Ryan Stewart
11/18/16
NE6699
Term Project

Introduction

This paper will examine a subassembly from a theoretical liquid lead cooled fast breeder reactor and determine the effects of homogenization on the multiplication factor and the total control rod worth of the subassembly. The subassembly contains uranium nitride fuel which is enriched to 15wt% U-235, and has a radius of 0.325cm, with a height of 130cm. Following the fuel, a lead bonding area is present with an inner radius of 0.325cm and an outer radius of 0.333cm, along with a height of 130cm. The cladding is made of TZM molybdenum, and has an inner radius of 0.333cm, and outer radius of 0.399cm and a height of 130cm. The fuel element is placed in a hexagonal lattice with a pitch of 0.9825cm, and the coolant is pure lead. Along with the fuel pins, there are seven control rods in each subassembly; the control rods have the same dimensions as a fuel rod with the fuel being replaced with a boron carbide poison. These poison rods are placed in a cylindrical guide tube, made of TZM molybdenum which has an inner radius of 0.419cm and an outer radius of 0.485cm. The subassembly contains 271 positions, of which 264 are fuel elements and 7 are either control rods or guide tubes - depending on if the control rods are inserted or withdrawn. Figure 1 shows a diagram of the detailed model, created in OpenMC. To determine the effect of homogenization, each component was homogenized separately and then combined to determine the overall effect on criticality and control rod worth.

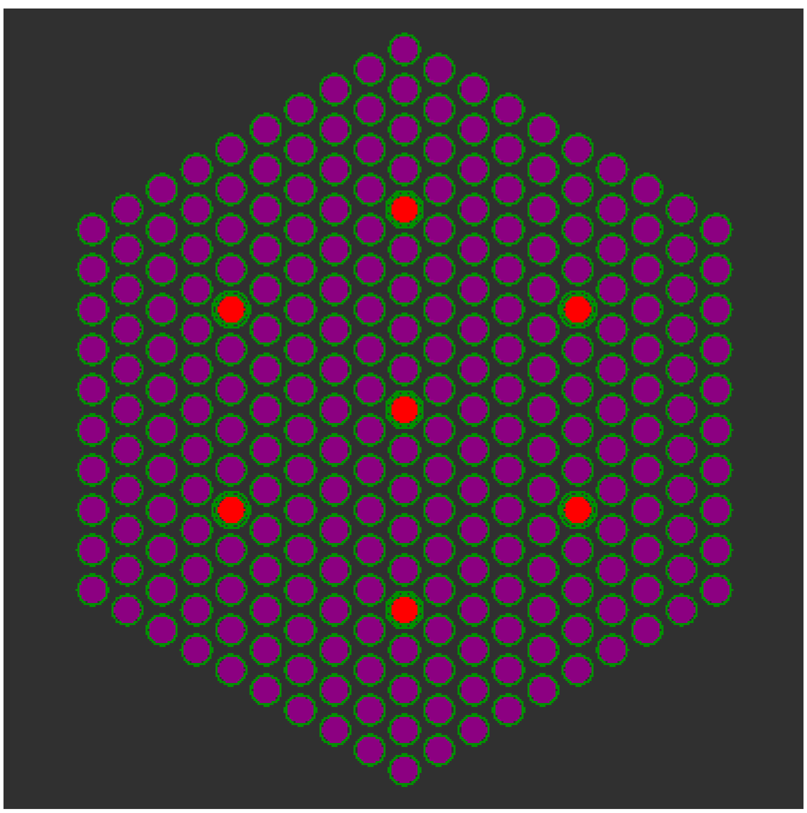

Figure 1

Theory

Nuclear reactors are highly complex and sensitive pieces of equipment. The reactor core itself contains numerous materials, temperatures, and neutron flux variations. These complications make it extremely difficult to model in computer simulations and obtain reliable results. To alleviate this difficulty, it is often more pertinent to create multiple models of a reactor, more specifically, a detailed and a simplified model. The detailed model acts as assurance that the results will make physical sense, and will provide a technical basis for future work. The simplified model allows for ease of manipulation in varying parameters without the hassle of recreating an entire detailed model. The easiest and most common simplification that can be made is the process of homogenizing different components. The results are then compared to the detailed model to determine the homogenizations effect on criticality, or other parameters that are of interest.

The homogenization process requires a detailed knowledge of the reactor core and a theoretical understanding of the implications of homogenization. To examine the effect of homogenization it is important to understand some conceptual reactor physics, namely the six factor formula. Although the six factor formula does not accurately describe a reactor, it is helpful to provide a basic intuition into the physics occurring.

In a homogeneous core, the fuel and all coolant (or moderator) are thoroughly mixed together, and in a heterogeneous core, the fuel and any coolant (or moderator) are separated. The most dramatic difference from changing a heterogeneous core to a homogeneous core is the decrease in the resonance escape probability. From a heuristic standpoint, this occurs because neutrons that are born in a heterogeneous fuel pin and leak out have a greater opportunity to scatter and slowdown in the coolant. Alternately, in a homogeneous mixture, the fuel and coolant is one, and as a neutron scatters it has a higher probability of being absorbed in the resonance escape region due to no separation between the fuel and coolant. This effect is most prominent in thermal reactors, but the same effect can also occur in a fast reactor.

The fast fission factor is also highly influenced by homogenization in a negative way. When neutrons are born in a fuel pin at high energies, they have the potential to cause additional fission neutrons before they leak out into the coolant. When the coolant and the fuel are homogenized, there is a higher probability that the neutron will encounter some type of moderating material, decreasing its energy before finding a heavier nucleus to cause fast fission. Although a lead cooled reactor has a fast neutron spectrum it is still important to note that the thermal utilization factor will slightly increase with homogenization. This is attributed to the thermal flux being depressed in the heterogeneous cell due to self-shielding, which causes less absorption in the fuel at thermal energies. Therefore, the thermal utilization factor is increased due to the fact that the thermal neutrons in a homogeneous mixture do not have self-shielding properties. For the purpose of this model, both non-leakage factors were effectively ignored due to specific constraints placed on the system, which will be discussed further on.

Experimental Procedures

The homogenization process was fulfilled in two separate steps for both the fuel elements and the control rods. Each step was performed on individual elements and then applied to each element in the subassembly. The first step was to homogenize the cladding with the lead bond and the lead coolant. This process involved finding the effective volume for each and then determining the new atom densities based on the new mixture. This atom density was then applied to the volume that contained the cladding and the coolant. Figure 2 shows the fuel cladding-coolant smear, while figure 3 shows the poison cladding-coolant smear.

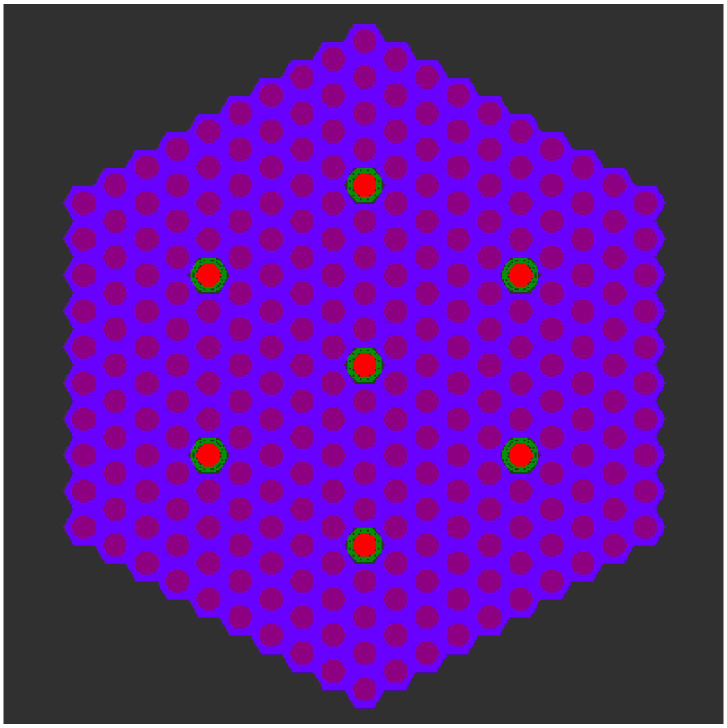

Figure 2

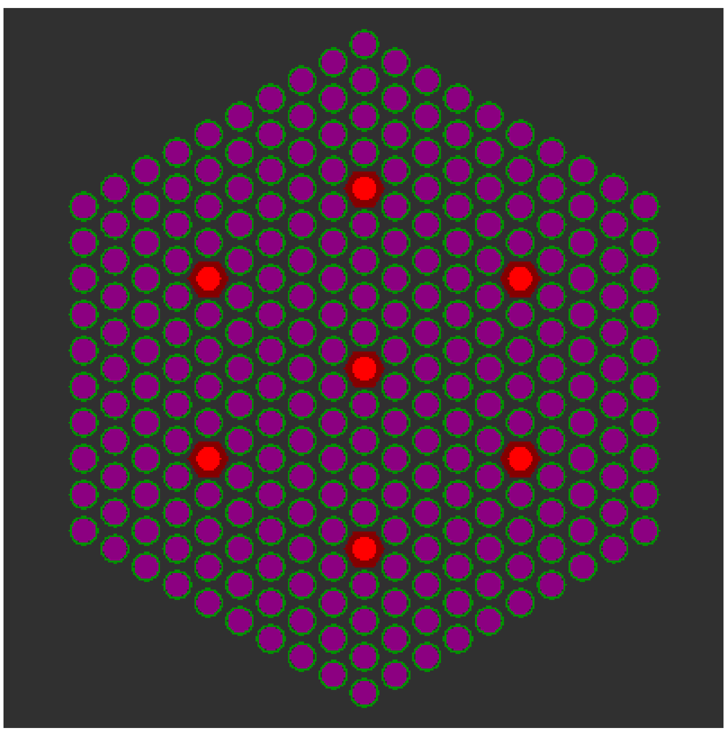

Figure 3

The second step was to homogenize the fuel or the poison pin into the cladding-coolant mixture to create a third mixture. Again, the effective volume was found and the atom densities were adjusted accordingly. Figure 3 shows the full smearing of the fuel, while figure 4 shows the full smearing of the control rods.

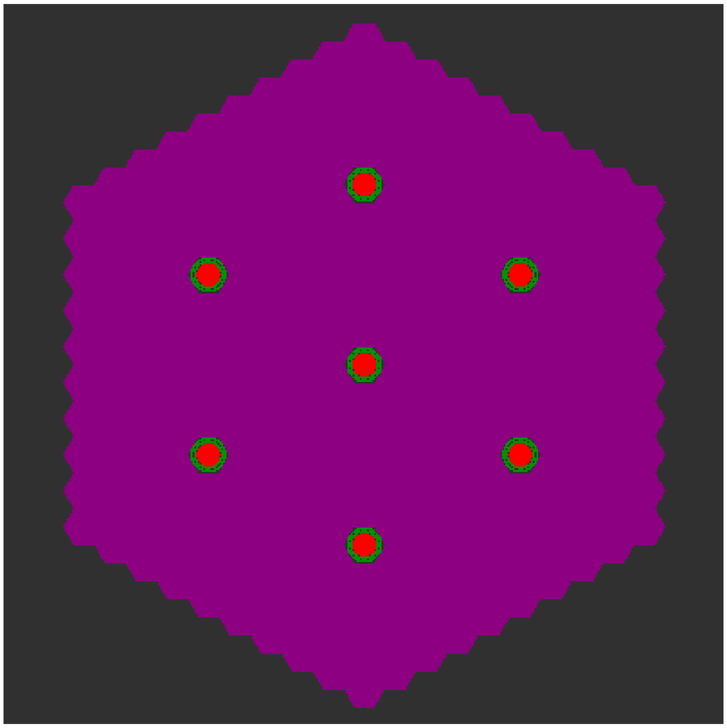

Figure 4

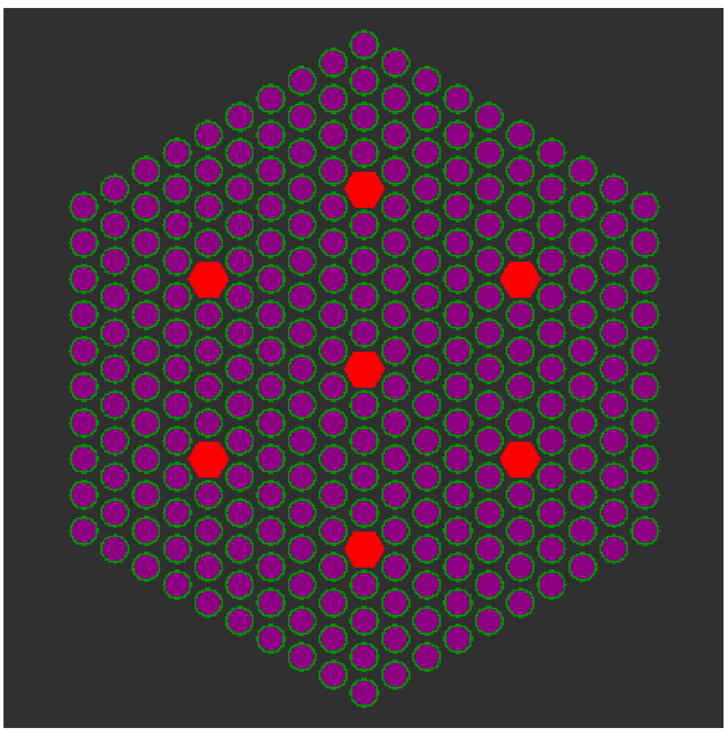

Figure 5

As mentioned, the effective volume was calculated based on the materials volume in relation to the total volume of materials being homogenized. Table 1 shows the volume percent for the fuel elements, while table 2 shows the volume percent for the control rods for each step of the process.

	Volume (cm^3)	% volume detailed	% volume fuel clad smear	% volume fuel smear
Fuel	43.14	26.47	N/A	26.46
Lead bond	2.15	1.32	1.79	1.32
Cladding	19.73	12.10	16.46	12.10
Coolant	98.00	60.11	81.75	60.12

Table 1

	Volume (cm^3)	% volume detailed	% volume poison clad smear	% volume poison smear
Poison	43.14	26.46	N/A	26.46
Lead Bond	2.15	1.32	1.79	1.32
Cladding	19.73	12.10	16.46	12.10
Lead Bond 2	6.68	4.10	5.57	4.10
Guide tube	24.76	15.19	20.66	15.19
Coolant	66.55	40.83	55.52	40.83

Table 2

The final step was to combine the two fully homogenized models into one fully homogenized fuel assembly. Figure 6 shows the fully homogenized model, with control rods fully inserted.

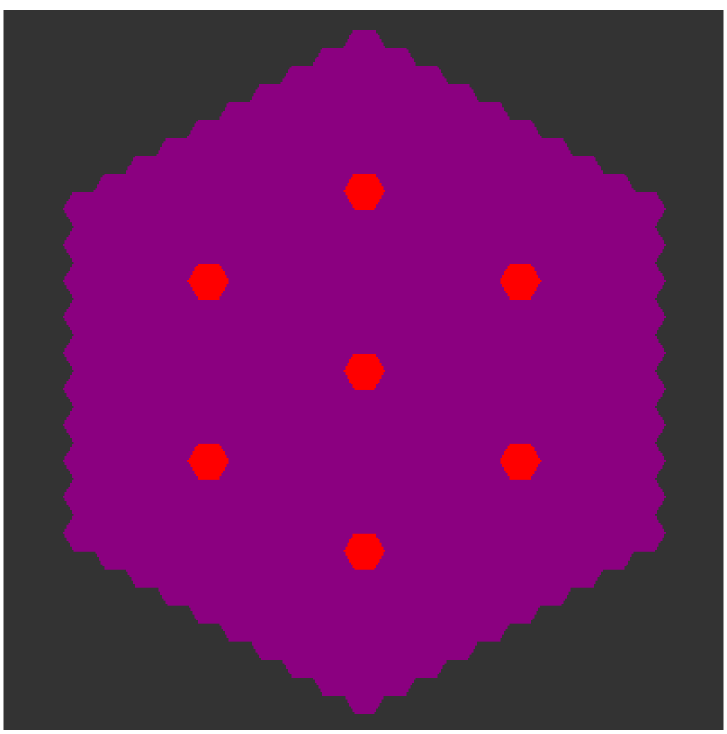

Figure 6

OpenMC was utilized to find the multiplication factor in addition to finding the control rod worth. The model utilized a single subassembly to determine the criticality. To better model a subassembly in a full reactor core, each of the hexagonal bounding edges had a reflective boundary type to resemble adjacent subassemblies. The top and bottom has a vacuum boundary, although a reflector would typically be present. In a simplified model, a vacuum boundary was utilized to prevent artificially driving the multiplication factor up. Each run utilized 250 batches with 50 batches skipped and 5000 particles per batch. For each process, the simulation ran with the control rods fully inserted, and the control rods being fully withdrawn.

When utilizing OpenMC it is important to understand the initial assumptions and limitations inherent in the model that is being utilized. The main assumption stems from the temperature, with each run at 294K. In a fast reactor such as this, expected temperatures range from 850K to 950K which will shift the neutron energies and cross-section libraries used. OpenMC comes preloaded with a 293.6K cross-section library. To get a better grasp of the problem, a cross-section library at 900K would need to be utilized.

Results & Analysis

The value for the multiplication factor and the uncertainty was pulled from each run. Table 3 shows the multiplication factor for each run and their difference from the detailed model. To find the %k_{eff} difference equation 1 was used.

$$\%k_{eff} = \frac{k_{hom} - k_{det}}{k_{det}}$$

Equation 1

	k_{eff}	unc	% k_{eff} difference
Detailed (CR withdrawn)	0.99416	0.00061	N/A
Detailed (CR inserted)	0.95109	0.00058	N/A
Fuel Clad-Coolant Smear (CR withdrawn)	1.08692	0.00059	9.33
Fuel Clad-Coolant Smear (CR inserted)	1.03527	0.00069	8.85
Fuel Full Smear (CR withdrawn)	0.99285	0.00065	0.13
Fuel Full Smear (CR inserted)	0.93261	0.00062	1.94
Poison Clad-Coolant (CR withdrawn)	0.99659	0.00065	0.24
Poison Clad-Coolant Smear (CR inserted)	0.95463	0.00065	0.37
Poison Full Smear (CR withdrawn)	0.998576	0.00068	3.65
Poison Full Smear (CR inserted)	0.99659	0.00065	0.24

Full Smear (CR withdrawn)	0.99535	0.00068	0.12
Full Smear (CR inserted)	0.98069	0.00067	3.11

Table 3

For the multiplication factor, we find closely related multiplication factors for nearly all of the control rod withdrawn runs. The multiplication factor tends to hover around 0.99, the exception being the homogenization of the fuel's cladding and the coolant. The results of this run are not understood as to why an extremely high multiplication factor was obtained. When comparing the fuel's cladding and coolant homogenization with the poison rods cladding and coolant homogenization, it is found that the poison rods multiplication factor slightly increased in both runs. This change is not to the degree in which the fuel's cladding smear changed the multiplication factor. The most prominent change in the homogenization process is the control rods ability to effect the multiplication factor and control the reactor.

The control rod worth was found by examining the multiplication factor when the rods were fully inserted, and then again when the rods were fully withdrawn. The two multiplication factors were then utilized in equation 2 to find the control rod worth (CRW). k_1 is the multiplication factor with control rods withdrawn, and k_2 is the multiplication factor with the control rods fully inserted. Table 4 shows the control rod worth and %CRW difference for each run, where the %CRW difference was calculated using the same method in equation 1.

$$CRW = \frac{k_1 - k_2}{k_1 * k_2}$$

Equation 2

	CRW	% CRW difference
Detailed	0.04555	N/A
Fuel Clad-Coolant Smear	0.04590	0.77
Fuel Full Smear	0.06506	42.83
Poison Clad-Coolant Smear	0.04410	3.18
Poison Full Smear	0.01102	75.8
Full Smear	0.01502	67.03

Table 4

The ability of the control rods to control the reactor are highlighted in the full fuel smear, full poison smear, and full core smear runs. For the full fuel smear, an increase in control rod effectiveness is found. This effect is correlated with the fuel being homogenized surrounding the control rods. When the fuel is homogenized there is a higher probability that a neutron will be born near a control rod and subsequently be absorbed by it. Alternately, in the full poison and full core smear the control rod effectiveness is decreased. Again, this effect is highly correlated with the homogenization of the control rods. When the control rods are heterogeneous, there is a region of pure absorbing material, which if a neutron enters, will most likely interact with a boron atom and be absorbed. In the homogeneous case, if a neutron enters the control rod cell, there are now two other major atom densities to compete with, lead and molybdenum. Lead has twice the atomic density of boron in the homogenized control rod, and molybdenum has nearly the same atomic density. It follows that a neutron would have a higher probability of interacting with a lead atom, despite the fact that it has a lower cross-section.

Conclusion

The homogenization process is used to simplify a complex reactor, and make it easier to simulate and model. Through the process of homogenizing a fuel assembly from a theoretical lead cooled fast reactor, a few major insights were obtained. Through the full homogenization of the fuel, the control rod withdrawn multiplication factor was not significantly changed. The major change in the multiplication factor occurred when the control rods were present, and the fuel was homogenized. The full homogenization of the control rods caused the overall control rod worth to significantly decrease. This effect was most significant in the full poison smear with detailed control rods. It was found that the homogenization process does come with a cost when homogenizing the control rods. If this process were to be utilized in a model, either a less simplified control rod, or a strong bias would be suggested for utilizing control rods. For a less simplified control rod, a homogenization of the cladding in the coolant would be sufficient to retain the structure and the effectiveness of the control rod. The bias would consist of the difference between the fully homogenized core, with control rods in, and the fully detailed core, with control rods in. This would yield a multiplication factor bias of –0.0296, for the homogenized core. This would drop the multiplication factor for the homogenized core, when all control rods were fully inserted. The multiplication factor for when the control rods are withdrawn are within 0.5% and thus would not require a multiplication factor.

For further research, it would be recommended to make an even more detailed model with depleted uranium axial reflector and a gas plenum. Along with this, obtaining cross-section libraries that better represent the problem would provide even more insight into the assembly. Finally, it would be worthwhile to investigate the fuel clad-coolant homogenization to determine why it had such a large effect on the multiplication factor.

The entirety of the project took me approximately 40 to 50 hours to complete, with an additional 10 to 20 hours of computational time.

References

Duderstadt, James J and Louis J Hamilton. Nuclear Reactor Analysis. 1st ed. New York: Wiley, 1976. Print.

Juutilainen, Pauli. "Simulating The Behavior Of The Fast Reactor JOYO". International Youth Nuclear Congress. Interlaken: Switzerland, 2008. Web.

Appendix A: Python Input File For Detailed Model

See attached

Appendix B: Python Input File For Full Smear Model