**NUEN 304**
Spring Semester 2025

**Reactor Design Problem (100 Points)**

**<u>Due Date: Apr 29, 2025</u>**
**by midnight electronically in Canvas**

**SUBMISSION POLICY (See Syllabus) – We treat this assignment as a small design project assignment**

<u>RDP Reports and materials:</u>

(1) **Minimum 5 pages (no hand writing except formulas). The report has to** include a <u>table of contents</u>, <u>lists of figures and tables, an introduction, a problem description, model development</u> (detailed mathematical derivations), <u>results, conclusions</u>, etc..

(2) if you created auxiliary materials (py-files, excel files) – list them in the Appendix and upload actual materials on Canvas as well together with your report

(3) list of references at the end but before the Appendix

Fast reactor technology is one of the key technologies needed for the future of nuclear energy. The technology is technically mature. **Let's design a Lead-Cooled fast reactor.** Imagine you are working for the Terra Power/General Electric team who just won an award from DOE to build a demonstration reactor in 7 years – Lead Power Production and Storage System

**https://www.terrapower.com/terrapower-and-ge-hitachi-nuclear-energy-launch-natrium-technology/**

| | |
|---|---|
| Fuel element arrangement (lattice type) | Triangular (Hexagonal) |
| Fuel element geometry type | Cylindrical |
| Fresh fuel (initial composition, metal fuel form) | ($^{239}$Pu, $^{238}$U) |
| Fuel density (g/cm$^3$) | 19.0 |
| Coolant | Lead |
| Cladding and structure | Stainless Steel 316 |
| Fuel element outer diameter (fuel + cladding) (cm) | 6.25 |
| Cladding thickness (cm) | 0.04 |
| Extrapolation correction for core dimensions (cm) | 20.0 |
| Thermal power (MW) | 1,200 |
| Limits for core parameters (not to exceed given values): | |
| - Pu-239 fraction in the fresh fuel (%) | <20 |
| - Lattice Pitch (p)/Fuel Region Diameter (D), (p/D) | <1.2 - 1.5 |
| - Active core height (fuel element length) (cm) | <90 – 180 |
| - Core Diameter (cm) | <250 - 330 |

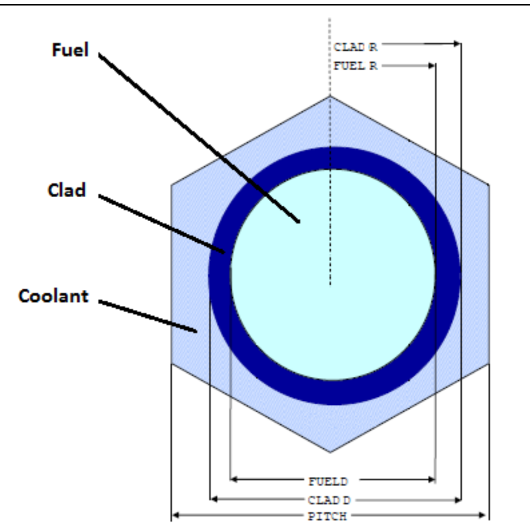


**Fig. 1. Unit cell of a triangular (hexagonal) lattice arrangement**

**Using the provided data, design the fresh-fueled fast reactor core with** $k_{eff} = 1.05 \pm 0.01$

- **Assumptions:**
    1. Multigroup Zero-Dimensional Model of the Reactor Core (8 energy groups)
    2. Assume no reflector
    3. Assume a uniform fuel element lattice.
    4. For SS316, assume that it can be replaced with iron.
    5. A simple cross-section homogenization approach with and without flux disadvantage factors is needed. In your report, you will need to explain why an approach without flux disadvantage factors is acceptable.
    6. Assume that the provided 8-group cross sections are at the operational conditions.
    7. Approximate the hexagonal lattice. Assume that lattices share the same values for all geometrical parameters: D, cladding thickness, and p/D ratio.

- **Design tasks:**

**A. (10 points)** Explain why fast reactor technology is considered important for nuclear energy's future. Search for online resources on fast reactors at energy.gov, IAEA.org, and other websites.

**B. (80 points)** Apply the multigroup Zero-dimensional model and simple cross section homogenization approach <u>without</u> flux disadvantage factors:

**1. (20 points) Model.**

Start with the derivation of the Zero Dimensional model. Explain why we use it and how we use it.

Show how you homogenize cross sections and other parameters. If you need to do any calculations or data preparation before you start coding, you need to specify, derive, and mention it explicitly in your report.

**Applying Python,** Excel, or other software capabilities, develop a computational model to **compute** $k_{eff}$ using the multigroup Zero-dimensional model and simple cross section homogenization approach without flux disadvantage factors. If you forgot to mention how you homogenize your cross sections, this is a time to go back and write it in the report.

- Your model should allow you to perform consistent variations of the lattice pitch (cm), Pu-239 fraction (%), and fuel element length (cm) (input variations). The resulting computed design data (output) should include core diameter (cm), number of fuel elements in the core, total fuel loading (kg), Pu-239 loading (kg), and $k_{eff}$. The model should also provide $\Phi(E)$ normalized to the given power level.

- **Hint:** see your solutions for your Homework

2. **(15 points) Limiting Configuration:** Assume the above-provided limiting values for the design parameters. Pick minimum or maximum values of these parameters and, using your model, compute the number of fuel elements in the core, total fuel loading (kg), Pu-239 loading (kg), and $k_{eff}$. Summarize these results in a table. Provide a plot of $\Phi(E)$ (n/(cm$^2$-s-eV)). Discuss obtained values and how far obtained $k_{eff}$ is from the design objective of $1.05 \pm 0.01$

3. **(10 points) Design Strategy Selection (Parametric Search selection to meet design criteria):** Select and justify your design approach to meet the objective $k_{eff} = 1.05 \pm 0.01$**.** Your justification should focus on explanations of your choices for parameter variations.

4. **(25 points) Final Design:** following your selected parametric search approach, design the fresh-fueled fast reactor core with $k_{eff} = 1.05 \pm 0.01$. Provide plots demonstrating selected parametric variations and their results. Summarize the final design configuration data in a table. Provide a plot of $\Phi(E)$ (n/(cm$^2$-s-eV)) that corresponds to the final design configuration with $k_{eff} = 1.05 \pm 0.01$. Discuss your strategy implementation and the final design configuration outcome from the performed parametric variations.

5. **(10 points)** Discuss the limitations of your model. How accurate is the assumption of a simple cross section homogenization approach without flux disadvantage factors for fast reactor calculations?

**C. (10 points) The report describes all of the above.**

**Your report file and everything you created and used in this project assignment (actual Excel files, Python scripts, etc.) must be submitted electronically via Canvas.**

## Extra Credit (50 points) – Required for students registered for Honor Section

Fast reactors have a triangular (hexagonal) fuel element lattice arrangement as shown above in Fig. 1. In this extra credit portion of the assignment, your task is to assess the corresponding fast reactor configuration with a a cylinder (circle) fuel element lattice arrangement. The relation between these lattice arrangements is illustrated below.

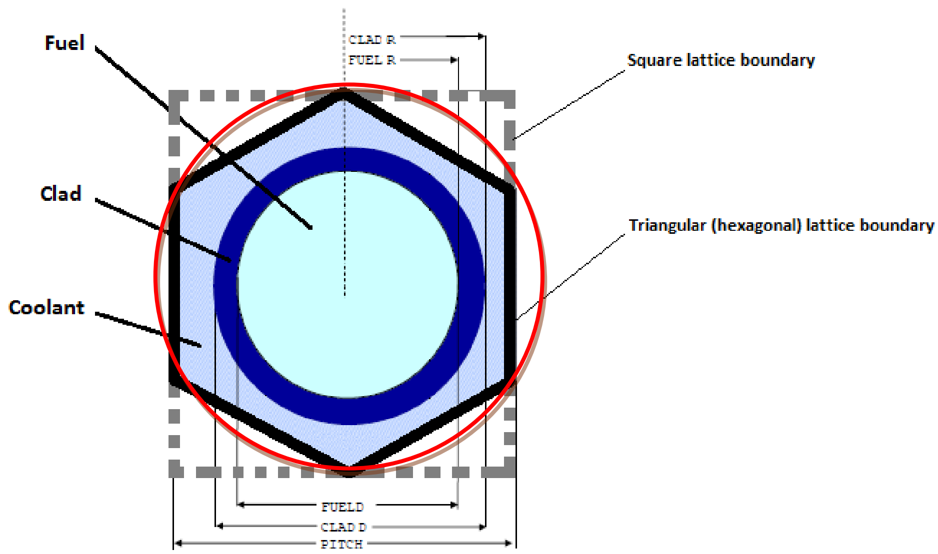


**Fig. 2. Relationship between traditional triangular (hexagonal) lattice unit cell and assumed corresponding square lattice unit cell. Lattices share the same values for all geometrical parameters: D, cladding thickness, and p/D ratio.**

To accomplish this task,

- **(20 points)** Starting with your final lattice design configuration obtained in Step 4, repeat your evaluation, assuming and implementing the corresponding a cylinder (circle) **lattice**. Analyze the differences and discuss their significance. What is the reactor physics implication of hexagonal vs. circle vs square fuel element lattices? Which one would be preferable?
- **(10 points)** Give a historical example of a fast reactor that was actually in operation (or is currently in operation) and used or uses a square fuel element lattice. Reference your information source.
- **(20 points)**Using your model and the final Design as obtained in Step 4, evaluate the impact of the simplified volumetric averaging without flux disadvantage factors on your obtained design parameters. The model needs to be enhanced to include flux disadvantage factors in the homogenization process recognizing differences between fluxes in the fuel, cladding and coolant regions, $\phi_i / \phi_{cell}$. For simplicity, assume the following set of flux disadvantage factors as given below. **Analyze the differences a**nd discuss their significance.

| Group | Fuel, $\phi_{fuel} / \phi_{cell}$ | Cladding, $\phi_{cladding} / \phi_{cell}$ | Coolant, $\phi_{coolant} / \phi_{cell}$ |
|---|---|---|---|
| **1** | 1.60 | 1.01 | 0.90 |
| **2** | 1.60 | 1.01 | 0.90 |
| **3** | 1.60 | 1.01 | 0.91 |
| **4** | 1.45 | 1.02 | 0.91 |
| **5** | 1.45 | 1.02 | 0.91 |
| **6** | 1.34 | 1.03 | 0.94 |
| **7** | 1.34 | 1.03 | 0.94 |
| **8** | 1.34 | 1.03 | 0.94 |

## 8-Group Data Set

### 8-Group Energy Structure

| Group | Lethargy Width, $\Delta u$ | Lower Energy | Fission Spectrum |
|---|---|---|---|
| **1** | 1.5 | 2.2 MeV | 0.365 |
| **2** | 1.0 | 820 keV | 0.396 |
| **3** | 1.0 | 300 keV | 0.173 |
| **4** | 1.0 | 110 keV | 0.050 |
| **5** | 1.0 | 40 keV | 0.012 |
| **6** | 1.0 | 15 keV | 0.003 |
| **7** | 3.0 | 750 eV | 0.001 |
| **8** | - | 0 | 0 |

### 8-Group Cross Sections

| Material | Group | $\sigma_{tr}$ (b) | $\sigma_{\gamma}$ (b) | $\sigma_f$ (b) | Removal due to Scattering, $\sigma_{s,R}$ (b) | $\nu_f$ |
|---|---|---|---|---|---|---|
| **Lead** | **1** | 1.5 | 0.0050 | - | 0.623 | - |
| | **2** | 2.2 | 0.0002 | - | 0.6908 | - |
| | **3** | 3.6 | 0.0004 | - | 0.4458 | - |
| | **4** | 3.5 | 0.0010 | - | 0.2900 | - |
| | **5** | 4.0 | 0.0010 | - | 0.3500 | - |
| | **6** | 3.9 | 0.0010 | - | 0.3000 | - |
| | **7** | 7.3 | 0.0090 | - | 0.0400 | - |
| | **8** | 3.2 | 0.0080 | - | 0.0000 | - |
| **Iron** | **1** | 2.2 | 0.0200 | - | 1.0108 | - |
| | **2** | 2.1 | 0.0030 | - | 0.4600 | - |
| | **3** | 2.4 | 0.0050 | - | 0.1200 | - |
| | **4** | 3.1 | 0.0060 | - | 0.1400 | - |
| | **5** | 4.5 | 0.0080 | - | 0.2800 | - |
| | **6** | 6.1 | 0.0120 | - | 0.0700 | - |
| | **7** | 6.9 | 0.0320 | - | 0.0400 | - |
| | **8** | 10.4 | 0.0200 | - | - | - |
| **$^{238}$U** | **1** | 4.3 | 0.0100 | 0.58 | 2.293 | 2.91 |
| | **2** | 4.8 | 0.0900 | 0.20 | 1.4900 | 2.58 |
| | **3** | 6.3 | 0.1100 | 0.00 | 0.3759 | 0.0 |
| | **4** | 9.3 | 0.1500 | 0.00 | 0.2935 | 0.0 |
| | **5** | 11.7 | 0.2600 | 0.00 | 0.2000 | 0.0 |
| | **6** | 12.7 | 0.4700 | 0.00 | 0.0900 | 0.0 |
| | **7** | 13.1 | 0.8400 | 0.00 | 0.0100 | 0.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **8** | 11.0 | 1.4700 | 0.00 | 0.0000 | 0.0 |
| **$^{239}$Pu** | **1** | 4.5 | 0.0100 | 1.85 | 1.4950 | 3.40 |
| | **2** | 5.1 | 0.0300 | 1.82 | 0.8260 | 3.07 |
| | **3** | 6.3 | 0.1100 | 1.60 | 0.3709 | 2.95 |
| | **4** | 8.6 | 0.2000 | 1.51 | 0.1905 | 2.90 |
| | **5** | 11.3 | 0.3500 | 1.60 | 0.1500 | 2.88 |
| | **6** | 13.1 | 0.5900 | 1.67 | 0.0900 | 2.88 |
| | **7** | 16.5 | 1.9800 | 2.78 | 0.0100 | 2.87 |
| | **8** | 31.8 | 8.5400 | 10.63 | 0.0000 | 2.87 |

**8-Group Scattering Matrices**

**Lead**

| $h$ \ $g$ | $\sigma_{s,h\to g}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **1** | 0.5200 | 0.0900 | 0.0030 | 0.0090 | 0.0010 | 0.0000 | 0.0000 |
| **2** | | 0.6900 | 0.0000 | 0.0004 | 0.0004 | 0.0000 | 0.0000 |
| **3** | | | 0.4400 | 0.0050 | 0.0008 | 0.0000 | 0.0000 |
| **4** | | | | 0.2900 | 0.0000 | 0.0000 | 0.0000 |
| **5** | | | | | 0.3500 | 0.0000 | 0.0000 |
| **6** | | | | | | 0.3000 | 0.0000 |
| **7** | | | | | | | 0.0400 |

**Iron**

| $h$ \ $g$ | $\sigma_{s,h\to g}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **1** | 0.7500 | 0.2000 | 0.5000 | 0.0100 | 0.0008 | 0.0000 | 0.0000 |
| **2** | | 0.3300 | 0.1000 | 0.0200 | 0.0100 | 0.0000 | 0.0000 |
| **3** | | | 0.1200 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **4** | | | | 0.1400 | 0.0000 | 0.0000 | 0.0000 |
| **5** | | | | | 0.2800 | 0.0000 | 0.0000 |
| **6** | | | | | | 0.0700 | 0.0000 |
| **7** | | | | | | | 0.0400 |

**$^{238}$U**

| $h$ \ $g$ | $\sigma_{s,h\to g}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **1** | 1.2800 | 0.7800 | 0.2000 | 0.0300 | 0.0030 | 0.0000 | 0.0000 |
| **2** | | 1.0500 | 0.4200 | 0.0100 | 0.0100 | 0.0000 | 0.0000 |
| **3** | | | 0.3300 | 0.0400 | 0.0050 | 0.0009 | 0.0000 |
| **4** | | | | 0.2900 | 0.0030 | 0.0005 | 0.0000 |
| **5** | | | | | 0.1800 | 0.0200 | 0.0000 |
| **6** | | | | | | 0.0900 | 0.0000 |
| **7** | | | | | | | 0.0100 |

**$^{239}$Pu**

| $h$ \ $g$ | $\sigma_{s,h\to g}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **1** | 0.6600 | 0.6000 | 0.1900 | 0.0400 | 0.0050 | 0.0000 | 0.0000 |
| **2** | | 0.6400 | 0.1500 | 0.0300 | 0.0060 | 0.0000 | 0.0000 |
| **3** | | | 0.3100 | 0.0500 | 0.0100 | 0.0009 | 0.0000 |
| **4** | | | | 0.1800 | 0.0100 | 0.0005 | 0.0000 |
| **5** | | | | | 0.1300 | 0.0200 | 0.0000 |
| **6** | | | | | | 0.0900 | 0.0000 |
| **7** | | | | | | | 0.0100 |