ENGY.4340 Nuclear Reactor Theory

Fall 2016

HW #7: 2-Group Theory Computations for the UMLRR with WPI Fuel

The UMass-Lowell Research Reactor (UMLRR) was converted several years ago from the use of HEU fuel (93 w/o U235) to LEU fuel (20 w/o U235). More recently, we also obtained the very slightly used LEU fuel from the decommissioned Worcester Polytechnic Institute (WPI) reactor. The UMLRR currently has a possession-only license for the WPI fuel, but formal use of the WPI fuel has been requested from the NRC as part of our recent license renewal application for the UMLRR. In particular, a study was successfully completed to evaluate the safety of the WPI UAl_x-Al fuel elements for use within the UMLRR -- either as standalone fuel or in combination with the original UMLRR LEU U_3Si_2-Al fuel elements. A tabulation of several key design characteristics for the two fuel types is given in Table I and, as apparent, the overall assembly dimensions and construction are nearly identical, which should allow the use of both assemblies types within the UMLRR grid structure.

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

One of the first steps in doing the formal safety analysis was to obtain a good estimate of the "critical" core size (i.e. number of fuel elements) required within the UMLRR if it was fueled only with WPI fuel elements. For reference, the existing "20-element core" -- which actually contains 19 full elements and 2 partial elements (which have half the fuel loading) -- had an excess reactivity of about 4 %Δk/k at the beginning of life (i.e. the core multiplication factor with no control inserted was about 1.04 at BOL) and this was selected as the target k-excess to be below the maximum allowed k-excess of 1.047, yet to be large enough to allow for many years of use (with a low duty cycle) before refueling.

This mini-project will have you do some simple computations for approximate "bare" and "water reflected" versions of the UMLRR fueled totally with WPI LEU fuel elements, with the goal of determining how many WPI fuel elements will be needed to get similar behavior to the original LEU core. Of course the actual homogeneous core models used here will be very crude, but we still should be able to get a rough relative comparison of the performance of the two fuel types. Your analyses should be guided by the outline given below (and you should also see the data in the Appendix for the results for the existing UMLRR U_3Si_2-Al fuel elements in a 4x5 configuration).

In particular, approximate assembly-homogenized densities for the WPI LEU fuel assembly design and a set of appropriately averaged 2-group microscopic cross sections are available in a file called **wpi_micros_2012.m** (these were generated in August 2012 based on a 238-group ENDFB-VII library that is distributed with the SCALE 6.1 package). Using these assembly-homogenized densities and the predetermined set of 2-group cross sections, you should perform the following computations:

a. Compute a complete set of 2-group macros for the WPI LEU fuel assembly using the densities and 2-group micros given in the **wpi_micros_2012.m** file. These should be the only cross section data used in this problem -- please **do not use any cross section data from any other source**. The data here have already been properly averaged for use within a variety of 2-group computations that utilize the WPI assembly (the data are appropriate for normal room temperature conditions).

b. With these macroscopic cross sections, calculate k_∞ for the WPI assembly design using two different methods:

   1. Use the formal 2-group expression derived in class:

$$k_\infty = \frac{\nu\Sigma_{f1}\Sigma_{a2} + \nu\Sigma_{f2}\Sigma_{1\to 2}}{\Sigma_{R1}\Sigma_{a2}}$$

   2. Use the basic definition of the four factors (η_T, f, p, and ε) within the expression for the 4-factor formula for k_∞. Also be sure to tabulate the computed value of each component. Are the individual factors and the composite estimate of k_∞ reasonable?

c. Determine k_{eff} for a bare Nx × Ny array of the WPI assemblies, where Nx and Ny are the number of assemblies in the x and y directions, respectively. The WPI fuel assembly size is 7.7724 cm square with an active fuel height of 59.69 cm (see Table I). Use the thermal diffusion coefficient to estimate the extrapolation distance d in your calculations. Note that the "bare" configuration should be substantially subcritical. In doing this, let's again compute k_{eff} several ways, as follows:

1. Use the formal 2-group expression for a bare finite system derived in class:

$$k_{eff} = \frac{\nu\Sigma_{f1}\left(D_2B^2 + \Sigma_{a2}\right) + \nu\Sigma_{f2}\Sigma_{1\to 2}}{\left(D_1B^2 + \Sigma_{R1}\right)\left(D_2B^2 + \Sigma_{a2}\right)}$$

2. Compute the fast and thermal non-leakage probabilities, and use the 6-factor formula to find k_{eff}.
3. Evaluate the thermal migration area and compute k_{eff} using modified 1-group theory.

d. Now, modify the above analysis procedure to include an infinite water reflector that completely surrounds the Nx × Ny array of assemblies (top, bottom, and sides). Use the following correlation (from Lamarsh)

$$\delta \approx 7.2 + 0.10\left(M_T^2 - 40.0\right) \qquad \text{(for water moderated and reflected systems)}$$

to estimate the reflector savings associated with the reflector, and compute the "effective dimensions" and new buckling associated with the reflected core. With this new buckling, re-compute k_{eff} for the water-reflected system using the three methods noted above. Are these values closer to what you expected for a real system?

Note: As mentioned above, the initial BOL LEU core with 20 equivalent full UMLRR U_3Si_2-Al fuel elements had a measured excess reactivity of roughly 4 %Δk/k. However, the fuel was not arranged in a simple Nx × Ny regular array, and it had a combination of both graphite and water reflection. Thus, the experimental value given here is just for use as a rough initial comparison. A better comparison for your calculations is given in the Appendix -- since the results given there were generated using the same relatively simple analysis methods that you are being asked to use. The data in the Appendix are specific for a 4×5 array of UMLRR U_3Si_2-Al fuel elements.

e. Also compute/tabulate the fast to thermal flux ratios for the infinite system, the Nx × Ny finite bare core, and the Nx × Ny fully reflected core.

f. For a power level of 1 MW_{th}, estimate the average thermal flux that would be expected in a Nx × Ny version of the UMLRR fueled with WPI elements (both bare and reflected). Finally, also estimate the peak flux for the bare and reflected systems if the peaking factors are roughly 3.75 and 2.75, respectively, for the bare and reflected cores (these values will differ for each configuration, but the 3.75 and 2.75 are "typical" for bare and reflected cores, respectively).

g. Finally, once you get everything working correctly, you should vary the value of Nx and Ny to see how these change the overall results. The ultimate goal here is to suggest a core size for the WPI-fueled core such that you get roughly an excess reactivity of about 4 %Δk/k. In addition, you certainly will want to compare all your results to the data contained for the current UMLRR fuel -- at least for the 4×5 configuration.

Documentation:

The above computations should be carried out in a **well-documented** Matlab program, Excel spreadsheet, or Mathcad worksheet (be sure to include a printed copy your program/worksheet as an Appendix to your full HW submission). **In the main report, you should tabulate the key**

results as well as the results from a number of intermediate computations and explain/ justify the main comparisons/conclusions of this study. The point here is to be sure to explain your computations, to identify any assumptions made, and to present and explain the primary results in a professional manner. This HW/mini-project is worth **50 points** towards your overall HW grade for the course, and it is expected that your summary results and discussion will be submitted as part of a complete professional document (I don't want just a bunch of numbers with no discussion/explanation!).

Good luck -- this should be a very useful and informative exercise. Upon completion, you should have a much better understanding of 2-group theory, the 4-factor and 6-factor formulas, and the approximations associated with modified 1-group theory for both bare and reflected critical systems…

Note: There is a lot of work here, so be sure you start this assignment early…

Appendix

Some Data for the UMLRR Full LEU Assembly (from umlrr_2g_calcs with 2010 data)

Assembly Average Density (atom/b-cm) & Microscopic Cross Sections (barns) (micro data from 2010):

Nuclide	density	tr1	tr2	fis1	fis2	abs1	abs2	nufis1	nufis2	scat12
U235	1.421e-004	1.195e+001	3.552e+002	7.994e+000	3.543e+002	1.226e+001	4.151e+002	1.960e+001	8.634e+002	5.357e-003
U238	5.702e-004	8.646e+000	1.016e+001	1.367e-001	1.078e-005	2.796e+000	1.727e+000	3.813e-001	2.686e-005	3.707e-003
H	4.158e-002	2.533e+000	2.493e+001	0.000e+000	0.000e+000	3.430e-003	2.403e-001	0.000e+000	0.000e+000	6.321e-001
O16	2.079e-002	2.538e+000	3.821e+000	0.000e+000	0.000e+000	3.301e-003	1.375e-004	0.000e+000	0.000e+000	1.486e-002
Al27	2.108e-002	2.102e+000	1.520e+000	0.000e+000	0.000e+000	5.079e-003	1.611e-001	0.000e+000	0.000e+000	3.374e-003
Si	4.749e-004	2.279e+000	1.947e+000	0.000e+000	0.000e+000	7.116e-003	1.054e-001	0.000e+000	0.000e+000	4.535e-003

Macroscopic Cross Sections (1/cm):

	tr1	tr2	fis1	fis2	abs1	abs2	nufis1	nufis2	scat12
	2.101e-001	1.205e+000	1.214e-003	5.036e-002	3.658e-003	7.341e-002	3.003e-003	1.227e-001	2.667e-002
Diff. Coeffs:	1.586e+000	2.766e-001 (cm)							

UMLRR Criticality Calculations (infinite, bare, and fully reflected systems):

Infinite System		Finite System (4x5 BARE array)		Finite System (4x5 REFLECTED array)	
eta	= 2.0461	L1sq (cm^2)	= 52.3105		
f	= 0.8169	tau (cm^2)	= 59.4854		
p	= 0.8794	L2sq (cm^2)	= 3.7672		
epsilon	= 1.0674	MTsq (cm^2)	= 63.2526	del (cm)	= 9.5253
		Bsq (1/cm^2)	= 0.0183	Bsq (1/cm^2)	= 0.0085
		PF	= 0.4788	PF	= 0.6652
		PT	= 0.9355	PT	= 0.9691
phi1/phi2	= 2.7528	phi1/phi2	= 2.9426	phi1/phi2	= 2.8405
kinf (2-group)	= 1.5689	keff (2-group)	= 0.7532	keff (2-group)	= 1.0561
kinf (4-factor)	= 1.5689	keff (6-factor)	= 0.7028	keff (6-factor)	= 1.0114
		keff (modified 1-g)	= 0.7272	keff (modified 1-g)	= 1.0220

Thermal Flux for the UMLRR at 1 MW:

	Finite System (4x5 BARE array)	Finite System (4x5 REFLECTED array)
sigfeff (1/cm) ==>	5.393e-002	5.381e-002
thmflxave (neuts/cm^2-s) ==>	8.025e+012	8.043e+012
thmflxpeak (neuts/cm^2-s) ==>	3.009e+013 (F = 3.75)	2.212e+013 (F = 2.75)