Design and Analysis of a Small Reactor Unit: Reactivity, Safety and Economic Assessment

Aurora Jahan, Faisal Ahmed Moshiur, Jeevan George

July 26, 2023

Abstract

This report presents the design and analysis of a small reactor unit with an electrical power output of 200 MW using enriched uranium oxide fuel. The objectives of this project include calculating reactivity swing, determining the control rod configuration to meet safety criteria, evaluating various coefficients related to fuel and coolant, assessing the emergency planning zone radius in case of severe accidents, and estimating the capital and operational costs for a multi-unit plant. The analysis is conducted with a focus on optimizing performance, safety, and economic feasibility. The results provide valuable insights into small reactor units' design considerations and operational aspects.

Keywords: *Small reactor unit, enriched uranium oxide fuel, reactivity swing, control rod configuration, fuel and coolant coefficients, emergency planning zone, severe accidents, capital costs, operational costs, multi-unit plant, performance optimization, safety considerations, economic feasibility.*

1 Introduction

The demand for small reactor units has been growing due to their potential advantages in flexibility, reduced investment risk, and improved safety features. This report presents a comprehensive study on the design and analysis of a small reactor unit with an electrical power output of 200 MW_e. The project aims to address critical aspects such as reactivity swing, control rod configuration, coefficient calculations, emergency planning, and cost estimation. The findings of this study will contribute to the understanding of the technical and economic feasibility of small reactor units and provide insights for future development and deployment of such systems.

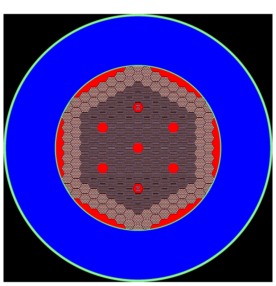


Figure 1: Control rod configuration for the maximum worth of 0.5 $.

2 Design

The Sunrise LFR design was used as a starting point for the simulation, with variations in the configuration to meet the project work criteria [3]. The design parameters are depicted in Tab. 1. Moreover, Fig. 1 shows the assembly configuration of the reactor.

Table 1: Design parameters for the reactor used for simulation.

Parameters	Values
Power	600 MW_{th}
Fuel assemblies	120
Fuel rods per assembly	169
Reflector assemblies	90
Reflector rods per assembly	37
Control rod assemblies	2
Control rods per assembly	5
Reactor core barrel outer radius	140 cm
Active fuel height	160 cm
Lattice pitch	17.16 cm
Fuel rod outer diameter	1.12 cm

2.1 Reactivity swing

According to the project descriptions, the 200 MW_e lead-cooled fast reactor unit fueled by UO_2 must have a maximum reactivity swing of 600 pcm for a fuel average burn-up of 50 GWd/ton [3].

Methodology

We started with the Sunrise LFR design input file to achieve this requirement. We modified it as follows:

1. we changed the fuel material card to use 12% enriched UO_2 fuel.

```
mat fuel -10.91  burn 1 %
      8016.09c   2.000
     92235.09c   0.12
     92238.09c   0.88
```

2. We expanded the reactor both radially and axially. The changes due to this design alteration are presented in Tab. 2.

Table 2: Changes in the design due to the axial and radial increase of the reactor.

Parameters	Values
Fuel assemblies	120
Reflector assemblies	90
Reactor core barrel outer radius	140 cm
Active fuel height	160 cm

3. We increased the reactor's power to 600 MW_{th}, which is assumed to correspond to 200 MW_e power output.

```
set power 600000000
```

4. We defined burnup steps up to 50 GWd/ton.

```
dep butot 5 10 15 20 25 30 35 40 35 50
```

Results

With our reactor design, we found the reactivity swing to be 533 pcm.

2.2 Control rod worth

According to the project descriptions, the design must be adjusted so that the maximum reactivity worth of any one control rod assembly is less than 0.5 $.

Methodology

We placed two assemblies of control rods some distance away from the center to satisfy this requirement. Each assembly was equipped with five control rods made of natural boron carbide. The control rod configuration is summarized in Tab. 3.

Table 3: Control rod configuration

Parameters	Values
Control rod material	natural B_4C
Control rod assemblies	2
Control rods per assembly	5

Results

We obtained -0.828 $ of combined control rod worth from two assemblies with our control rod configuration. Since the two assemblies are symmetrical, the reactivity worth of each control rod assembly is -0.414 $, which is less than the 0.5$ requirement.

2.3 Reactivity coefficients

The reactivity coefficients for our reactor were calculated at the beginning of its operational life. Four coefficients were determined: the Doppler coefficient, the coolant temperature coefficient, the axial expansion coefficient, and the radial expansion coefficient.

Methodology

The Doppler coefficient, α_D, was computed using the Doppler constant, K_D, [8] which is defined as

$$\alpha_D = \frac{K_D}{T_f} \tag{1}$$

where T_f is the fuel temperature, and the Doppler constant is defined as

$$K_D = \frac{\rho(T_1) - \rho(T_2)}{\ln\left(\frac{T_2}{T_1}\right)}. \tag{2}$$

The coolant temperature feedback, denoted as $\alpha_{coolant}$, was determined as the ratio of the change in reactivity to the change in temperature. To measure it, we observed the reactivity change due to changing the temperature and corresponding density of the coolant [8]. Finally, the coefficient was calculated as follows:

$$\alpha_{coolant} = \frac{\Delta\rho}{\Delta T} \tag{3}$$

The expansion of the fuel rods due to increased temperature increases height, causing a decrease in fuel density and an increase in neutron leakage.

To assess the impact of axial expansion on reactivity, we increased the height of the fuel rods by 5% as the $\frac{H}{D} > 0.5$ for our dimension will cause a significant change in a slight increase in dimension. We estimated the corresponding change in density and temperature [4]. The change in reactivity was then calculated using a similar equation as for $\alpha_{coolant}$:

$$\alpha_{axial} = \frac{\Delta\rho}{\Delta T} \tag{4}$$

The diagrid radial expansion coefficient accounts for the expansion of the diagrid, which holds the fuel assemblies when the temperature rises. The change in reactivity was observed by expanding the pitch in correspondence [1] to the temperature of 2770 K. The diagrid radial expansion was calculated using the formula:

$$\alpha_{radial} = \frac{\Delta\rho}{\Delta T} \tag{5}$$

Results

The values for each coefficient computed at several temperatures are summarized in Tab. 4.

Table 4: Reactivity Coefficients

Reactivity Coefficient	Values
K_D	-935.651 pcm
α_D	-1.040 pcm/K
$\alpha_{coolant}$	$+0.040$ pcm/K
α_{axial}	-0.168 pcm/K
α_{radial}	-0.683 pcm/K

3 Radiological Impact

The radiological impact assessment in nuclear power plants ensures public safety and emergency preparedness. In this section, we focus on determining the radius of the emergency planning zone (EPZ) for a severe accident scenario involving a core with an average burn-up of 50 GWd/ton. Specifically, we analyzed the release of xenon and iodine isotopes, assuming a 100% release of xenon and a 0.1% release of iodine. Considering the dose acceptance criterion of 20 mSv, we aim to establish the EPZ radius to safeguard the public and minimize potential radiological risks associated with the accident.

Methodology

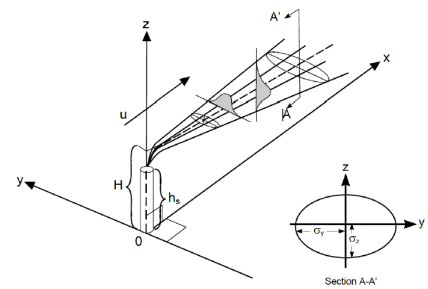


Figure 2: Coordinate system of the Gaussian plume model.

As shown in Fig. 2, plume rise height was modeled as

$$\Delta h(r) = \frac{1.6}{u} \times r^{\frac{2}{3}} \left(\frac{g}{\pi} V \left(\frac{T_s - T_a}{T_s} \right) \right)^{\frac{1}{3}} \tag{6}$$

where u is the wind speed, g is the gravitational acceleration, V is the volumetric rate of release, T_s is the temperature of the source, T_a is the temperature of air, and r is the distance from the release point [2].

The dispersion half-width was calculated as

$$\sigma_i = \exp\left(a_i + b_i \times \left(\ln \tfrac{r}{1000}\right) + c_i \times \left(\ln \tfrac{r}{1000}\right)^2\right) \tag{7}$$

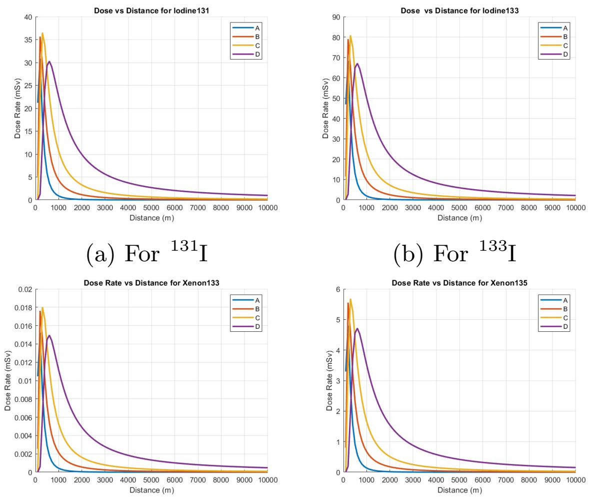
where a_i, b_i, and c_i are the dispersion half-width parameters corresponding to the Pasquill atmospheric stability conditions [2].

Eq. 8 is used in the CAP-88 dispersion model[6] to calculate the ground-level air concentration [5].

$$\chi = \frac{2Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{8}$$

where χ is the air concentration, Q is the release rate, u is wind speed, σ_z is the vertical dispersion coefficients, and H is the effective stack height ($H = h_s + \Delta h$) as shown in Fig. 2. The dispersion coefficients are functions of the downwind distance, x, so χ is also a function of x. The dose is calculated from χ assuming the average adult breathing rate is 2.1 m^3/hr [7].

Results



(a) For ^{131}I (b) For ^{133}I

(c) For ^{133}Xe (d) For ^{135}Xe

Figure 3: Radiological impact of different isotopes released from the core.

The radiological impact assessment determined an exclusion zone radius of 2.2 km based on a dose acceptance criterion of 20 mSv, matching the maximum value obtained from the graphs of I and Xe isotopes in Fig. 3.

4 SMR Cost Analysis

This report presents an economic analysis of an 8-unit 200 MW Lead Fast Reactor nuclear power plant. The analysis considers various factors such as the number of units, plant availability, economic life, total power sales, sales price, scaling factor, estimated capital cost, estimated operational cost, and the levelized cost of electricity (LCOE). The results provide insights into the economic feasibility and viability of the proposed nuclear power plant.

Assumptions

The following assumptions were considered in the financial analysis:

- The nuclear power plant site consists of 8 units, each contributing to the overall power generation capacity.
- Plant availability: The plant availability is assumed to be 90%.
- Economic life: The expected economic life of the nuclear power plant was assumed to be 25 years. This duration represents the period during which the plant is expected to operate efficiently and economically.
- Total power sales: The analysis assumes a total power sales volume of 12623 GWh. This represents the electricity the power plant is expected to generate and sell to the grid.
- Sales price: The electricity sales price is assumed to be 55 USD/MWh.
- Scaling factor: The scaling factor is the square root of the number of units. It is used to determine the relationship between the cost and capacity of the power plant.

Results

Based on the parameters mentioned above, the following estimated costs have been determined for the 8-unit nuclear power plant:

Estimated Capital Cost: The estimated capital cost for the 8-unit plant is 8.4 billion USD. This cost encompasses the investment required to construct and commission the power plant.

Estimated Operational Cost: The estimated operational cost for the 8-unit plant is 287 million USD. This cost includes plant maintenance, fuel, personnel, and other operational aspects over the plant's economic life.

Estimated LCOE: The levelized cost of electricity (LCOE) is estimated to be 120 USD/MWh. LCOE represents the average cost of generating each unit of electricity over the plant's economic life, considering both capital and operational costs.

5 Discussion

In this study, we focused on designing and analyzing a small reactor unit with enriched uranium oxide fuel. We successfully achieved a maximum reactivity swing of 533 pcm, meeting the design criteria for the reactor.

Our control rod configuration, consisting of two assemblies with five control rods each, resulted in a combined control rod worth -0.828 \$, or -0.414 \$ reactivity worth for each assembly, ensuring the safe operation of the reactor.

We also evaluated the reactivity coefficients of our reactor design. We found that the Doppler coefficient was -1.040 pcm/K, the coolant temperature coefficient was $+0.040$ pcm/K, the axial expansion coefficient was -0.168 pcm/K, and radial expansion coefficient was -0.683 pcm/K. The values of the axial expansion coefficient were high, while the radial expansion coefficient was low because the H/D radio of our reactor was more significant than 0.5.

The radiological impact assessment determined the emergency planning zone radius for a severe accident involving releasing xenon and iodine isotopes. Considering 100% release of xenon and a 0.1% release of iodine, we established an exclusion zone radius of 2.2 km, ensuring public safety and minimizing potential radiological risks.

We finally carried out the cost estimation for our reactor design. Our analysis assumed the capital and operational costs to be 8.4 billion USD and 287 million USD, respectively. These estimations suggested that the levelized cost of electricity (LCOE) of our plant will be 120 USD/MWh. Since no LFR units have been built, many initial assumptions made before the cost estimation are rough rather than precise values. Therefore, the estimation presented in this report might be erroneous.

6 Conclusion

In conclusion, our study on designing and analyzing a small reactor unit with enriched uranium oxide fuel has yielded significant insights. We successfully optimized the reactivity swing and implemented a control rod configuration that meets safety criteria. The evaluation of reactivity coefficients provides valuable data for reactor control and operation.

The radiological impact assessment also allowed us to determine the emergency planning zone radius, emphasizing public safety and preparedness during severe accidents. Although we acknowledge the uncertainties in cost estimates due to the absence of an operational Lead Fast Reactor, our economic analysis provides essential insights into the feasibility of 8-unit nuclear power plants.

Our findings contribute to understanding small reactor units, highlighting safety, performance optimization, and economic feasibility as essential to their successful deployment. As we continue to advance in nuclear power research, the knowledge gained from this study will pave the way for more sustainable and efficient nuclear energy solutions in the future.

References

[1] Kevin G. Field et al. "Handbook on the Material Properties of FeCrAl Alloys for Nuclear Power Production Applications (FY18 Version: Revision 1)". In: (Aug. 2018). DOI: `10.2172/1474581`. URL: `https://www.osti.gov/biblio/1474581`.

[2] Janne Wallenius. *SMR course, Lecture: Radiological impact*. Course lecture. Course code: SH2611. 2023. URL: `https://canvas.kth.se/courses/37962/files/6477805/download?download_frd=1`.

[3] Janne Wallenius. *SMR course, Lecture: SMR cost estimate*. Course lecture. Course code: SH2611. 2023. URL: `https://canvas.kth.se/courses/37962/files/6560354/download?download_frd=1`.

[4] Pacific Northwest National Laboratory. *MatLib-1.0: Nuclear Material Properties Library prepared for the U.S. Nuclear Regulatory Commission*. 2021. URL: `https://fast.labworks.org/file-download/download/public/454`.

[5] M. Mcnaughton et al. "Accuracy of Cloudshine Gamma Dose Calculations in the CAP-88 Dispersion Model". In: *Health Physics Society* 112.4 (2017), pp. 414–419. DOI: `10.1097/HP.0000000000000653`. URL: `https://www.researchgate.net/publication/315732368_Accuracy_of_Cloudshine_Gamma_Dose_Calculations_in_the_CAP-88_Dispersion_Model`.

[6] U.S. Environmental Protection Agency. *CAP-88 Dispersion Model*. Technical Report RAGS-BGM-1.1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1993. URL: `https://www.epa.gov/radiation/cap88-PC`.

[7] U.S. Environmental Protection Agency. *Exposure Factors Handbook*. Table 6-1, Chapter 6. 2011. URL: `https://www.epa.gov/sites/default/files/2015-09/documents/efh-chapter06.pdf`.

[8] J. Wallenius and S. Bortot. "Fast reactor kinetics and reactivity feedbacks". In: *Fast Neutron Generation IV Reactors*. Ed. by M.A. Pouchon and A. Ballagny. Amsterdam, Netherlands: Elsevier, 2016. Chap. 3, pp. 23–31. URL: `https://canvas.kth.se/courses/37978/files/6292970/download?download_frd=1`.