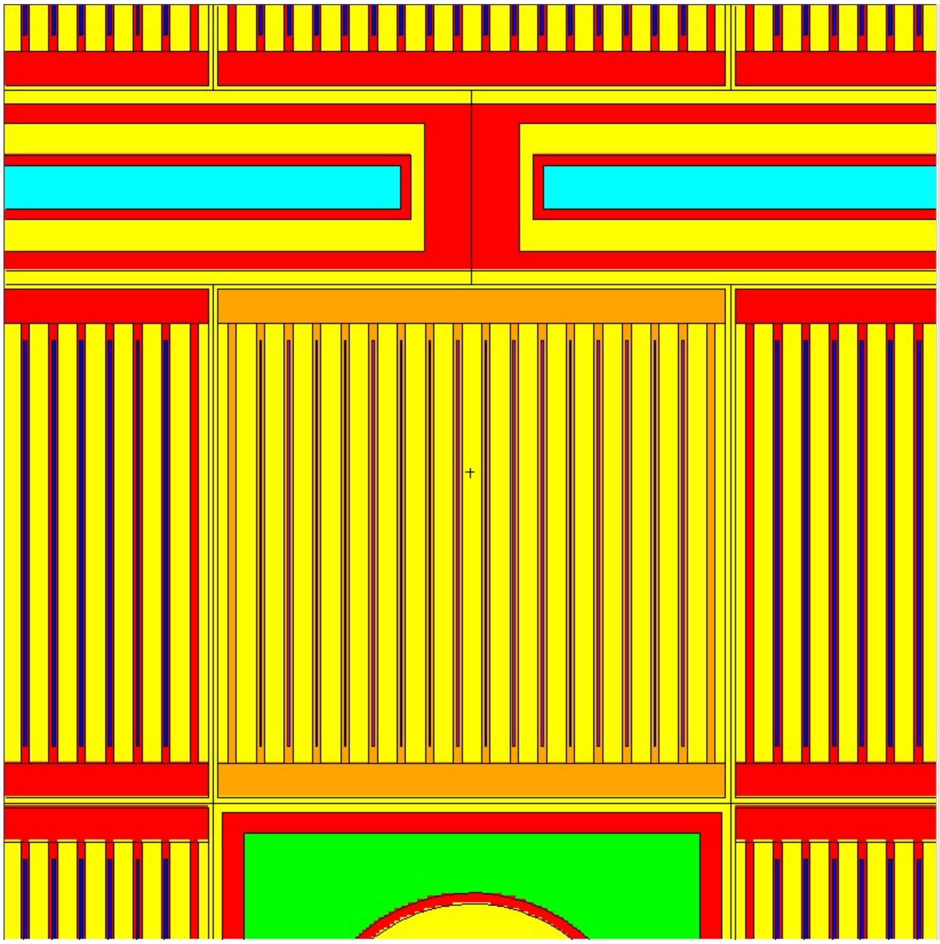

Fig. 9 Expanded XY view of the UMLRR M-1-3 core focused on location C5 (z = 60 cm).

Comments:

This figure gives an expanded view of a portion of several assemblies focused on the partial fuel element in location C5. The key difference between a partial and full fuel assembly is that the fuel meat in a partial fuel plate is only half the thickness of a full fuel plate. However, even in this expanded view, this geometry difference is hard to see -- thus, a new material number was defined for the fuel and aluminum within the partial assembly so that they would have different colors in the current visualization. It should be emphasized, however, that the material compositions are identical in the two assemblies (only the thicknesses of the fuel meat and corresponding clad layers are different).

In this view one can also clearly see that the fuel assemblies have 16 fuel plates and a dummy Al end plate on each side, giving a total of 18 plates per assembly -- and this is true for the both the full and partial assemblies.

Finally, we note that, since this XY cut was taken at z = 60 cm in the model (note that z = 0 in the MCNP model is just above the core grid plate), the four large control blades are visible in the current view, with the light blue Boral inner region surrounded by the red Al clad layer all centered inside the Al control blade shroud that was highlighted in the previous figure.

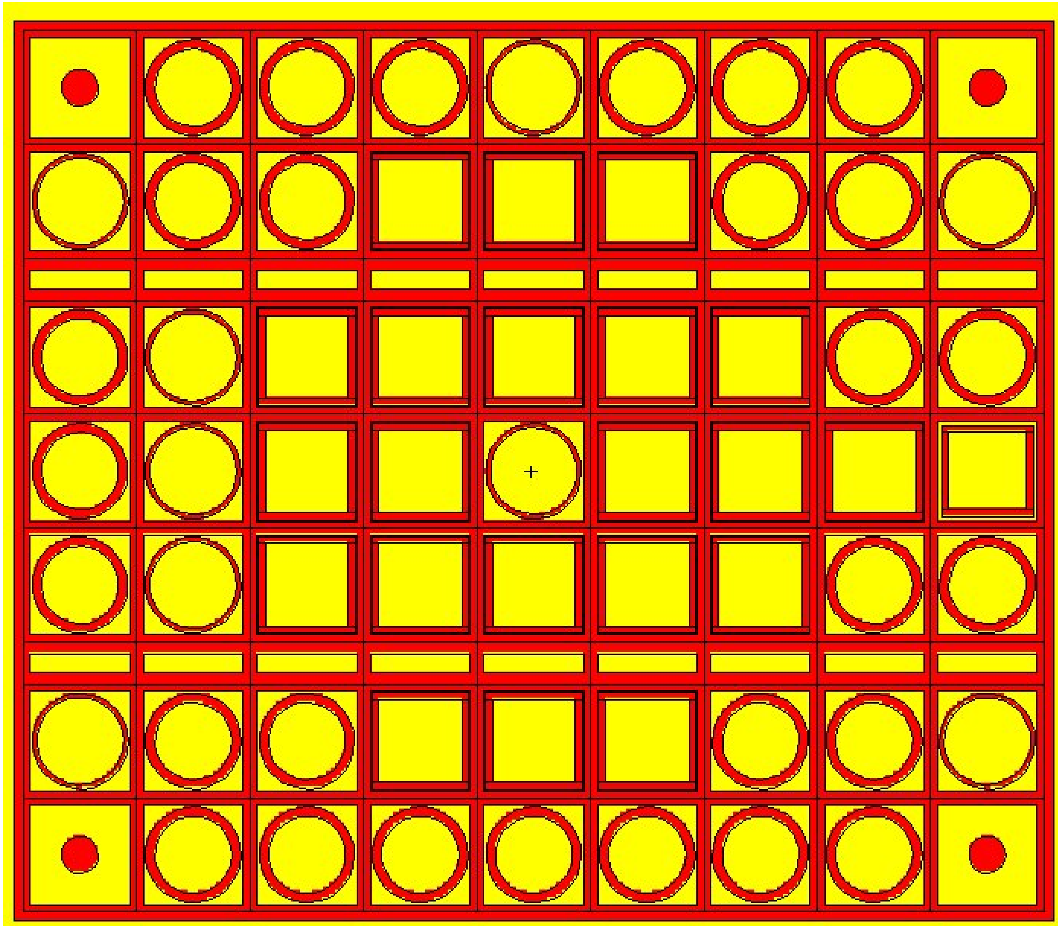

Fig. 10 Full XY view of UMLRR M-1-3 core model (z = -3 cm).

Comments:

This diagram gives an XY view just inside the grid plate at the z = -3 cm level. This axial layer contains only Al structure and water. The red structural material seen here represents the actual grid plate itself and a portion of the end boxes associated with each of the different assemblies that sit on and within the grid plate. The three main end box types include those associated with the fuel elements (square box just inside the grid plate), the radiation/water baskets (relatively thin cylindrical shells), and the graphite reflector assemblies (larger cylindrical shells). In addition, the solid cylinders in each of the four corner posts model the large solid threaded rods and nuts that secure the corner posts (and whole support structure) to the grid plate -- which, in turn, holds all the different elements in place inside the core box.

Fig. 11 Full XZ view of UMLRR M-1-3 core model (y = 23 cm).

Comments:

This figure shows an XZ view near the mid-plane of the core in the y-direction (along a line that connects the center of the central flux trap in location D5 and the regulating blade in D9). From left to right, one can distinguish a graphite reflector element, a radiation basket, two fuel elements, the central flux trap, three more fuel assemblies and, finally, the regulating blade in its fully inserted position. Portions of the upper and lower end boxes of the individual assemblies are also visible. Finally, we note that, since the regulating blade can traverse a total of 26 inches in the axial direction, the regulating blade shroud extends well above the core box (as seen here).

Fig. 12 Full YZ view of UMLRR M-1-3 core model (x = 10 cm).

Comments:

This figure represents a YZ cut just to the left of core center in the x-direction. This location was chosen to highlight the axial position of the control blades (specifically Blades 1 and 2) and to include as many of the other assembly types as possible. In particular, from left to right, this view includes a graphite reflector element, a full fuel element, a partial fuel assembly, the central flux trap, another sequence of partial and full fuel elements and, finally, the radiation basket that served as the startup source holder. Note, however, that one cannot distinguish between the full and partial assemblies because the precise x location was chosen to correspond to a water channel between two fuel plates (see next figure for a traverse directly through the fuel meat).

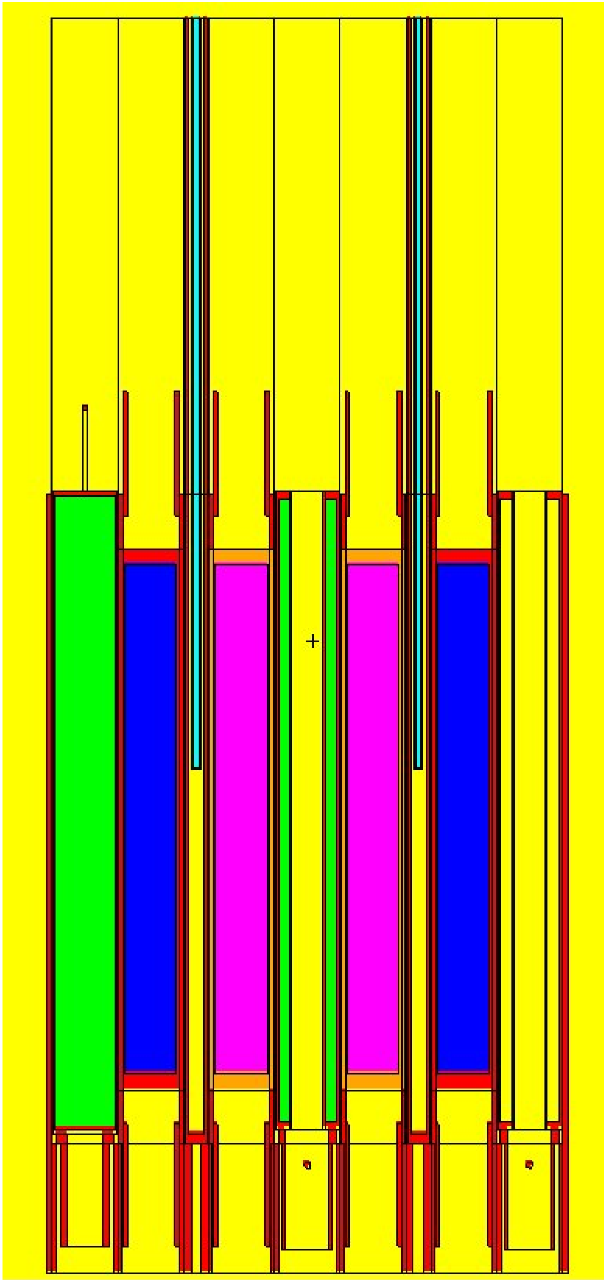

Fig. 13 Full YZ view of UMLRR M-1-3 core model (x = 10.17 cm).

Comments:

This figure is nearly identical to the previous YZ cut, with the exception that this is taken at a location 0.17 cm to the right of the previous one. This specific x location gives a cut directly through the center of one of the fuel plates. Therefore, in this view, it is indeed easy to see the difference between a full fuel plate (the dark blue color) and partial fuel plate (the pinkish color). Thus, this diagram, in addition to all the other features that it shows, also gives a good view of the fuel plate model used -- which was one of the key building blocks for this overall MCNP model of the UMLRR LEU core.