Comparison of the WPI and UMLRR Fuel Assembly Models

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Introduction

A series of reactor physics and thermal analysis computations are needed to support and justify the safe use of the Worcester Polytechnic Institute (WPI) UAl_x-Al fuel elements within the UMass-Lowell research reactor (UMLRR) -- either as standalone fuel or along side the existing U_3Si_2-Al fuel elements. The first step in doing these analyses is to have a good description of the actual WPI fuel element design and to make appropriate comparisons to the existing uranium-silicide fuel elements within the UMLRR. This report documents and compares both assembly designs and develops the geometry and densities needed for various models used within subsequent analyses. In particular, a set of individual region densities (fuel meat, structure, and water) and a 1-zone homogenous model are needed for the cross section processing codes, and a 3-zone homogenized element model (including separate zones for the fuel center, fuel edge, and side plates within the fuel assembly) are required for use in the existing VENTURE 3-D core models at UMass-Lowell. This report reviews the geometry and composition data developed for the WPI UAl_x-Al fuel element and compares these to the existing U_3Si_2-Al fuel data. The data for the WPI assemblies were obtained from several available engineering drawings (Ref. 1) and from the 1987 WPI HEU to LEU fuel conversion report generated by Argonne National Lab (ANL) (see Ref. 2). The data for the existing UMLRR fuel comes from a variety of documents that describe previous modeling efforts for the LEU-fuelled UMLRR core (see Ref. 3-7, for example). The detailed fuel element information presented here will serve as the basis for much of the subsequent modeling studies involving the WPI fuel assemblies.

Fuel Element Geometry Description

The UMLRR and WPI fuel assemblies are quite similar in overall size and shape and material composition, but there are enough key differences so that a formal comparison and safety evaluation for their combined use is warranted. In particular, Table 1 highlights many of these similarities and differences. For example, both assemblies have 18 plates within the two side plates -- but the WPI element has 18 fuel plates, whereas the UMLRR element has 16 fuel plates and two aluminum end plates for a total of 18 plates. The fuel meat for the WPI plate is UAl_x-Al with a U235 loading of about 9.3 g, whereas the UMLRR full fuel plate contains U_3Si_2-Al fuel with 12.5 g of U235 per plate (the UMLRR partial fuel plate contains about half of this loading). In addition, although the nominal cladding thicknesses are essentially identical, the WPI fuel meat is slightly thicker than the UMLRR fuel -- thus, the overall fuel plate thickness is a little larger, with a slightly decreased channel thickness for the WPI element.

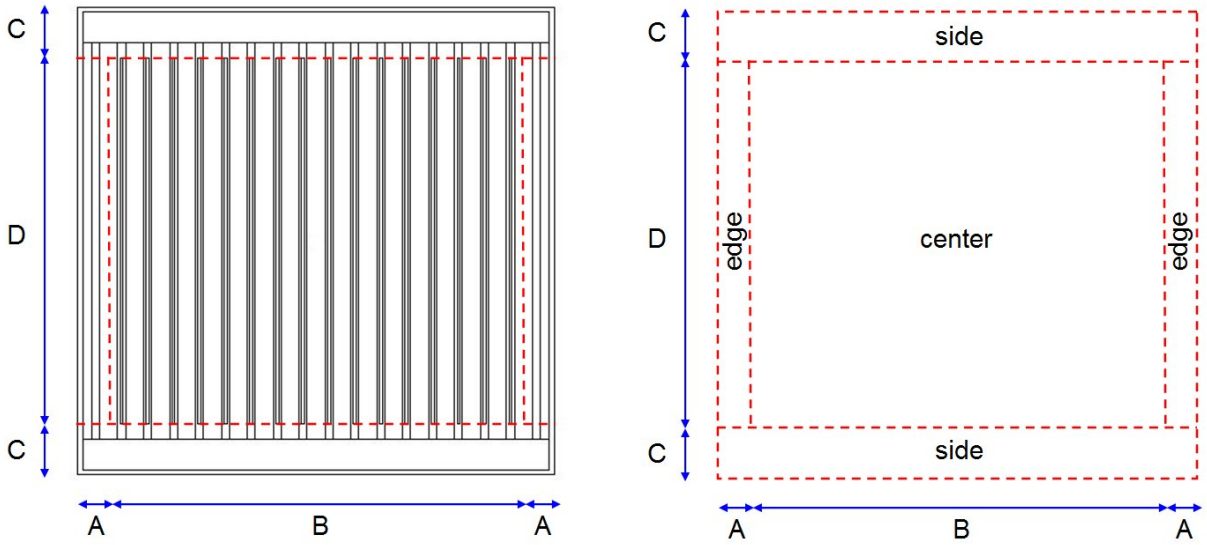
Table 1 Physical data for the UMLRR and WPI standard fuel elements.

Parameter	UMLRR Full Fuel Element (nominal value)	WPI Fuel Element (nominal value & range, if appropriate)
Plate Data:		
fuel type	U_3Si_2-Al	UAl_x-Al
enrichment (w/o)	19.75	19.75
U235 loading (g/plate)	12.5	9.28
plate width (cm)	7.140	7.049
meat width (cm)	6.085	6.085 (5.44 – 6.35)
plate thickness (cm)	0.1270	0.1524 (0.147 – 0.157)
meat thickness (cm)	0.0510	0.0762
clad thickness (cm)	0.0380	0.0381
plate height (cm)	63.50	62.55
meat height (cm)	59.69	59.69 (57.2 – 61.0)
Assembly Data:		
fuel plates/element	16	18
aluminum plates/element	2	0
U235 loading (g/element)	200.0	167.0
side plate thickness (cm)	0.5080	0.4572
channel thickness (cm)	0.2963	0.2709
assembly dimension (cm × cm)	7.620 × 7.620	7.620 × 7.620
assy. dim. with gap (cm × cm)	7.7724 × 7.7724	7.7724 × 7.7724

As apparent in the above table, some of the quoted WPI dimensions given in the last column show both the nominal values to be used in subsequent modeling at UMass-Lowell and the expected range of values based on various manufacturing uncertainties (shown in parentheses). Clearly, similar tolerances were also originally given for the UMLRR fuel, but the data given in the second column in Table 1 refer specifically to the nominal values currently used in our existing UMLRR mathematical models (which, in most cases, have been shown to give reasonable comparisons to measured results as shown in Refs. 6 and 7, for example). Note that the nominal values selected for the WPI assembly models were either near the midpoint of the uncertainty range or they were chosen to match the existing UMLRR value for ease in using both designs within the same VENTURE geometry.

In particular, a key dimension that allows one to easily insert both fuel elements within the same geometry is the fuel meat width. If this dimension for the WPI fuel was chosen differently, then the dividing line between the fuel center and side plate regions as seen in Fig. 1 would be different -- and this would make the subsequent VENTURE model much more difficult to build. By selecting

the WPI nominal fuel meat width at 6.085 cm (i.e. the same as the UMLRR fuel), the simple 5-region, 3-zone fuel element model shown on the right side of Fig. 1 can easily accommodate both fuel types and allow the same relatively straightforward VENTURE geometry model to be used for both assemblies. Thus, although the 6.085 cm value is not directly in the center of the uncertainty range, it was chosen to greatly simplify subsequent modeling tasks. Note, however, that the proper fissile loading is always maintained by computing the nuclide densities for the given model based on the known U235 content and the nominal dimensions given in Table 1.



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.

Fuel Element Material Compositions

With the nominal fuel element geometry defined, one can now focus on the material compositions to be used within the various computational modeling tools used at UMass-Lowell. Since several different models will be utilized, a variety of heterogeneous and homogeneous material specifications are required -- where, of course, the zone-averaged homogeneous atom densities are specific to the particular homogeneous geometry used. In particular, for subsequent cross section unit cell/unit assembly computations and for any detailed MCNP models that may be used to benchmark/validate the 1-D cell models, region-specific nuclide atom densities are required (the three regions of interest within the fuel element are the fuel meat, Al structure, and water regions). For the homogeneous models, both 1-zone and 3-zone representations are used -- a 1-zone homogeneous fuel element model is used within various 1-D XSRDN models when processing cross sections (see Ref. 8) and the 3-zone center/edge/side representation for a fuel assembly, as shown in Fig. 1, is the basis of all our 2-D and 3-D VENTURE models. Thus, appropriate atom densities are required for each of the three model configurations (heterogeneous model and the 1-zone and 3-zone homogeneous models).

A short Matlab code called **umlrrden.m** was written to facilitate the computation of the desired material compositions and to provide explicit documentation on how these were produced. The main **umlrrden** script file uses one of three case-specific data files that contain the needed geometry and material information for the three different assembly types used here, as follows:

leufdata.m -- contains data for the UMLRR full uranium-silicide fuel element

leupdata.m -- contains data for the UMLRR partial uranium-silicide fuel element

wpifdata.m -- contains data for the WPI full uranium-aluminide fuel element

Most of the information given in these data files was obtained directly from Table 1 with the exception of the ***ffrac*** variable, which represents the U_3Si_2 fraction in the U_3Si_2-Al mix or the U fraction in the UAl_x-Al fuel meat. Appendix I of IAEA TECDOC-643 was used to obtain/justify the value of ***ffrac*** used here (see Ref. 9). This quantity is needed to determine the amount of Al within the fuel meat once the U or U_3Si_2 content is known.

With the specific geometry and fuel fraction known, **umlrrden** computes the needed volume fractions, region densities, and finally, the homogeneous atom densities for the 3-zone and 1-zone representations. A listing of these Matlab codes (the main **umlrrden** script file and the three data files noted above) is given at the end of this report as formal documentation of the complete process. In addition, a detailed hand calculation for the U_3Si_2 fuel meat densities is given in Ref. 10 as an example of the details coded within **umlrrden** (this hand computation is used to illustrate the development of nuclide atom densities as part of the Introduction to Nuclear Engineering I course at UMass-Lowell).

The results from the Matlab codes are summarized below in Tables 2 – 4 for the standard WPI fuel assembly and for the UMLRR full and partial assemblies, respectively. These atom densities (in atoms/barn-cm) are the values used within the various core models developed for this study.

Table 2 Material composition data for the standard WPI fuel element.

```
          Data for the LEU WPI Standard Fuel Assembly

Region Volume Fractions (fuel meat, structure, & water):
  CENTER volume fractions:  0.1800   0.1800   0.6400
  EDGE volume fractions:    0.1525   0.1525   0.6951
  SIDE volume fractions:    0.0000   0.6611   0.3389

Region Atom Densities [at/b-cm]
           Fuel Meat     Structure       Water
  U235    8.5888e-004   0.0000e+000   0.0000e+000
  U238    3.4458e-003   0.0000e+000   0.0000e+000
  Al      4.6300e-002   6.0261e-002   0.0000e+000
  Si      0.0000e+000   0.0000e+000   0.0000e+000
  H       0.0000e+000   0.0000e+000   6.6857e-002
  O       0.0000e+000   0.0000e+000   3.3428e-002

Zone Averaged Atom Densities [at/b-cm]
            CENTER         EDGE          SIDE          HOMO 1-REGION    Mass (grams)
  U235    1.5461e-004   1.3095e-004   0.0000e+000       1.1866e-004       167.00
  U238    6.2028e-004   5.2534e-004   0.0000e+000       4.7606e-004       678.57
  Al      1.9183e-002   1.6246e-002   3.9837e-002       2.3371e-002      3775.88
  Si      0.0000e+000   0.0000e+000   0.0000e+000       0.0000e+000         0.00
  H       4.2786e-002   4.6470e-002   2.2659e-002       3.8788e-002       234.11
  O       2.1393e-002   2.3235e-002   1.1330e-002       1.9394e-002      1857.89
```

Table 3 Material composition data for the full UMLRR fuel element.

Data for the UMLRR LEU Full Fuel Assembly

Region Volume Fractions (fuel meat, structure, & water):

CENTER volume fractions:	0.1205	0.1795	0.7000
EDGE volume fractions:	0.0000	0.2541	0.7459
SIDE volume fractions:	0.0000	0.6808	0.3192

Region Atom Densities [at/b-cm]

	Fuel Meat	Structure	Water
U235	1.7290e-003	0.0000e+000	0.0000e+000
U238	6.9364e-003	0.0000e+000	0.0000e+000
Al	3.9540e-002	6.0261e-002	0.0000e+000
Si	5.7769e-003	0.0000e+000	0.0000e+000
H	0.0000e+000	0.0000e+000	6.6857e-002
O	0.0000e+000	0.0000e+000	3.3428e-002

Zone Averaged Atom Densities [at/b-cm]

	CENTER	EDGE	SIDE	HOMO 1-REGION	Mass (grams)
U235	2.0831e-004	0.0000e+000	0.0000e+000	1.4211e-004	200.00
U238	8.3571e-004	0.0000e+000	0.0000e+000	5.7013e-004	812.66
Al	1.5583e-002	1.5312e-002	4.1024e-002	2.1079e-002	3405.58
Si	6.9601e-004	0.0000e+000	0.0000e+000	4.7483e-004	79.85
H	4.6798e-002	4.9868e-002	2.1343e-002	4.1581e-002	250.97
O	2.3399e-002	2.4934e-002	1.0671e-002	2.0790e-002	1991.68

Table 4 Material composition data for the partial UMLRR fuel element.

Data for the UMLRR LEU Partial Fuel Assembly

Region Volume Fractions (fuel meat, structure, & water):

CENTER volume fractions:	0.0602	0.2398	0.7000
EDGE volume fractions:	0.0000	0.2541	0.7459
SIDE volume fractions:	0.0000	0.6808	0.3192

Region Atom Densities [at/b-cm]

	Fuel Meat	Structure	Water
U235	1.7290e-003	0.0000e+000	0.0000e+000
U238	6.9364e-003	0.0000e+000	0.0000e+000
Al	3.9540e-002	6.0261e-002	0.0000e+000
Si	5.7769e-003	0.0000e+000	0.0000e+000
H	0.0000e+000	0.0000e+000	6.6857e-002
O	0.0000e+000	0.0000e+000	3.3428e-002

Zone Averaged Atom Densities [at/b-cm]

	CENTER	EDGE	SIDE	HOMO 1-REGION	Mass (grams)
U235	1.0415e-004	0.0000e+000	0.0000e+000	7.1055e-005	100.00
U238	4.1786e-004	0.0000e+000	0.0000e+000	2.8507e-004	406.33
Al	1.6832e-002	1.5312e-002	4.1024e-002	2.1931e-002	3543.16
Si	3.4801e-004	0.0000e+000	0.0000e+000	2.3741e-004	39.93
H	4.6798e-002	4.9868e-002	2.1343e-002	4.1581e-002	250.97
O	2.3399e-002	2.4934e-002	1.0671e-002	2.0790e-002	1991.68

Assembly k_∞ Comparisons

As a quick preliminary check on the base nuclide densities for the WPI model, a series of assembly k_∞ computations were made using MCNP with ENDF/B-VII cross sections (with all data at 300 K). Because of the lighter fuel loading (i.e. 167 g of U235 per assembly for the WPI element versus 200 g for the UMLRR full assembly), k_∞ was expected to be lower for the WPI standard element relative to the UMLRR full element. And, since the UMLRR partial element only has 100 g of U235, this assembly should have the lowest k_∞. Summary results from these three cases are given

in Table 5 and the relative magnitudes of k_∞ are exactly as expected. Note also that these values will be used to check the consistency of the simplified 1-D SCALE models that will be used during the generation of the few group cross sections needed for the subsequent 2-D and 3-D VENTURE full core models. Thus, the MCNP k_∞ results are useful for the current relative comparison of the three assembly designs, and they will also be useful to help validate some of the subsequent models generated with other codes.

Table 5 MCNP k_∞ values for the three assembly designs.

Parameter	WPI Fuel Assembly (167 g U235)	UMLRR Full Element (200 g U235)	UMLRR Partial Element (100 g U235)
k_∞	1.5384	1.5670	1.3715
std. dev.	0.00025	0.00026	0.00023
H/U235 ratio	326	292	585

In completing this section, we should say a few words about the MCNP k_∞ calculations. Here the fuel element is modeled in explicit detail -- that is, each fuel plate (meat and clad), dummy aluminum plate, and water channel is modeled explicitly within the two structural side plates within the physical assembly. A small 0.03″ water gap is included around the element to represent the unit assembly size within the UMLRR core (the small gap allows for easy insertion and removal of individual assemblies within the UMLRR support grid). However, since we are interested in k_∞, only the active fuel height is modeled, and all six bounding surfaces are reflected. Thus the model is effectively equivalent to a 2-D XY cut through a unit assembly within the active fuel region. A visualization of the three MCNP assembly models -- highlighting the fuel element details and the basic similarity of the three designs -- is given in Fig. 2 below.

Finally, to put the k_∞ values given in Table 5 into perspective, a brief sensitivity study of k_∞ versus the water to fissile uranium ratio (H/U235 ratio) for a typical LEU fuel assembly was performed. For this parametric study, a full UMLRR assembly with 18 U_3Si_2-Al fuel plates was assumed as the reference (i.e. no dummy aluminum plates were included in this parametric MCNP study). With this reference point, the number of fuel plates was increased and decreased to give a range of water to fuel ratios that bound the H/U235 ratios for the above three physical assembly designs. In all cases, the fuel plates present were equally spaced within the standard 7.62 cm side plate length. Thus, as the number of fuel plates changed, the amount of water was also varied to maintain the overall assembly geometry dimensions.

The results of this brief study, along with the three points for the actual assembly designs, are summarized in Fig. 3. Here we see that, as expected, the reactivity decreases with increasing H/U235 value and that the three specific assembly designs (UMLRR full and partial assemblies and the WPI assembly) follow the same trend -- and also lie reasonably close to the generic curve. Since there are a variety of differences (i.e. no Al plates in the sensitivity study and the use of UAl_x-Al fuel instead of U_3Si_2-Al fuel for the WPI case), the individual points are not expected to lie directly on the generated curve -- but it is clear from this simple comparison that the variation in the H/U235 ratio among the three designs is, without doubt, the main component of the trend in k_∞ values seen in Table 5.

Summary

This brief report summarizes the WPI fuel assembly model that will be used in subsequent computational analyses. The physical geometry is compared to the existing UMLRR LEU uranium-silicide fuel elements and the material atom densities for a variety of model representations are developed and fully documented for each of the assembly designs. Finally, a quick check on k_∞ for the WPI standard assembly and the UMLRR full and partial assemblies shows the expected trend versus the H/U235 ratio for this important assembly property. The data tabulated here will serve as the basis for much of the subsequent model development and computational analysis to be performed to certify that the WPI fuel elements can indeed be used safely within the UMLRR.

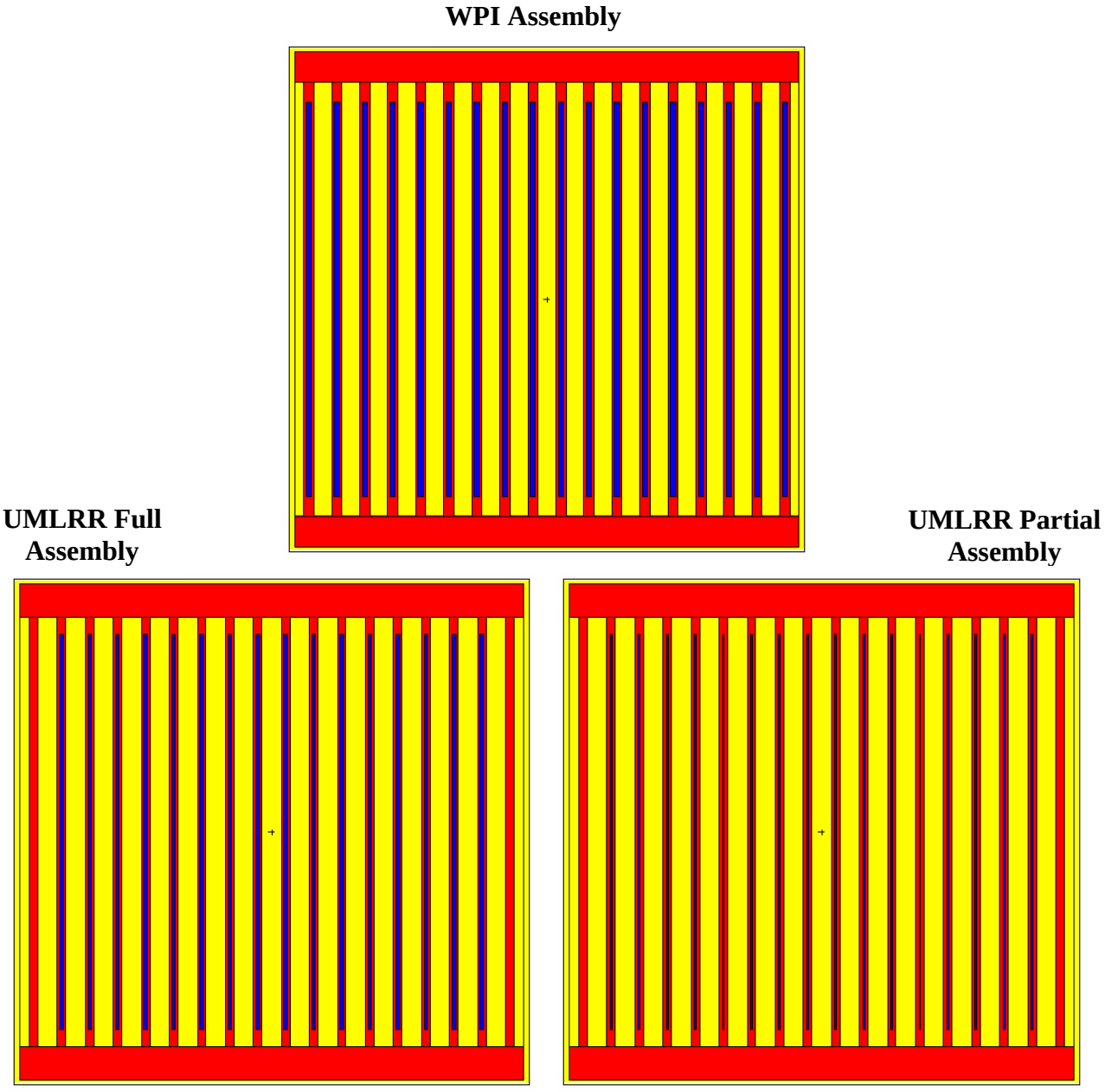


Fig. 2 MCNP models for calculation of the assembly k_∞ values.

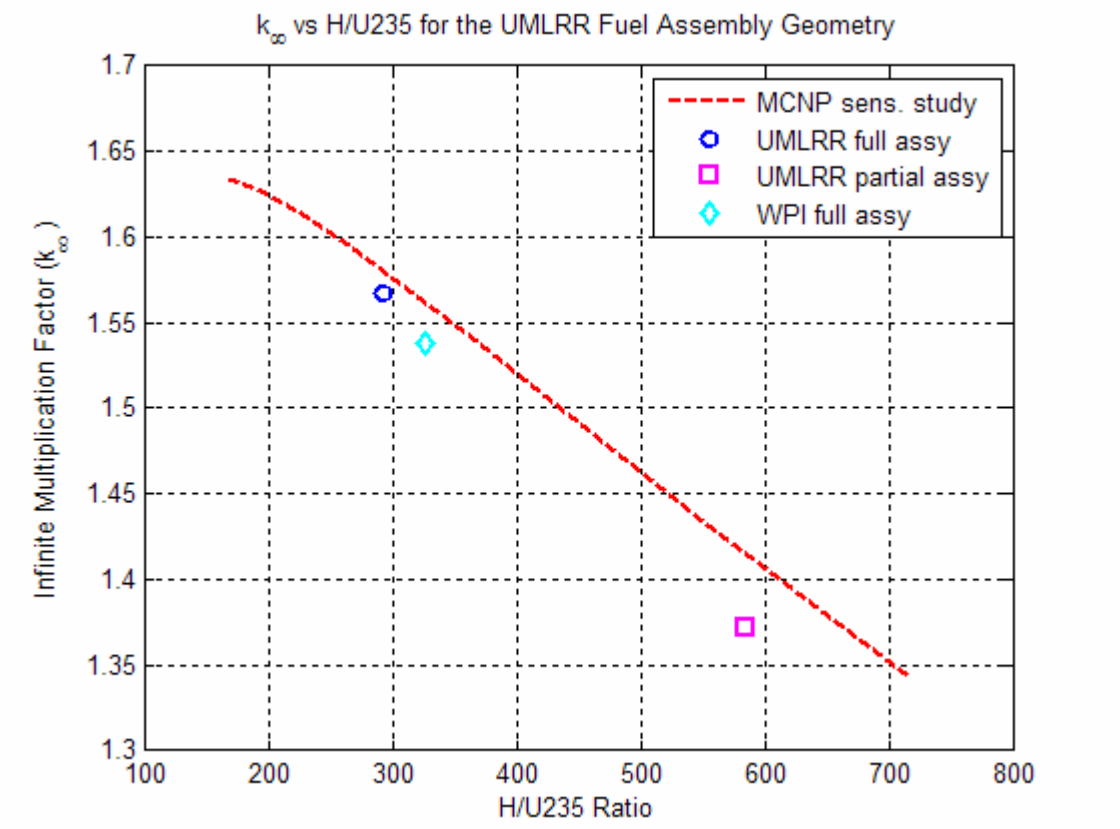


Fig. 3 Results from the parametric MCNP study -- k_∞ versus H/U235 ratio.

References

1. Several drawings of the Worcester Polytechnic Institute (WPI) fuel plate, side plate, fuel assembly, etc., EG&G Idaho, Inc. (fuel plate drawing dated 1978 and the rest dated 1987).
2. J. E. Matos and K. E. Freese, "Analyses for Conversion of the Worcester Polytechnic Institute Reactor from HEU to LEU Fuel," ANL RERTR Program (August 1987).
3. "FSAR Supplement for Conversion to Low Enrichment Uranium (LEU) Fuel," Document submitted for review by the NRC for conversion of the UMass-Lowell Research Reactor (May 1993).
4. J. R. White, et. al., "Calculational Support for the Startup of the LEU-Fueled UMass-Lowell Research Reactor," Advances in Reactor Physics and Mathematics and Computation, Pittsburgh, PA (May 2000).
5. J. R. White, et. al., "Preliminary Characterization of the Irradiation Facilities within the LEU-Fueled UMass-Lowell Research Reactor," Advances in Reactor Physics and Mathematics and Computation, Pittsburgh, PA (May 2000).
6. "Report on the HEU to LEU Conversion of the University of Massachusetts Lowell Research Reactor," submitted to the US Nuclear Regulatory Commission in fulfillment of Amendment No. 12 to License No. R-125 (April 2001).

7. J. R. White and L. Bobek, “Startup Test Results and Model Evaluation for the HEU to LEU Conversion of the UMass-Lowell Research,” 24th International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR 2002), San Carlos de Bariloche, Argentina (Nov. 2002).
8. J. R. White, “Cross Section Libraries and Preliminary Modeling for the Reference UMLRR LEU Core Configuration,” UMass-Lowell Informal Project Documentation (Jan. 1999).
9. “Research Reactor Core Conversion Guidebook, Volume 4: Fuels (Appendices I – K),” International Atomic Energy Agency, IAEA TECDOC-643 (1992).
10. J. R. White, “Basic Atomic and Nuclear Physics,” part of a series of Lecture Notes for the Nuclear Power Fundamentals Program at UMass-Lowell.

Appendix -- Listing of Matlab Codes to Compute Atom Densities for Various Fuel Assembly Designs

```
%
%   UMLRRDEN.M  Create densities for UMLRR Fuel Assemblies
%
%   A set of base data is first processed for the particular assembly of
%   interest:  HEUFDATA.M  - script file with data for HEU Full Fuel Assembly
%              HEUPDATA.M  - script file with data for HEU Partial Fuel Assembly
%              LEUFDATA.M  - script file with data for LEU Full Fuel Assembly
%              LEUPDATA.M  - script file with data for LEU Partial Fuel Assembly
%              WPIFDATA.M  - script file with data for LEU WPI Standard Fuel Assembly
%
%   A series of geometry calculations determine the appropriate volume fractions
%   of fuel, structure, and water in each of the center + edge + side regions.
%
%   Finally, the atom densities (at/b-cm) are computed for six isotopes, as
%   follows:  U235, U238, Al, Si, H, O
%
%   File prepared by J. R. White, UMass-Lowell
%     Original --  based on data from UMLRDEN.XLS  (Dec. 16, 1997)
%     Also give average densities over a single homogenized region  (Jan. 5, 1999)
%     Added capability to compute the mass of materials in the HOMO model (11/19/00)
%     Added capability to process data for the WPI standard fuel assembly (1/9/08)
%     Slight edits and detailed review for formal WPI modeling (finally...)
%       Note here that I changed Na slightly (from 0.60225 to 0.60221)     (6/25/11)
%

%
%   getting started
      clear all,   close all
%
%   identify assembly of interest
      iassy = menu('Choose assembly type','HEU Full Fuel Assembly', ...
                   'HEU Partial Fuel Assembly','LEU Full Fuel Assembly', ...
                   'LEU Partial Fuel Assembly','WPI Standard Fuel Assembly');
      if iassy == 1,  heufdata;   end
      if iassy == 2,  heupdata;   end
      if iassy == 3,  leufdata;   end
      if iassy == 4,  leupdata;   end
      if iassy == 5,  wpifdata;   end
%
%   calculate region volume fractions (area fractions actually)
%
      tat = assydimg*assydimg;            % total area of assy
%
%   CENTER (width defined by mwdth and thickness defined by nfpc)
      mac = mthk*mwdth*nfpc;              % meat area
      sac = (pthk-mthk)*mwdth*nfpc;       % structure area
      wac = chthk*mwdth*nfpc;             % water area
      tac = mac+sac+wac;                  % total area
      mvfc = mac/tac;   svfc = sac/tac;   wvfc = wac/tac;   % volume fractions
%
%   EDGE (width defined by mwdth and thickness defined by nfpe+nspe+gap thickness)
      mae = mthk*mwdth*nfpe;              % meat area
      sa1 = (pthk-mthk)*mwdth*nfpe;       % structure area for fuel plates
      sa2 = pthk*mwdth*nspe;              % structure area for Al plates
      sae = sa1+sa2;                      % structure area
      tae = mwdth*assydimg-tac;           % total area
      wae = tae-(mae+sae);                % water area
      mvfe = mae/tae;   svfe = sae/tae;   wvfe = wae/tae;   % volume fractions
%
%   SIDE (width is everything and thickness is everything (assydimg) minus mwdth
      totp = nfpc+nfpe+nspe;              % total number of plates
      sa1 = pthk*totp*(assydim-2*spthk-mwdth); % structure area for fuel plates
      sa2 = 2*assydim*spthk;              % structure area for Al side plates
      sas = sa1+sa2;                      % structure area
      tas = tat-(tac+tae);                % total area
      was = tas-sas;                      % water area
      mvfs = 0;   svfs = sas/tas;   wvfs = was/tas;   % volume fractions
%
%   edit region volume fractions
      fid = 1;
      fprintf(fid,'\n           Data for the %s \n\n',stitl);
```

```
      fprintf(fid,'  Region Volume Fractions (fuel meat, structure, & water):\n');
      fprintf(fid,'    CENTER volume fractions:  %6.4f   %6.4f   %6.4f   \n', ...
                  mvfc,svfc,wvfc);
      fprintf(fid,'    EDGE volume fractions:    %6.4f   %6.4f   %6.4f   \n', ...
                  mvfe,svfe,wvfe);
      fprintf(fid,'    SIDE volume fractions:    %6.4f   %6.4f   %6.4f   \n', ...
                  mvfs,svfs,wvfs);
%
%   now compute region atom densities
%
%   set some constants (isotope order -> U235, U238, Al, Si, H, O)
      Na = 0.60221;           % Avrogardro's number (x 10^-24) (at/g-mole)
      MW = [235.04 238.05 26.982 28.086 1.008 15.999 ];  % Molecular Wt (g/g-mole)
      MWW = 2*MW(5)+MW(6);                               % Molecular Wt for water
      MWU = 1/(enrich/MW(1)+(1-enrich)/MW(2));           % Molecular Wt for U
      MWF = MWU;                                         % Molecular Wt of Fuel
      if ftype == 2,  MWU = 3*MWU;  MWF = MWU+2*MW(4);  end
%
%   fuel meat densities
      gpp = u5load/(nfpc+nfpe);            % grams U235 per fuel plate
      fmvol = mwdth*mthk*mht;              % fuel meat vol
      u5d = gpp/fmvol;                     % U235 mass density
      fuelmd = u5d*MWF/(enrich*ffrac*MWU); % fuel meat mass density
      fmad = zeros(1,6);                   % initialize vector for atom densities
      fmad(1) = fuelmd*ffrac*(MWU/MWF)*enrich*Na/MW(1);          % U235
      fmad(2) = fuelmd*ffrac*(MWU/MWF)*(1-enrich)*Na/MW(2);      % U238
      fmad(3) = fuelmd*(1-ffrac)*Na/MW(3);                       % Al
      if ftype == 2,   fmad(4) = (2/3)*(fmad(1)+fmad(2));  end   % Si
%
%   aluminum structure densities
      sad = zeros(1,6);                    % initialize vector for atom densities
      ald = 2.70;                          % Al mass density (g/cc)
      sad(3) = ald*Na/MW(3);               % Al
%
%   water region densities
      wad = zeros(1,6);                    % initialize vector for atom densities
      wd = 1.0;                            % water mass density (g/cc)
      wad(6) = wd*Na/MWW;                  % O
      wad(5) = 2*wad(6);                   % H
%
%   edit region atom densities
      isot = ['U235';'U238';'Al  ';'Si  ';'H   ';'O   '];
      fprintf(fid,'\n  Region Atom Densities [at/b-cm] \n');
      fprintf(fid,'             Fuel Meat     Structure       Water  \n');
      for i = 1:6
        fprintf(fid,'    %s    %8.4e   %8.4e   %8.4e   \n', ...
                    isot(i,:),fmad(i),sad(i),wad(i));
      end
%
%   finally let's compute the zone averaged densities
%     c - CENTER     e - EDGE     s - SIDE      h - single homogeneous region
%
      aveadc = mvfc*fmad + svfc*sad + wvfc*wad;
      aveade = mvfe*fmad + svfe*sad + wvfe*wad;
      aveads = mvfs*fmad + svfs*sad + wvfs*wad;
      aveadh = (aveadc*tac + aveade*tae + aveads*tas)/tat;
%
%   compute mass (in grams) based on the fuel meat height
      totalvol = tat*mht;
      mass = aveadh*totalvol.*(MW/Na);
%
%   edit zone averaged atom densities (No B-10 in Al)
      fprintf(fid,'\n  Zone Averaged Atom Densities [at/b-cm] \n');
      fprintf(fid,'              CENTER         EDGE          SIDE          HOMO 1-REGION    Mass
(grams)\n');
      for i = 1:6
        fprintf(fid,'    %s    %8.4e   %8.4e   %8.4e        %8.4e     %8.2f\n', ...
                    isot(i,:),aveadc(i),aveade(i),aveads(i),aveadh(i),mass(i));
      end
%
%   end of program
```

```
%
%   WPIFDATA.M  Basic geometry data for the LEU WPI Standard Fuel Assembly
%
%   This file contains raw data for the LEU WPI Standard Fuel Assembly that is used by
%   UMLRRDEN.M to compute the atom densities of interest for this assembly.
%
%   Similar data sets exist for other fuel assembly types.
%
%   File prepared by J. R. White, UMass-Lowell  (Jan. 2008)
%   Detailed review with several modifications, including the fuel meat width to be
%   consistent with the UMLRR fuel, were made.  This data set will be the formal
%   specifications for the nominal WPI fuel element model at UMass-Lowell. (6/12/11)
%

%
%   basic assembly geometry data
      stitl = 'LEU WPI Standard Fuel Assembly';
      nfpc = 16;         % # of fuel plates in center region
      nfpe = 2;          % # of fuel plates in edge region
      nspe = 0;          % # of structure plates in edge region
      u5load = 167;      % U235 loading per element (grams)
      spthk = 0.4572;    % side plate thickness (cm)
      chthk = 0.2709;    % channel thickness (cm)
      assydim = 7.620;   % square assembly dimension (cm)
      assydimg = 7.7724; % square assembly dimension with water gap (cm)
%
%   basic plate geometry data
      ftype = 3;         % fuel type: 1 -> HEU U-Al alloy;
                         %            2 -> LEU U3Si2-Al alloy
                         %            3 -> LEU UAlx-Al
      ffrac = 0.45;      % fuel frac (U frac for aluminide or U3Si2 frac for silicide)
      enrich = 0.1975;   % U235 enrichment fraction
      pwdth = 7.049;     % plate width (cm)   (note: not used directly in calc)
      mwdth = 6.085;     % fuel meat width (cm)
      pthk = 0.1524;     % plate thickness (cm)
      mthk = 0.0762;     % fuel meat thickness (cm)
      pht = 62.55;       % plate height (cm)
      mht = 59.69;       % fuel meat height (cm)
%
%  end of data file




%
%   LEUFDATA.M  Basic geometry data for the LEU Full Fuel Assembly
%
%   This file contains raw data for the LEU Full Fuel Assembly that is used by
%   UMLRRDEN.M to compute the atom densities of interest for this assembly.
%
%   Similar data sets exist for other fuel assembly types.
%
%   File prepared by J. R. White, UMass-Lowell  (Dec. 1997)
%   Reviewed with minor edits only -- no change in values (6/12/2011)
%

%
%   basic assembly geometry data
      stitl = 'UMLRR LEU Full Fuel Assembly';
      nfpc = 16;         % # of fuel plates in center region
      nfpe = 0;          % # of fuel plates in edge region
      nspe = 2;          % # of structure plates in edge region
      u5load = 200;      % U235 loading per element (grams)
      spthk = 0.508;     % side plate thickness (cm)
      chthk = 0.2963;    % channel thickness (cm)
      assydim = 7.620;   % square assembly dimension (cm)
      assydimg = 7.7724; % square assembly dimension with water gap (cm)
%
%   basic plate geometry data
      ftype = 2;         % fuel type: 1 -> HEU U-Al alloy;
                         %            2 -> LEU U3Si2-Al
                         %            3 -> LEU UAlx-Al
      ffrac = 0.6754;    % fuel frac (U frac for aluminide or U3Si2 frac for silicide)
      enrich = 0.1975;   % U235 enrichment fraction
      pwdth = 7.14;      % plate width (cm)   (note: not used directly in calc)
```

```
      mwdth = 6.085;     % fuel meat width (cm)
      pthk = 0.1270;     % plate thickness (cm)
      mthk = 0.0510;     % fuel meat thickness (cm)
      pht = 63.5;        % plate height (cm)
      mht = 59.69;       % fuel meat height (cm)
%
%  end of data file




%
%   LEUPDATA.M  Basic geometry data for the LEU Partial Fuel Assembly
%
%   This file contains raw data for the LEU Partial Fuel Assembly that is used by
%   UMLRRDEN.M to compute the atom densities of interest for this assembly. This
%   is very similar to LEUFDATA.M, except that the fuel meat thickness is
%   reduced by 50%.
%
%   Similar data sets exist for other fuel assembly types.
%
%   File prepared by J. R. White, UMass-Lowell  (Dec. 1997)
%   Reviewed with minor edits only -- no change in values (6/12/2011)
%

%
%   basic assembly geometry data
      stitl = 'UMLRR LEU Partial Fuel Assembly';
      nfpc = 16;         % # of fuel plates in center region
      nfpe = 0;          % # of fuel plates in edge region
      nspe = 2;          % # of structure plates in edge region
      u5load = 200/2;    % U235 loading per element (grams)
      spthk = 0.508;     % side plate thickness (cm)
      chthk = 0.2963;    % channel thickness (cm)
      assydim = 7.620;   % square assembly dimension (cm)
      assydimg = 7.7724; % square assembly dimension with water gap (cm)
%
%   basic plate geometry data
      ftype = 2;         % fuel type: 1 -> HEU U-Al alloy;
                         %            2 -> LEU U3Si2-Al alloy
                         %            3 -> LEU UAlx-Al
      ffrac = 0.6754;    % fuel frac (U frac for aluminide or U3Si2 frac for silicide)
      enrich = 0.1975;   % U235 enrichment fraction
      pwdth = 7.14;      % plate width (cm)   (note: not used directly in calc)
      mwdth = 6.085;     % fuel meat width (cm)
      pthk = 0.1270;     % plate thickness (cm)
      mthk = 0.0510/2;   % fuel meat thickness (cm)
      pht = 63.5;        % plate height (cm)
      mht = 59.69;       % fuel meat height (cm)
%
%  end of data file
```