Reactor Design Project

[Document subtitle]

Introduction

The purpose of this design project was to use the given material data and limiting parameters to design a sodium-cooled fast reactor. This type of reactor is considered to be important to our energy future because they are more efficient in utilizing uranium than thermal reactors and able to burn long-lived nuclear wastes during operation. These attributes make fast reactors desirable and are the reasons why development on these reactor types continue.

Problem Description

Table 1: Design Parameters

Lattice Type	Hexagonal
Fuel Element Geometry	Cylindrical
Fuel Composition	^{239}Pu,^{238}U
Fuel Density (g/m^3)	19
Coolant	Sodium
Cladding	Stainless Steel 316
Fuel Region Diameter (cm)	0.9
Cladding Thickness (cm)	0.05
Extrapolation Distance (cm)	20
Thermal Power (MW)	100

Table 2: Design Limiting Factors

Limiting Core Parameters	
^{239}Pu Fraction (%)	<20
Lattice Pitch/Fuel Diameter	<1.5
Active Core Height (cm)	<150
Core Diameter (cm)	<300

This reactor is fueled by a SS316 clad metallic U-Pu mixture arranged into cylindrical fuel elements and is cooled by liquid sodium. For design purposes, the core of the reactor is divided up into hexagonal lattices centered around each fuel element. The exact properties of the reactor are shown in Table 1 and the limiting parameters of the design are shown in Table 2. The goal of this project was to produce a design with a k_{eff} of 1.15 ± 0.02. The assumptions for this model are that the energy dependence of the neutron flux can be split into eight energy groups, no reflector is present, uniform fuel element lattice, the cross sections of SS316 can be approximated with those of iron, no flux disadvantage is necessary, and that all cross sections values are those at operational conditions. The model uses only simple homogenization instead of flux disadvantage factors because the mean free path of a neutron in a fast reactor is larger than the dimensions of core elements and, as an effect, the neutron flux within the reactor is not as affected by spatial variations within the reactor core.

Model Development

The computational model of the reactor was written using Python and allows one to calculate k_{eff}, number of fuel elements, total fuel loading (kg), and ^{239}Pu loading by manually inputting values for lattice pitch (cm), ^{239}Pu fraction (%), active core height (cm), and core diameter(cm). The cross sections used for the reactor calculations were homogenized over the unit cell to simplify calculations. The model also provides a plot of the neutron flux within the reactor core during operation. The first iteration of the design was to test out the computational model by inputting the limiting values into the model and obtaining the outputs and graph of the scalar neutron flux.

Table 3: Reactor Model at Limiting Parameter Values

Keff	1.776
Number of Fuel Elements	61
Total Fuel Loading (kg)	110598.6
^{239}Pu Loading (kg)	22119.7

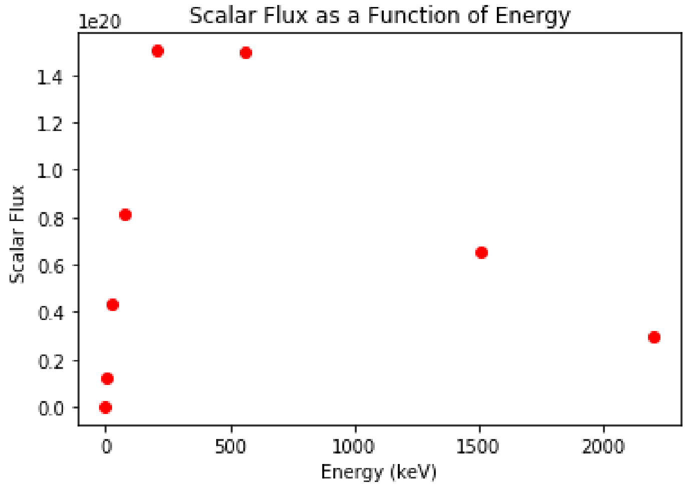

Figure 1:

The number of fuel elements and both types of fuel loading were calculated using the inputted core dimensions. The fuel element numbers were calculated by dividing the core volume by the volume of a single fuel lattice. The fuel loading was calculated by multiplying the volume of the fuel element by the number of fuel elements and the density of the fuel. The plutonium loading was calculated by multiplying the fuel loading by the plutonium fraction. The k_{eff} value was calculated by using the given cross section data and their variations with the inputted reactor parameters. The outputs produced by inputting the limiting values are shown in Table 3 and the neutron flux for this configuration is shown in Figure 1. The k_{eff} obtained is much higher than the 1.15 ± 0.02 value required by the design specifications so the reactor dimensions and composition must be altered to reduce the k_{eff} down to acceptable values.

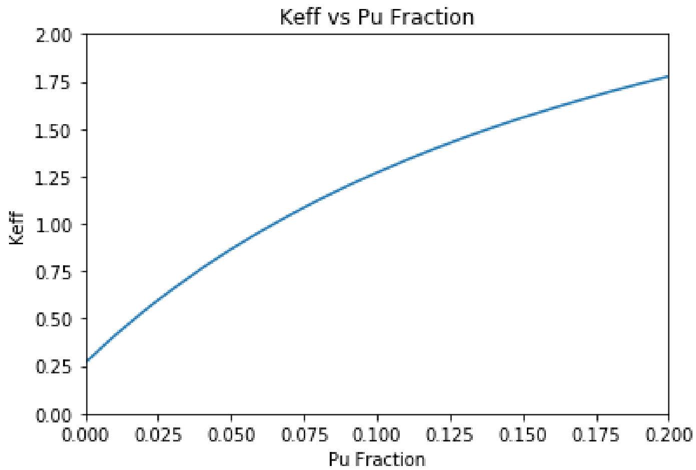

Figure 2:

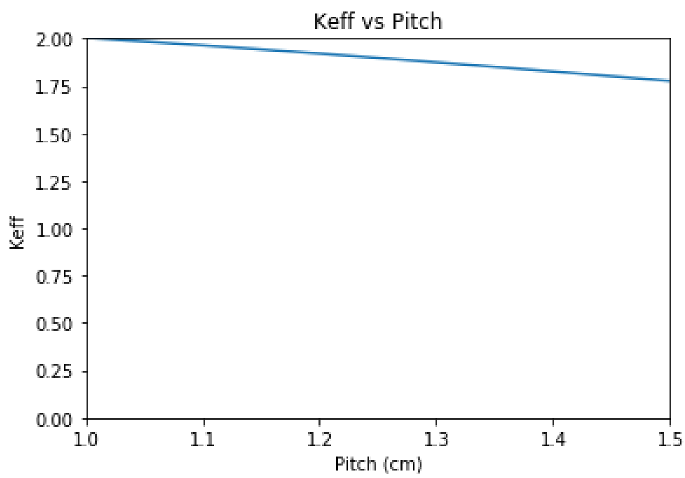

Figure 3:

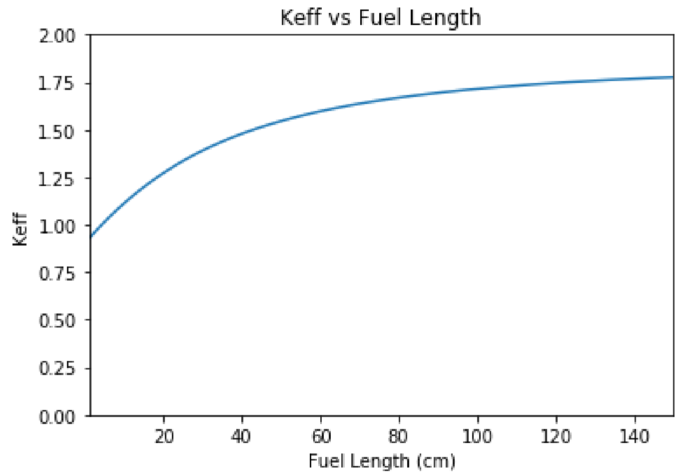

Figure 4:

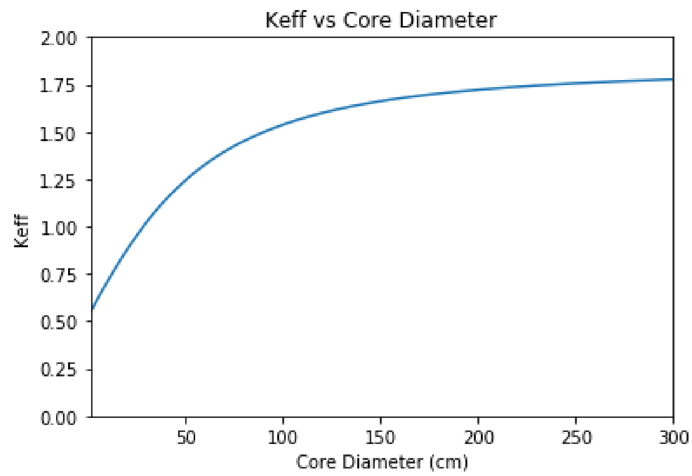

Figure 5:

Figure 2 through Figure 5 show the variation in k_{eff} as their respective parameters are changed while the other parameters are held at the limiting values. All but the plot for pitch show that the k_{eff} is lower at lower values of the respective parameters. To provide a viable final design within the specified k_{eff} values, the reactor dimensions must be reduced. The final design must require the smallest amount of fuel and is preferably compact. The pitch value was not reduced in the search for the final design due to k_{eff} and fuel loading increasing as the pitch value was reduced. In order to simplify the parametric search procedures, only 1-2 reactor dimensions will be altered while the rest will remain at limiting value. The plutonium percentage will be kept at max value due to the fact that a higher Pu percentage allows for the reactor to stay critical for longer periods of times. This is due to the fact that the reactor cannot run purely on ^{238}U due to both the lower neutron flux values at high energy and the low fission cross sections for natural uranium. The thermal fission of plutonium is needed to produce the necessary fast neutrons needed to burn uranium fuel. At a certain concentration, the breeding of ^{238}U into ^{239}Pu may be possible. In the end, it was decided to alter only the reactor diameter while keeping the other dimensions at the limiting values due to the fact that this configuration allows for the least number of fuel elements necessary and, thus, the least amount of fuel required and the smallest volume of the reactor core. A taller reactor also allows for better thermal properties and coolant flow.

Final Design

Table 4: Reactor Properties for Final Design

Lattice Pitch (cm)	1.5
^{239}Pu Fraction (%)	20
Core Diameter (cm)	41
Fuel Element Length (cm)	150
Number of Fuel Elements	9
Total Fuel Loading (kg)	16317.82
^{239}Pu Loading (kg)	3263.56
Keff	1.15507

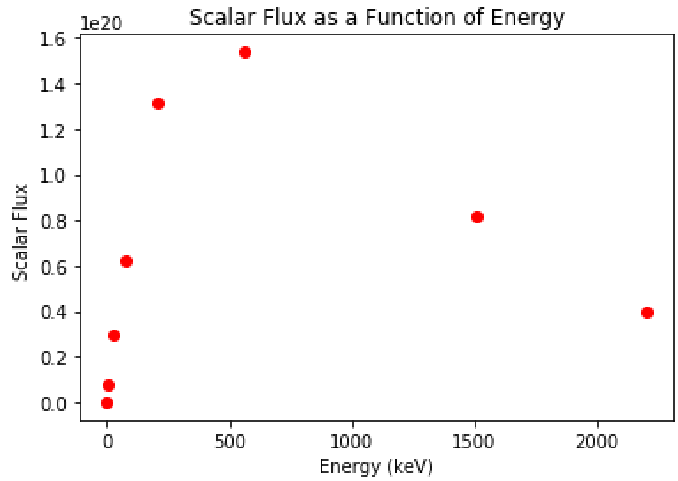

Figure 6

The results for the final design are summarized in Table 4 and the accompanying flux plot is shown in Figure 6. These values were obtained by utilizing a conditional loop within the computational model that outputs the diameter of the reactor once the condition of keff=1.15±0.02 is reached. Several values were returned due to the condition being inputted as a range of values from 1.13 to 1.17 so the value closest to 1.15 that returned a diameter that was a whole number was selected to be the diameter for the final design.

Changes to Final Design as Lattice Shape Changes to Square

Table 5: Final Reactor Properties for Square Lattice

Lattice Pitch (cm)	1.5
^{239}Pu Fraction (%)	20
Core Diameter (cm)	52
Fuel Element Length (cm)	150
Number of Fuel Elements	10
Total Fuel Loading (kg)	18130.9
^{239}Pu Loading (kg)	3626.18
Keff	1.1523

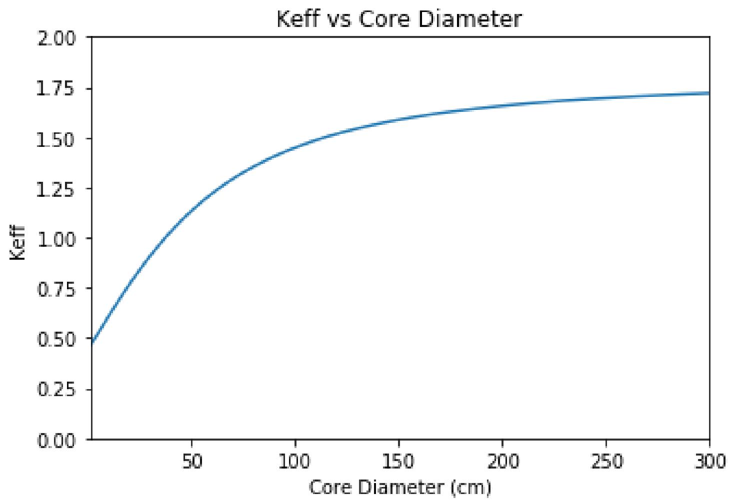

Figure 7

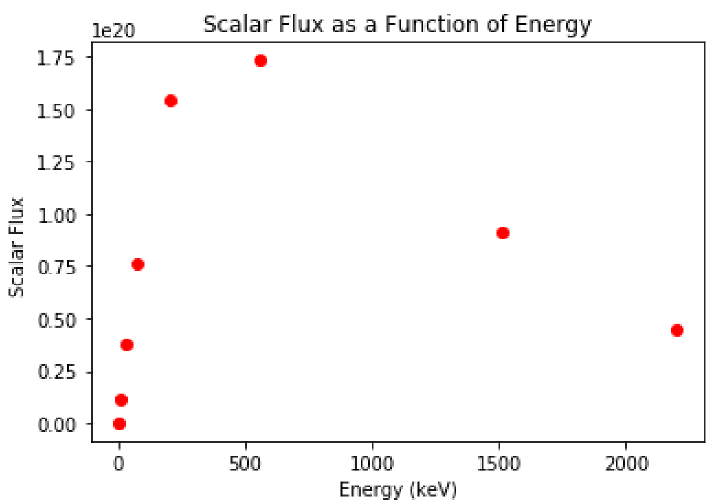

Figure 8:

When the lattice shape was changed from a hexagon to a square, the resulting properties for the final reactor design changed as well. The values for the new configuration are summarized in Table 5 and the resulting plots are shown in Figure 6 and Figure 7. The square lattice caused the reactor to have a larger diameter than the original hexagonal lattice. The new diameter of the reactor is 10 cm greater than that of the original and the fuel loadings are correspondingly higher as well. The difference in the required diameter is due to the changes to the neutron cross sections cause by the increase in the lattice volume. Because the fuel volume remains fixed, the increase in lattice volume only increases the volume of the coolant, thus reducing the averaged fission and absorption cross sections. The change in shape of the lattice also reduces the amount of fuel elements that can fit within a given area and increase the average distance between fuel elements. This can cause an increase in spatial variations of the neutron flux. The reduced cross sections, coupled with the increase in spatial variations in the neutron flux, cause the neutron production rate and keff to be lower for any given reactor size. The hexagonal lattice is preferable for fast reactors due to it being able to allow the greatest amount of fuel within a given area and decreasing the average distance between fuel elements.

A historical example of a fast reactor using a square lattice is Fermi 1 at the Enrico Fermi Nuclear Generating Station in Michigan. This reactor was constricted from 1956 to 1963 and was decommissioned in 1972. [1]

Conclusion

Using a computational model and parametric search procedures, a sodium-cooled fast reactor with a keff of 1.15±0.02 was designed with limiting reactor dimensions. The ideal configuration was found to be obtained when keeping Pu-fraction, lattice pitch, and core height at maximum limits while changing the diameter of the core to obtain the necessary keff. The optimal diameter was found to be 41 cm and this design produced a reactor that required the least amount of fuel loading. One limitation to this design is the limited model used. Thermal considerations were not accounted for, and the small size of the reactor may cause problems due to over heating if the reactor is to operate at the stated value of 100 MW

References

1. IAEA. Fast Reactor Database 2006 Update.https://www-pub.iaea.org/MTCD/Publications/PDF/te_1531_web.pdf, pg.20 [1]
2. "Fast Neutron Reactors". http://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx
3. *"Fast Breeder Reactor Programs: History and Status" (PDF)*. International Panel on Fissile Materials. February 2010.

Appendix

1.RDP Model (python script)