NewClear Small Modular Reactor

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1. Abstract

This report outlines the design of a 30 MWe Small Modular Reactor (SMR) using systems engineering principles from the NASA Handbook. It details the selection of a pressurized light water reactor, fuel type, core configuration, and material choices. Thermodynamic and heat transfer analyses, including Nusselt number calculations, were performed to verify heat removal capability. The design integrates technical decisions and verification steps to ensure safety, efficiency, and feasibility.

2. Introduction

India's growing energy demands, coupled with the need for clean, reliable, and decentralized power generation, make Small Modular Reactors (SMRs) a promising solution. Their compact size, enhanced safety features, and scalability offer a practical alternative to traditional large-scale reactors, especially in remote or developing regions. Motivated by this national need, our project focuses on the conceptual design of a 30 MWe SMR using a systems engineering approach inspired by the NASA Systems Engineering Handbook. The design process involved careful selection of reactor type, fuel, core configuration, and materials, followed by detailed thermal and structural verification. This report captures the full design workflow, key engineering decisions, and validation steps. The outcome reflects a technically feasible and systemically sound reactor concept tailored to India's energy landscape.

3. System Engineering Framework Applied

3.1. Stakeholder Needs and Mission Objectives

The primary mission objective of this project is to design a Small Modular Reactor (SMR) with a net electrical output of 30 MWe, suitable for deployment in India's diverse energy landscape. Stakeholder needs were identified based on India's increasing demand for clean and reliable electricity, the challenges of energy access in remote areas, and the need for enhanced safety and ease of deployment. Accordingly, key performance needs were defined:

- **Power Output:** Steady electrical output of 30 MWe with a thermal efficiency of approximately 30%.
- **Safety:** Passive safety systems, conservative design margins, and proven technology choices.
- **Efficiency:** Optimal thermal performance and long fuel cycle to minimize operational costs.
- **Modularity:** Scalable design that allows multiple units to be deployed in phases.

These needs shaped the design decisions throughout the project, ensuring alignment with both national goals and practical deployment considerations.

3.2. Requirements Development

Using a top-down systems engineering approach, the following functional and non-functional requirements were derived:

Functional Requirements:

- The reactor shall generate a net electrical output of 30 MWe.
- The core shall maintain safe operating conditions during nominal and off-nominal events.
- The system shall transfer heat efficiently from the core to the secondary loop.

Non-Functional Requirements:

- Use of commercially available fuel (e.g., UO_2) with enrichment below 5%.
- Use of light water as coolant and moderator.
- Core materials must have high corrosion resistance and structural integrity at elevated temperatures.
- Design life of at least 40 years with refueling cycles as required.

3.3. Trade Studies and Decision Rationale

Several trade studies were conducted to identify the most feasible configuration for the SMR. Major decisions include:

Why Light Water Reactor?. A Light Water Reactor (LWR) was selected due to its extensive operational history, regulatory maturity, and the existing infrastructure in India for fuel fabrication, handling, and water chemistry management. LWRs offer lower initial R&D costs and enhanced public acceptance compared to advanced reactor types such as molten salt or gas-cooled reactors.

Why Pressurized Water Reactor (PWR) over Boiling Water Reactor (BWR)?. A Pressurized Water Reactor configuration was chosen over a BWR primarily for its compact design and better containment of radioactive material. PWRs maintain high-pressure conditions in the primary loop, which minimizes the risk of coolant boiling and allows more straightforward thermal control. Additionally, the separation of primary and secondary loops provides better isolation from radioactivity, enhancing overall safety.

Fuel Type, Enrichment, and Cladding Material. Uranium dioxide (UO_2) was chosen as the fuel due to its widespread use, thermal stability, and availability. The enrichment level was kept below 5% to remain within low-enriched uranium (LEU) limits, avoiding proliferation concerns. Zirconium alloy (Zircaloy) was selected as the cladding material for its low neutron absorption cross-section, corrosion resistance, and mechanical performance under irradiation.

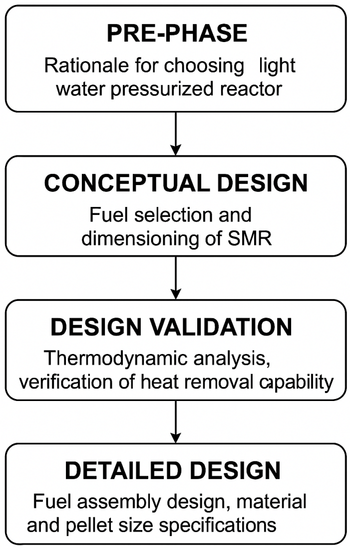

Figure 1. *Block diagram for system engineering design principles*

3.4. System Architecture and Decomposition

The overall system was decomposed into key subsystems to simplify design, analysis, and integration:

- **Reactor Core:** Contains fuel assemblies, control rods, structural supports, and reflectors.
- **Control System:** Monitors core parameters and actuates control rods and safety systems.
- **Containment System:** Ensures physical and radiological isolation of reactor components.

This structured decomposition allows clear allocation of requirements to subsystems and enables parallel development and verification efforts. Each subsystem was analyzed in detail in subsequent sections to ensure performance and compliance with overarching system requirements.

4. Design Choices and Rationale

4.1. Core Design and Configuration

The reactor core was designed with compactness, thermal efficiency, and neutron economy in mind. A cylindrical core geometry was adopted to simplify manufacturing and enhance neutron flux symmetry. Based on thermal-hydraulic and neutron flux considerations, the following configuration was finalized:

- **Core Dimensions:** Height = 1.08 m, Diameter = 1.08 m. This ensures a height-to-radius ratio of 2, which is favorable for effective heat removal and core stability.
- **Fuel Assemblies:** The core contains 21 fuel assemblies, arranged in a symmetric configuration to ensure uniform power distribution and effective moderator utilization.
- **Fuel Rods per Assembly:** Each fuel assembly comprises approximately 297 fuel rods with size of Height=180mm and Diameter=13mm, resulting in a total of over 6,200 fuel rods in the core.
- **Pellet Dimensions:** Height = 10mm and diameter =12mm to ensure that it does not buckle under the pressure inside fuel rod. The number of pellets inside a fuel rod is 17.
- **Control Assemblies:** 16 control assemblies are distributed strategically among the fuel assemblies to provide fine control over the reactivity, ensuring both operational flexibility and safety shutdown capabilities.
- **Internal Components:** Neutron reflectors are placed around the core periphery to reduce neutron leakage and enhance fuel utilization. Spacers and grid supports are used to maintain precise rod alignment, ensure coolant flow uniformity, and minimize vibration-induced wear.

This configuration strikes a balance between power density, safety margins, and mechanical simplicity, making it ideal for a compact Small Modular Reactor. Here are the engineering drawings of different components of the reactor core for dimensions we have choosen.

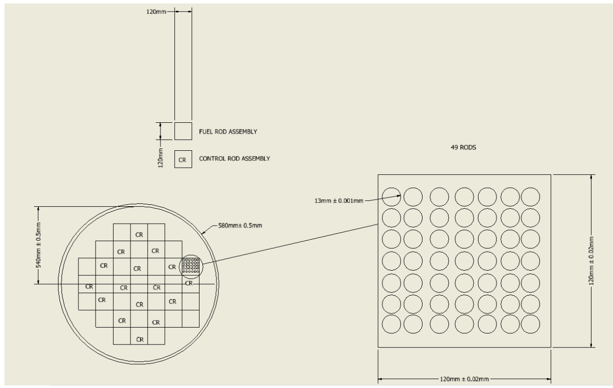

Figure 2. *Top View of Reactor Core*

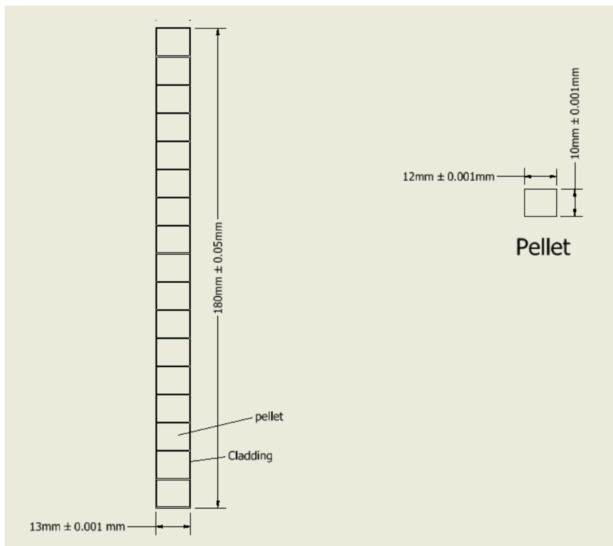

Figure 3. *Fuel Rod with pellets*

In nuclear reactor components, dimensional tolerances are chosen based on the functional criticality and manufacturing feasibility. Highly sensitive components like fuel rods (Ø13 mm) and fuel pellets (Ø12 mm) require extremely tight tolerances (±0.001 mm) to ensure proper heat transfer, neutron

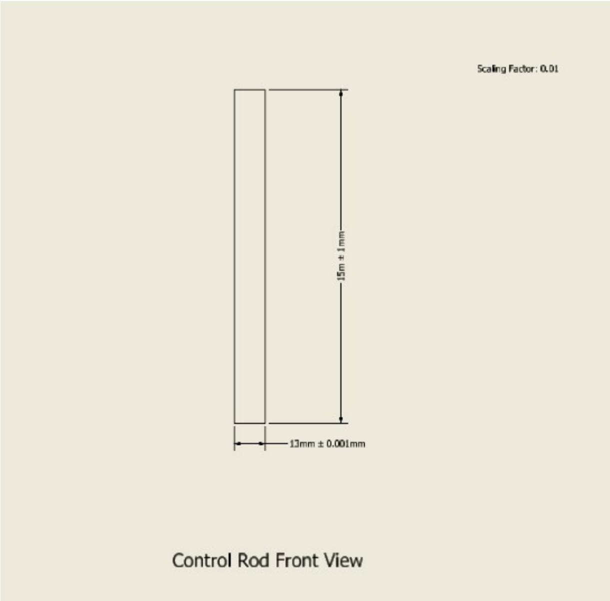

Figure 4. *Front View of Control Rod*

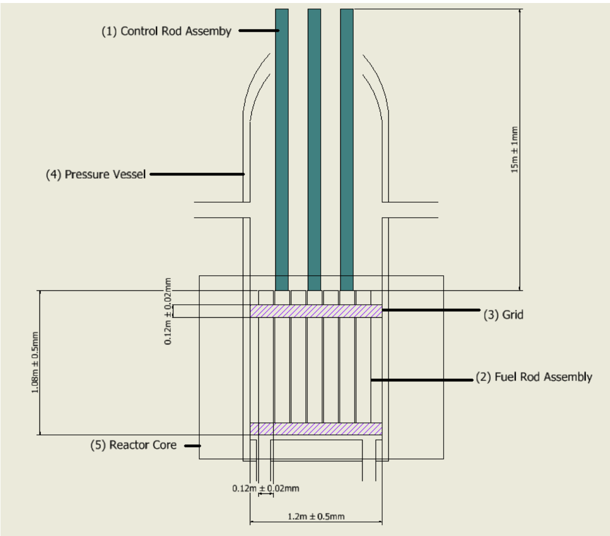

Figure 5. *Front View of Reactor Core with Control Rods*

moderation, and to prevent mechanical interference, as even minor deviations could compromise reactor safety. For larger structural dimensions such as 120 mm assemblies or cladding housing, tolerances of ± 0.02 mm to ± 0.5 mm are acceptable, balancing manufacturability and assembly fit. Control rod heights (15 m) can tolerate up to ± 1 mm variation due to lower sensitivity to minor dimensional shifts over long lengths. These tolerances align with standard practices in precision engineering and metrology for nuclear-grade manufacturing.

4.2. Thermal Power and Power Conversion

The reactor is designed to operate at a steady-state thermal output of approximately 100 MWt. This value was chosen to match the expected electrical output requirement while maintaining safe thermal margins and manageable core size.

- **Thermal Output:** 100 MWt, determined based on the core's geometry, fuel configuration, and allowable heat flux.
- **Power Conversion Efficiency:** Assuming a Rankine cycle with an efficiency of roughly 30%, the system delivers an electrical output of approximately 30 MWe.

The chosen thermal-to-electrical conversion efficiency accounts for parasitic losses and is consistent with typical values for pressurized water reactors operating at similar conditions. This configuration ensures that the reactor meets its primary mission objective of delivering 30 MWe while maintaining robust thermal and structural safety margins.

5. Material Selection

The selection of materials for various components of the SMR is driven by the need for excellent corrosion resistance, mechanical integrity under irradiation, compatibility with coolant chemistry, and longevity in high-pressure, high-temperature conditions.

Table 1. *Material Selection for Key Reactor Components*

Part Name	Material
Reactor Core	Stainless Steel 304
Cladding Material	Zircaloy
Control Rod Absorber	Boron
Reactor Pressure Vessel	SA-508 Grade 3 Class 1
Core Support Structures	Stainless Steel 304
Guide Tubes	Stainless Steel 316

The **reactor pressure vessel** is made from SA-508 Grade 3 Class 1 steel, a widely accepted choice in the nuclear industry due to its high toughness, excellent weldability, and strong resistance to radiation-induced embrittlement. This material provides the structural integrity required to withstand the internal pressure and temperature of the core.

For the **core internals and structural support**, Stainless Steel 304 is used. It offers good corrosion resistance in high-temperature water environments and maintains mechanical strength under thermal cycling and neutron irradiation, making it suitable for long-term structural applications within the core.

The **guide tubes** are fabricated from Stainless Steel 316, which contains additional molybdenum compared to SS 304, enhancing its resistance to pitting and crevice corrosion in pressurized water environments. This makes it a more robust option for components directly interacting with coolant flow and control systems.

Zircaloy is selected as the cladding material due to its low neutron absorption cross-section and excellent corrosion resistance in high-temperature water and steam. This ensures minimal parasitic absorption and structural stability around the fuel pellets, which is critical for fuel performance.

Boron is used in the control rod absorber due to its very high neutron absorption cross-section and predictable behavior under irradiation. Its effectiveness in controlling reactivity makes it a standard choice for safe and reliable reactor shutdown mechanisms.

All materials are chosen to be compatible with the light water coolant used in the reactor. This ensures minimized corrosion, enhanced safety margins, and extended component life with proper coolant chemistry management.

6. Thermal Physics Calculations

6.1. Thermal to Electrical Power Conversion

The reactor operates on a Rankine cycle with an assumed efficiency of 30%. Hence, the electrical power output is calculated as:

$$P_{\text{electrical}} = \text{Efficiency} \times P_{\text{thermal}} = 0.3 \times 100 = 30\,\text{MWe}$$

This validates that 30% efficiency is sufficient to meet the desired electrical output. Later sections reaffirm that our reactor is capable of delivering approximately 30 MWe.

6.2. Mass Flow Rate Calculation

Assuming a coolant temperature rise of 35°C across the core, the required mass flow rate is:

$$m = \frac{Q}{C_p \Delta T} = \frac{100 \times 10^6}{4.2 \times 10^3 \times 35} = 680\,\text{kg/s}$$

6.3. Coolant Flow Velocity

Given a flow cross-sectional area of 0.3 m^2 and fluid density $\rho = 700\,\text{kg/m}^3$:

$$v = \frac{m}{\rho A} = \frac{680}{700 \times 0.3} \approx 3.24\,\text{m/s}$$

6.4. Reynolds Number Calculation

With diameter $d = 0.01$ m and dynamic viscosity $\mu = 0.0001\,\text{Pa} \cdot \text{s}$:

$$Re = \frac{\rho v d}{\mu} = \frac{700 \times 3.24 \times 0.01}{0.0001} = 226,800$$

Since $Re > 4000$, the flow is confirmed to be turbulent.

Nusselt Number Calculation

Using the Dittus-Boelter equation for turbulent flow:

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4}$$

Assuming Prandtl number $Pr = 0.9$:

$$Nu = 0.023 \times (226800)^{0.8} \times (0.9)^{0.4} = 807$$

6.5. Convective Heat Transfer Coefficient

With $k = 0.6\,\text{W/m} \cdot \text{K}$ and $d = 0.01$ m:

$$h = \frac{Nu \cdot k}{d} = \frac{807 \times 0.6}{0.01} = 48,420\,\text{W/m}^2 \cdot \text{K}$$

6.6. The heat transfer from the fuel rods to the coolant follows Newton's Law of Cooling:

Using the formula:

$$q'' = h \cdot \Delta T_{\text{log}}$$

Where:

$$\Delta T_{\text{log}} = \frac{(T_s - T_{in}) - (T_s - T_{out})}{\ln\left(\frac{T_s - T_{in}}{T_s - T_{out}}\right)}$$

Assuming:

- Fuel rod surface temperature -> $T_s = 600$ K (approximate safe operating surface temperature)
- Coolant inlet temperature -> $T_{\text{in}} = 563$ K
- Coolant outlet temperature -> $T_{\text{out}} = 598$ K

$$\Delta T_{\text{log}} = \frac{(600 - 563) - (600 - 598)}{\ln\left(\frac{600-563}{600-598}\right)} = \frac{35}{\ln(18.5)} \approx \frac{35}{2.9} = 12.1\,\text{K}$$

Thus, the heat flux is:

$$q'' = 48,420 \times 12.1 = 586,000\,\text{W/m}^2$$

6.7. Heat Transfer per Fuel Rod

Outer surface area of one rod:

$$A_{\text{rod}} = \pi d L = \pi \times 0.0107 \times 1 = 0.0336\,\text{m}^2$$

Heat transfer per rod:

$$Q_{\text{rod}} = q'' \cdot A_{\text{rod}} = 586,000 \times 0.0336 = 19.7\,\text{kW}$$

Total for 5000 rods:

$$Q_{\text{total}} = 19.7 \times 5000 = 98.5\,\text{MW}$$

This is very close to 100 MW, confirming that 5000 rods can handle the required power more effectively.

6.8. Heat Absorption by Control Rods

Control rods absorb around 10% of the reactor's power:

$$Q_{\text{total, control}} = 10\,\text{MW}$$

If there are 300 control rods:

$$Q_{\text{control per rod}} = \frac{10,000,000}{300} = 33.3\,\text{kW}$$

Assuming each rod has similar dimensions as fuel rods and $k = 30\,\text{W/m-K}$ for B_4C:

$$\Delta T_{\text{control}} = \frac{Q \cdot L}{k \cdot A} = \frac{33,300 \times 1}{30 \times 0.0336} = \frac{33,300}{1.008} = 33\,\text{K}$$

This indicates the control rod surface temperature exceeds the coolant temperature by only 33 K — which is acceptable.

7. Verification

The verification of the Small Modular Reactor (SMR) design was conducted through analytical evaluations, thermal-hydraulic calculations, and materials assessments.

7.1. Thermal Performance Verification

To verify the thermal capacity of the reactor, a detailed energy balance and heat transfer analysis was performed:

- The reactor's **thermal output of 100 MWt** was confirmed to provide the desired **30 MWe electrical output**, assuming a Rankine cycle with 30% efficiency.
- **Coolant velocity** and **Reynolds number (~227,000)** calculations confirmed fully turbulent flow, ensuring efficient convective heat transfer.

7.2. Heat Transfer Capacity of Fuel Rods

- The **surface area of each fuel rod** was used to calculate its heat transfer capacity, which came out to be approximately 19.7 kW per rod.

- With around **5000 rods**, the total heat transfer capability closely matches the thermal output (98.5 MW vs. 100 MW), confirming the sufficiency of the fuel rod configuration.

7.3. Core Geometry and Neutron Economy

- Our report outlines the core dimensions (Height = 1.08 m, Diameter = 1.08 m) and mentions a height-to-radius ratio of 2. Referring to symmetry, a symmetrical design simplifies control rod effectiveness and helps flatten power distribution.

7.4. Fuel Loading and Assembly Configuration

- We have:

  21 fuel assemblies × 297 rods each = 6,200+ rods

  With 17 fuel pellets per rod

  Loaded fuel provides enough energy to sustain 100 MW for more than 3 years, which is realistic for a cycle between refueling or load-following operation.

  This verifies that the fuel volume and configuration is consistent with the power target and our fuel burnup and core energy density are in a reasonable range.

7.5. Control Rod Thermal Absorption

- Control rods were estimated to absorb **10% of the total power (10 MW)**.

- Each control rod (assuming 300 total) was verified to absorb **∼33.3 kW**, with a **temperature rise of ∼33 K**, which is within safe thermal margins given the thermal conductivity of Boron Carbide (B_4C).

7.6. Material Compliance

- We've selected:

  - Zircaloy for cladding
  - SS 304 and SS 316 for internal structures
  - B_4C for control rods

  The **selection of materials** was verified based on their mechanical and corrosion performance under reactor operating conditions. Each material choice, such as SA-508 for the pressure vessel and Zircaloy for fuel cladding, was validated against industry standards for neutron interaction.

7.7. Fluid flow Verification

- The **coolant flow cross-sectional area and density** were used to verify that the velocity of 3.24 m/s is practical and falls within design constraints.

7.8. Structural Compliance

- Tolerances used:

  - Fuel rods/pellets: ±0.001 mm
  - Structural parts: up to ±0.5 mm
  - Control rods: ±1 mm

- **Dimensional tolerances** of ±0.001 mm to ±0.5 mm were specified based on the criticality of the components, ensuring compatibility with standard manufacturing and safety practices.

8. Challenges and Learnings

8.1. Balancing Power Output and Size

Challenge: Designing a compact reactor core capable of generating 100 MW of thermal power posed a challenge. Increasing power output often demands more fuel or larger assemblies, but a bigger core becomes difficult to manufacture, transport, and control.
Learning: We learned how variations in the number of fuel assemblies, pellet dimensions, and fuel enrichment levels influence both the power output and core reactivity. These trade-offs helped us understand that higher power density, while beneficial for compactness, demands stricter thermal and safety margins to prevent overheating.

8.2. Material Selection for High Performance and Safety

Challenge: Selecting suitable materials for cladding, grids, and guide tubes was critical, as they must withstand high temperature, pressure, and neutron flux for extended periods. Materials like Zircaloy are popular but require thorough evaluation in terms of corrosion resistance, neutron absorption cross-section, and mechanical stability.
Learning: We compared advanced materials such as M5 alloy, stainless steel, and Inconel, evaluating their performance in nuclear environments. This taught us how material properties directly influence the safety, lifetime, and efficiency of the reactor core.

8.3. Fuel Assembly Design

Challenge: Each fuel assembly's geometry—including the number of fuel rods, pitch, and control rod integration—directly affects the neutronics and thermal performance. Our design incorporated 21 fuel assemblies with 297 rods each, requiring optimized spacing for uniform power generation and efficient coolant flow.
Learning: Through 3D modeling and spatial analysis, we understood the influence of rod pitch, diameter, and arrangement on moderation ratio and heat transfer characteristics.

8.4. Thermal Management

Challenge: Effective heat removal was essential to prevent local hot spots and ensure the cladding did not exceed safety limits.
Learning: We performed heat generation calculations at the rod level, followed by radial and axial heat spread estimates. This helped us understand the role of parameters like cladding thickness, pellet radius, and fuel thermal conductivity in maintaining safe operating temperatures.

8.5. Applying Systems Engineering Principles

Challenge: Translating abstract systems engineering concepts such as "reliability" and "compactness" into quantifiable design parameters was a non-trivial task.
Learning: Guided by the NASA Systems Engineering Handbook, we:

- Identified stakeholder needs like modularity, safety, and maintainability.
- Decomposed the core into functional subsystems (e.g., fuel rods, cladding, control rod channels).
- Developed functional block diagrams to relate subsystems to overall performance.
- Ensured traceability by linking every design decision back to a defined requirement.

8.6. Documentation and Communication

Challenge: Coordinating among team members while tracking calculations, assumptions, and iterations was challenging. Precise communication was vital for ensuring design consistency and clarity.
Learning: We developed clear part descriptions and used detailed CAD annotations and exploded views to communicate complex geometry. We also focused on defining **manufacturing tolerances** where necessary, particularly in fuel rod spacing and grid supports, to ensure assembly precision and safety under operational conditions.

9. Future Aspects

9.1. Integration with Full Plant Systems

Although our design focused solely on the reactor core, future work could extend to integrating it with the broader plant infrastructure—such as the primary coolant loop, steam generator, and turbine. Ensuring thermal compatibility in terms of heat transfer rates, coolant flow, and operating pressure is essential. The core's pressure boundary and fuel lifespan must also align with the full system's performance and safety requirements.

9.2. Neutronics and Thermal Simulation

Advanced simulation tools can significantly refine the design. Future iterations may use Monte Carlo-based neutronics codes like `OpenMC` or `MCNP` to model neutron flux and power distribution more accurately. Coupling these with thermal-hydraulic solvers such as `ANSYS Fluent` or `COMSOL Multiphysics` would help validate the heat removal capabilities under both steady-state and transient conditions.

9.3. Core Optimization

With a preliminary layout established, future work can aim to enhance:

- **Fuel burnup:** Extract more energy from each fuel assembly before needing replacement.
- **Fuel loading patterns:** Place higher enriched fuel at the center and lower at the periphery to flatten power distribution.
- **Control rod design:** Optimize location and movement to regulate reactivity with minimal power distortion.

9.4. Modular Manufacturing and Deployment

A key strength of SMRs lies in factory-based manufacturing. Future efforts can focus on:

- Standardizing components for repeatability and ease of assembly.
- Designing within size and weight constraints for road or rail transport.
- Exploring sub-assembly or cartridge-based approaches to simplify onsite deployment and reduce construction time.

9.5. Safety and Accident Tolerance

Next steps include evaluating the core's response under accident scenarios:

- Analyzing passive shutdown strategies such as gravity-driven control rods.
- Simulating loss-of-coolant accidents and verifying thermal limits.
- Exploring the use of accident-tolerant fuel (ATF) and passive cooling technologies to enhance inherent safety.

10. Conclusion

In this project, we successfully designed a Small Modular Reactor (SMR) capable of delivering 30 MWe, using a structured systems engineering approach. From defining mission objectives to detailed core design and thermal analysis, each step was driven by safety, efficiency, and feasibility. The selection of a light water pressurized reactor, UO_2 fuel, and corrosion-resistant structural materials ensures operational reliability. Tolerances were carefully chosen to balance manufacturability with precision where critical. The design reflects India's growing need for clean, scalable nuclear energy. Overall, this work lays a strong foundation for deploying compact nuclear solutions to meet future energy demands.

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