A Bottom-Up Cost Estimation Tool for Nuclear Microreactors

INL/RPT-25-87273
Revision 0

U.S. Department of Energy—
Microreactor Program (MRP)

AUGUST 2025

Botros N. Hanna,
Khaldoon Al-Dawood,
Paul RM Seurin,
Reham Abdelnasser, and
Abdalla Abou-Jaoude

Idaho National Laboratory

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

INL/RPT-25-87273
Revision 0

A Bottom-Up Cost Estimation Tool for Nuclear Microreactors

Botros N. Hanna,
Khaldoon Al Dawood,
Paul RM Seurin,
Reham Abdelnasser, and
Abdalla Abou-Jaoude
Idaho National Laboratory

August 2025

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

The rising interest in nuclear microreactors has highlighted the need for comprehensive technoeconomic assessments. However, the scarcity of publicly available designs and cost data has posed significant challenges. To address this issue, the Microreactor Optimization Using Simulation and Economics (MOUSE) tool was developed.

MOUSE integrates nuclear microreactor design with reactor economics. The design calculations encompass core simulations using the OpenMC Monte Carlo Particle Transport Code, along with simplified balance-of-plant calculations. On the economic side, MOUSE provides detailed bottom-up cost estimates, calculating both the total capital cost and the levelized cost of energy for first-of-a-kind and Nth-of-a-kind microreactors. The cost estimation correlations are developed using data from the Microreactor Applications Research, Validation, and Evaluation (MARVEL) project and additional literature sources. MOUSE was released as an open-source tool on GitHub (MOUSE Tool). Figure 1shows the public release of MOUSE GitHub repository under “IdahoLabResearch.”

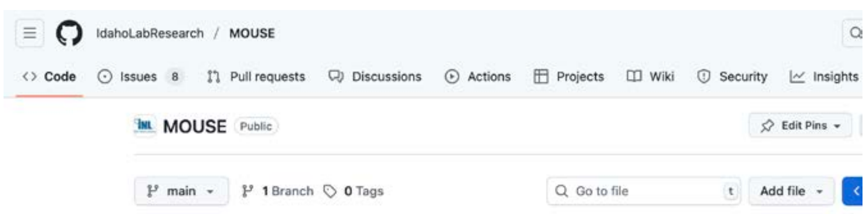

Figure 1. MOUSE GitHub repository.

By combining design calculations with cost equations, MOUSE enables users to evaluate the impact of various technological considerations, advanced moderators, design changes, material/fuel changes, and geometry modifications—as well as economic parameters such as interest rate and construction duration. This comprehensive framework can guide stakeholders toward technological solutions that enhance microreactor competitiveness. Additionally, powered by the Workflow and Template Toolkit for Simulation (WATTS) (Romano et al. 2022), MOUSE supports optimization studies, parametric analyses, and uncertainty calculations/propagation.

Currently, preconceptual designs of three microreactor types are included in MOUSE: a liquid-metal thermal microreactor (LTMR), a tristructural isotropic (TRISO)-fueled gas-cooled microreactor (GCMR), and a TRISO–fueled heat-pipe microreactor (HPMR). To showcase its ability, MOUSE was used to conduct detailed bottom-up cost estimates for the first-of-a-kind (FOAK) and Nth-of-a-kind (NOAK) units of the following microreactors:

- A 20-MWt LTMR that is built on the ongoing MARVEL demonstration at Idaho National Laboratory (INL)
- A 15-MWt GCMR that was designed to be more representative of the typical commercial microreactor

- A 7-MWt HPMR that was built on previous work (Choi et al. 2024).

The reader should note that these three designs and corresponding cost estimates are examples to demonstrate the MOUSE capability. The designs are pre-conceptual, the reactor designs were not fully optimized, and the cost estimates were developed with incomplete information. Nevertheless, the tool demonstrated the ability to perform relatively complex tradeoff analyses to evaluate different design options. In the future, the tool could be expanded to assess a broader variety of designs that may differ from the examples provided in this report.

The MOUSE tool can also be used to study how design choices affect economics. To demonstrate its capability, MOUSE was used to conduct parametric studies such as examining the economic impact of the reflector’s material and thickness, the moderator’s booster material and dimensions, fuel composition and enrichment, core size, and power level. Several insights were gained from these parametric studies.

ACKNOWLEDGMENTS

This report was authored at Idaho National Laboratory (INL) by Battelle Energy Alliance, LLC, under contract no. DE-AC07-05ID14517 with the U.S. Department of Energy (DOE). This work was prepared for the U.S. DOE through the Microreactor Program (MRP).

The authors would like to express their gratitude to Stacie L. Strain for helping with harvesting cost data from the MARVEL project and to recognize Chandrakanth Bolisetti, Gyutae Park, and Jakub Toman for helping with the cost estimation of the gas-cooled microreactor and to Mustafa Jaradat for providing the OpenMC code for the heat-pipe microreactor. The authors would also like to recognize Stefano Terlizzi and Alexander Huning for providing technical advice along with James E. Lainsbury for editorial and formatting edits.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

DOE	Department of Energy
FOAK	first of a kind
GCMR	gas-cooled microreactor
GN-COA	General Nuclear Code of Account
HALEU	high-assay low-enriched uranium
HPMR	heat-pipe microreactor
HX	heat exchanger
I&C	instrumentation and control
INL	Idaho National Laboratory
LCOE	levelized cost of energy
LTMR	liquid-metal thermal microreactor
MARVEL	Microreactor Applications Research, Validation, and Evaluation
MOUSE	Microreactor Optimization Using Simulation and Economics
MRP	Microreactor Program
NOAK	Nth-of-a-kind
O&M	operations and maintenance
OCC	overnight construction cost
PM/CM	project management / construction management
RVACS	reactor vessel auxiliary cooling system
SWU	separative work unit
TCI	total capital investment
TRIGA	Training, Research, Isotopes, General Atomics
TRISO	tristructural isotropic
WATTS	Workflow and Template Toolkit for Simulation
WEP	water-extended polyester

A Bottom-Up Cost Estimation Tool for Nuclear Microreactors

1. INTRODUCTION

There is growing interest in nuclear microreactors due to their numerous advantages. They can be deployed more quickly than traditional large-scale reactors, allowing for faster access to energy. Their smaller size and modular design result in lower initial capital costs, making them a more cost-effective option. Additionally, their compact size facilitates transportation to remote or off-grid locations, making them ideal for areas not connected to a centralized power grid. Moreover, deploying microreactors can provide valuable operational experience, helping to refine technologies and processes that can be applied to larger-scale nuclear projects in the future.

The rising interest in nuclear microreactors has highlighted the need for comprehensive technoeconomic assessments. However, the scarcity of publicly available designs and cost data has posed significant challenges. In previous work by the authors (Al-Dawood et al. 2025, Hanna et al. 2024), cost estimations for microreactors were developed. However, since these cost estimations are based on assumptions regarding design specification and economic parameters, a tool that can flexibly estimate the cost based on design changes and the adoption of several technologies and materials was needed. This report introduces this cost estimation tool: Microreactor Optimization Using Simulation and Economics (MOUSE). MOUSE has been developed with the following goals in mind:

- To generalize the cost estimations developed in previous work to encompass additional types of microreactor designs, specifically tristructural isotropic (TRISO)–fueled, gas-cooled variants.
- To quantify the effects of different technology considerations (e.g., heat-pipe-based designs, advanced moderator) that are supported by the Microreactor Program's (MRP's) research and development efforts.
- To include multiple microreactor designs and extensive cost data in a single tool that stakeholders can leverage.
- To develop a holistic framework to guide the MRP and stakeholders toward technological solutions that enhance microreactor competitiveness.
- To enable cost uncertainty quantification, parametric studies, and economic optimization.

The scope of this work builds on the Fiscal Year (FY)-24 framework for detailed microreactor cost estimation, which is based on MARVEL data. It generalizes the FY-24 framework to encompass additional types of microreactor designs, namely tristructural isotropic (TRISO)–fueled, gas-cooled variants. The framework will be leveraged to quantify the effect of different technology considerations, such as heat-pipe-based designs and advanced moderator, that are supported by the Microreactor Program's (MRP's) R&D efforts. Ultimately, the intent is to develop a holistic framework that can help guide the MRP and stakeholders to technological solutions that can drive microreactor competitiveness.

This work addresses the aforementioned scope by building on the existing FY-24 cost estimation framework, incorporating additional microreactor design types, and integrating extensive cost data. Specifically, MOUSE includes 3 types of microreactor including the tristructural isotropic (TRISO)–fueled gas-cooled microreactor and heat-pipe microreactor. MOUSE allows for flexible and comprehensive cost estimations based on various design changes and technology considerations. For example, MOUSE was used to conduct parametric studies such as examining the economic impact of the reflector's material and thickness, the moderator's booster material and dimensions, fuel composition and enrichment, core size, and power level. By including multiple microreactor designs and leveraging advanced simulation and economic optimization capabilities, MOUSE provides a robust tool for stakeholders. MOUSE has been released to the public on GitHub (MOUSE Tool). The structure of MOUSE is presented in Section 2, and the capability of MOUSE is illustrated by examples in Section 3.

2. MOUSE TOOL

MOUSE is a Python-based tool for the detailed cost estimation of microreactors. MOUSE integrates reactor design and economics, enabling users to assess the impact of various technological factors and economic parameters, helping stakeholders identify solutions to improve microreactor competitiveness. The main elements of MOUSE are depicted in Figure 2.

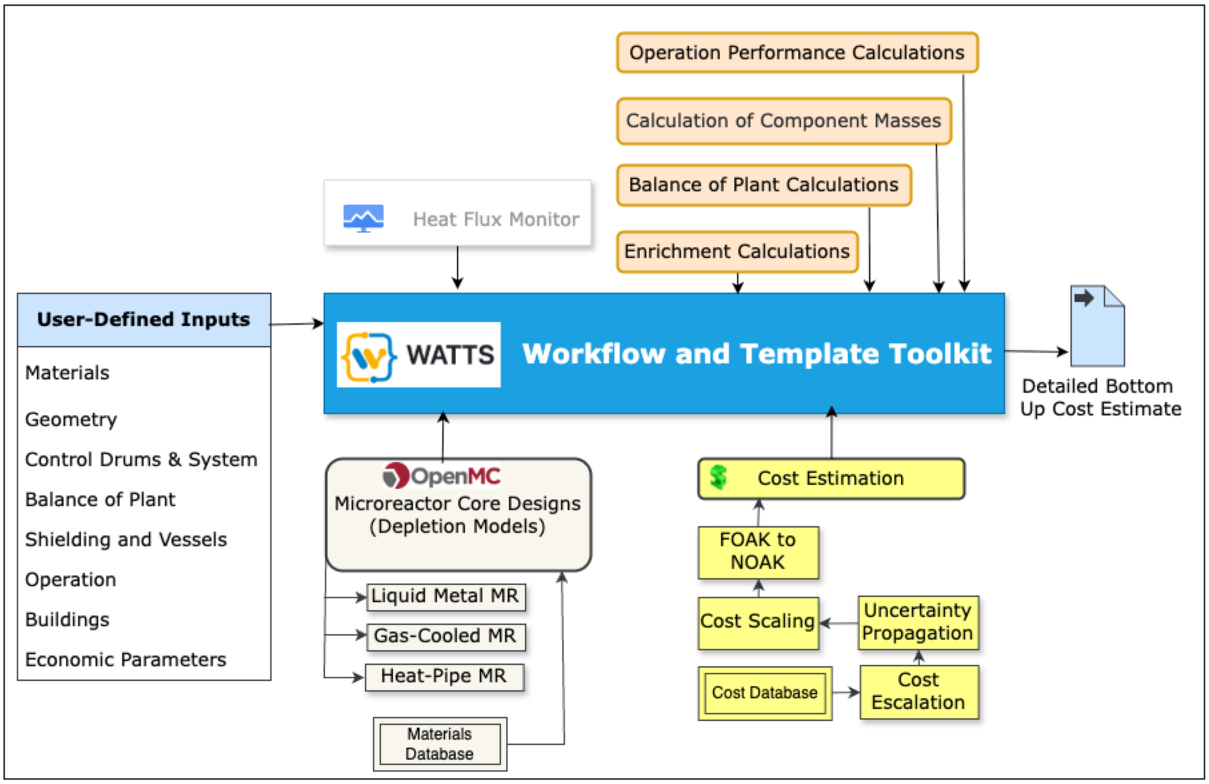

Figure 2. The MOUSE tool structure.

1. User-Defined Inputs

Users can modify design inputs or economic inputs such as:

- Overall system: reactor power (mwt), thermal efficiency (%), heat flux criteria
- Geometry: fuel pin radii, triso packing fraction, coolant channel radius, moderator booster radius, lattice pitch, rings per assembly, assemblies per core, core active height, reflector thickness, control drum dimensions
- Materials: fuel, enrichment, coolant, reflector, matrix material, moderator, moderator booster, control drum absorber/reflector, fuel pin materials
- Shielding: in/out vessel shield thickness, material, dimensions
- Vessels: vessel radius, thickness, materials, gaps between vessels

- Balance of plant: coolant inlet/outlet temperatures, compressor pressure ratio, pump efficiency
- Operation: operation mode, number of operators, plant lifetime, refueling period, number of emergency shutdowns per year, startup durations
- Buildings: dimensions of reactor, turbine, control, refueling, spent fuel, emergency, storage, radioactive waste buildings
- Economic parameters: interest rate, dollar escalation year, construction duration, debt to equity ratio.

2. OpenMC Microreactor Core Design

OpenMC is a neutronics code used to develop simplified 2D reactor designs for cost estimation purposes. It is crucial for cost estimation because the core design determines the fuel mass and lifetime, both of which affect the cost of microreactors. Additionally, the core design dictates the material requirements for each component, further impacting costs. Three reactor designs are included so far:

- Liquid-metal thermal microreactor (LTMR)
- Gas-cooled microreactor (GCMR)
- Heat-pipe microreactor (HPMR).

A materials database for the three reactors is developed so the user can easily change the materials. The three microreactor core OpenMC models are presented in Section 2.1. Note that 2D OpenMC models are used (instead of higher-fidelity computationally expensive 3D models) to reduce the simulation time since MOUSE is developed for parametric studies and optimization. To compensate for the inaccuracy of the 2D models, a correction factor is applied based on neutron non-leakage probability (see Section 2.1.4).

3. Other Design Calculations

Simplified calculations for the balance of plant, the operation performance, and the masses of all the components are performed to develop a complete cost estimation. These calculations are summarized in Section 2.2.

4. Cost Estimation

The cost estimation includes the following steps:

A. Developing a cost database
B. Escalating the cost for the same dollar year
C. Scaling the cost (based on component mass or reactor power or…)
D. Quantifying and propagating the cost uncertainty
E. Estimating the NOAK cost.

These steps are detailed in Section 2.3.

5. WATTS

MOUSE is powered by the Workflow and Template Toolkit for Simulation (WATTS) (Romano et al. 2022), developed by Argonne National Laboratory. It facilitates parametric studies by integrating various code components**.**

6. Output: Detailed Bottom-Up Cost Estimate

A detailed bottom-up cost estimate is presented, in this report, using the structure of the General Nuclear Code of Account (GN-COA), which is a structure for organizing the cost of nuclear reactors so the costs of several reactors can be compared.

2.1. Reactor Core Design Models

2.1.1. Liquid-Metal Thermal Microreactor (LTMR)

The LTMR is a 20-MWth compact design microreactor derived from the Microreactor Applications Research, Validation, and Evaluation (MARVEL) (Gerstner and Arafat 2023) project's reactor concept. The LTMR uses zirconium hydride (ZrH) as the moderator, UZrH metal as fuel (i.e., Training, Research, Isotopes, General Atomics [TRIGA] fuel), and sodium-potassium (NaK) eutectic as coolant. For more details on the LTMR design process and the parametric study, see Hanna et al. (2024). The resulting design is a hexagonal lattice reactor core with 12 rings of fuel/moderator pins. Figure 3 shows the fuel pins and moderator pins arranged in the hexagonal lattice core and surrounded by the control drums and the reflector. The control drums are graphite cylinders on which a layer of boron carbide (B_4C) neutron absorber has been mounted. The design specifications for the LTMR are summarized in Table 1.

2.1.2. Gas-Cooled Microreactor (GCMR)

The GCMR reactor core is a 15-MWth TRISO-fueled, helium (He)-cooled reactor that serves as a highly downsized high-temperature gas-cooled reactor. The GCMR is much larger than the LTMR, primarily due to its reliance on particle-based fuel. To further reduce the size of the GCMR core, a ZrH moderator booster was inserted between the TRISO fuel assemblies. Figure 4 shows the GCMR fuel assembly (TRISO compact fuel elements, coolant channels, moderator booster elements). Figure 5 shows the arrangement of the fuel assemblies in the reactor core, and Table 2 summarizes the design specifications for the GCMR. For more info on the reactor physics of the GCMR, see Al-Dawood et al. (2025).

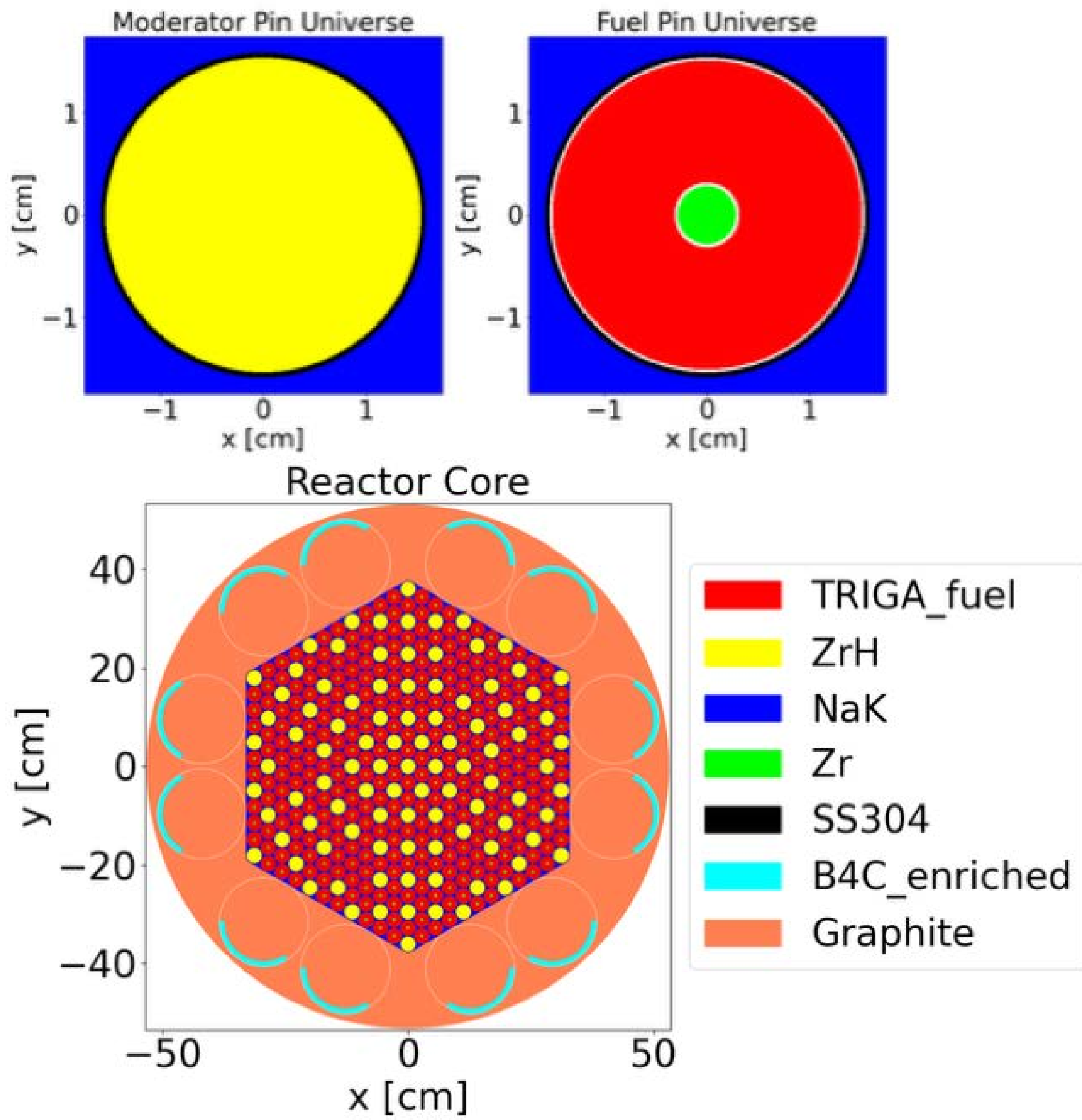

Figure 3. LTMR core OpenMC model. The fuel and moderator pins are shown at the top, and the reactor core (hexagonal assembly surrounded by 12 control drums and the graphite reflector) at the bottom.

Table 1. LTMR design specifications.

Parameter	Value	Units
Fuel	UzrH	
Enrichment	0.1975	
Proportion of Hydrogen to Zirconium Atoms	1.6	
Weight Ratio of Uranium to Total Fuel Weight	0.3	
Coolant	NaK	
Reflector	Graphite	
Moderator	ZrH	
Control Drum Absorber	B_4C enriched	
Control Drum Reflector	Graphite	
Heat Exchanger Material	SS316	
Fuel Pin Outer Radius	1.5875	cm
Moderator Pin Outer Radius	1.5875	cm
Pin Gap Distance	0.1	cm
Number of Rings per Assembly	12	
Reflector Thickness	14	cm
Hexagonal Lattice Radius	39.2	cm
Active Height	78.4	cm
Axial Reflector Thickness	14	cm
Total Number of Fuel Pins	300	
Total Number of Moderator Pins	97	
Moderator Mass	316	kg
Core Radius	53.2	cm
Drum Radius	9	cm
Drum Absorber Thickness	1	cm
Drum Height	106	cm
All Control Drums Mass	573	kg
Reflector Mass	331	kg
Axial Reflector Mass	212	kg
Power (MWt)	20	MWt
Thermal Efficiency	0.31	
Power MWe	6.2	MWe
Heat Flux	0.85	MW/m^2
Fuel Lifetime	1,963	days
Mass of U-235	67,539	grams
Mass of U-238	27,7942	grams

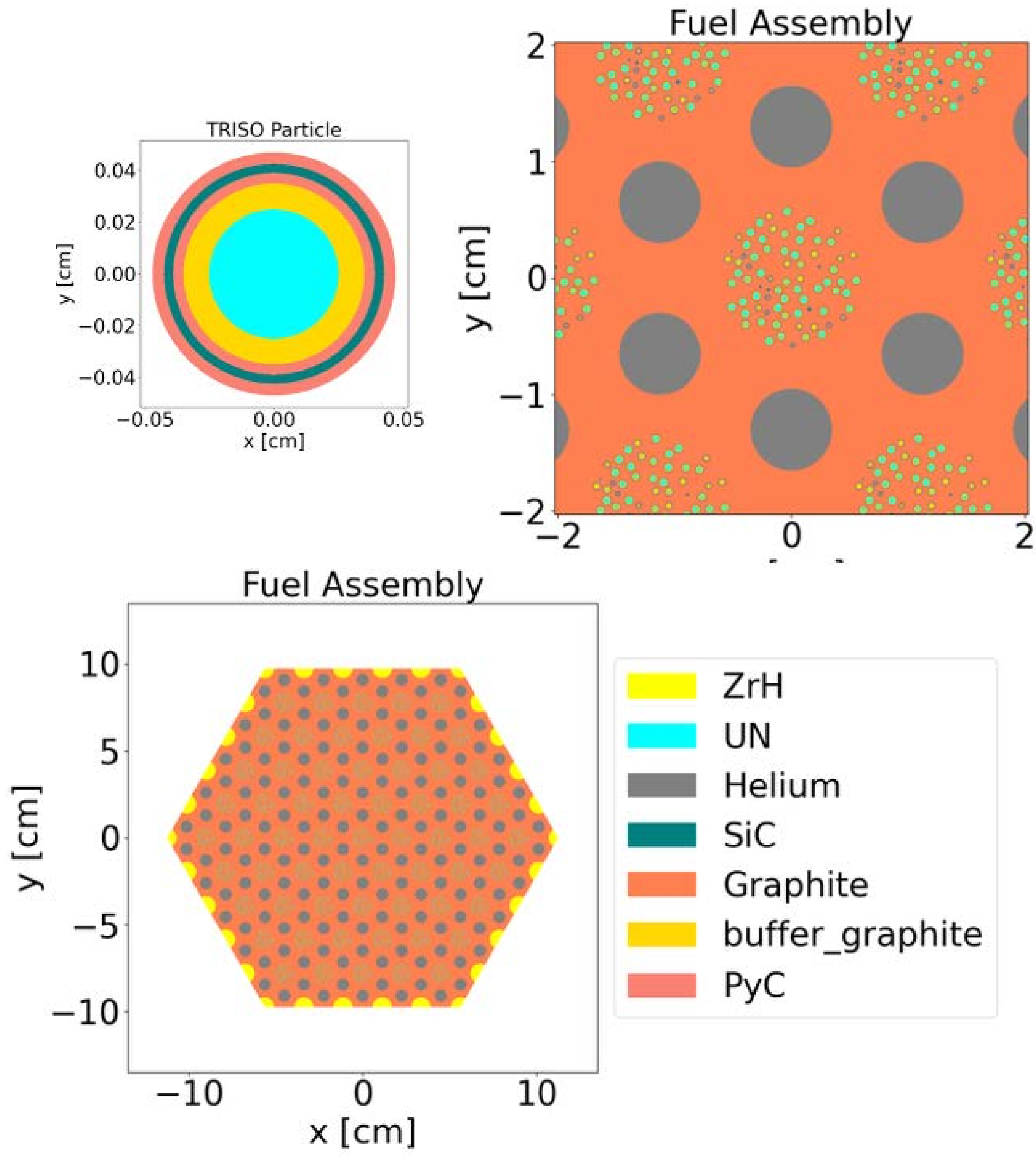

Figure 4. The TRISO-fueled GCMR fuel assembly. *Top left*: The composition of the TRISO particle. *Top right*: A zoomed-in view of the fuel assembly showing the fuel (TRISO particles) surrounded by the coolant (He) channels. *Bottom*: A full view of the fuel assembly with the moderator booster (ZrH) pins along the sides of the assembly. The background material within the TRISO particles is graphite.

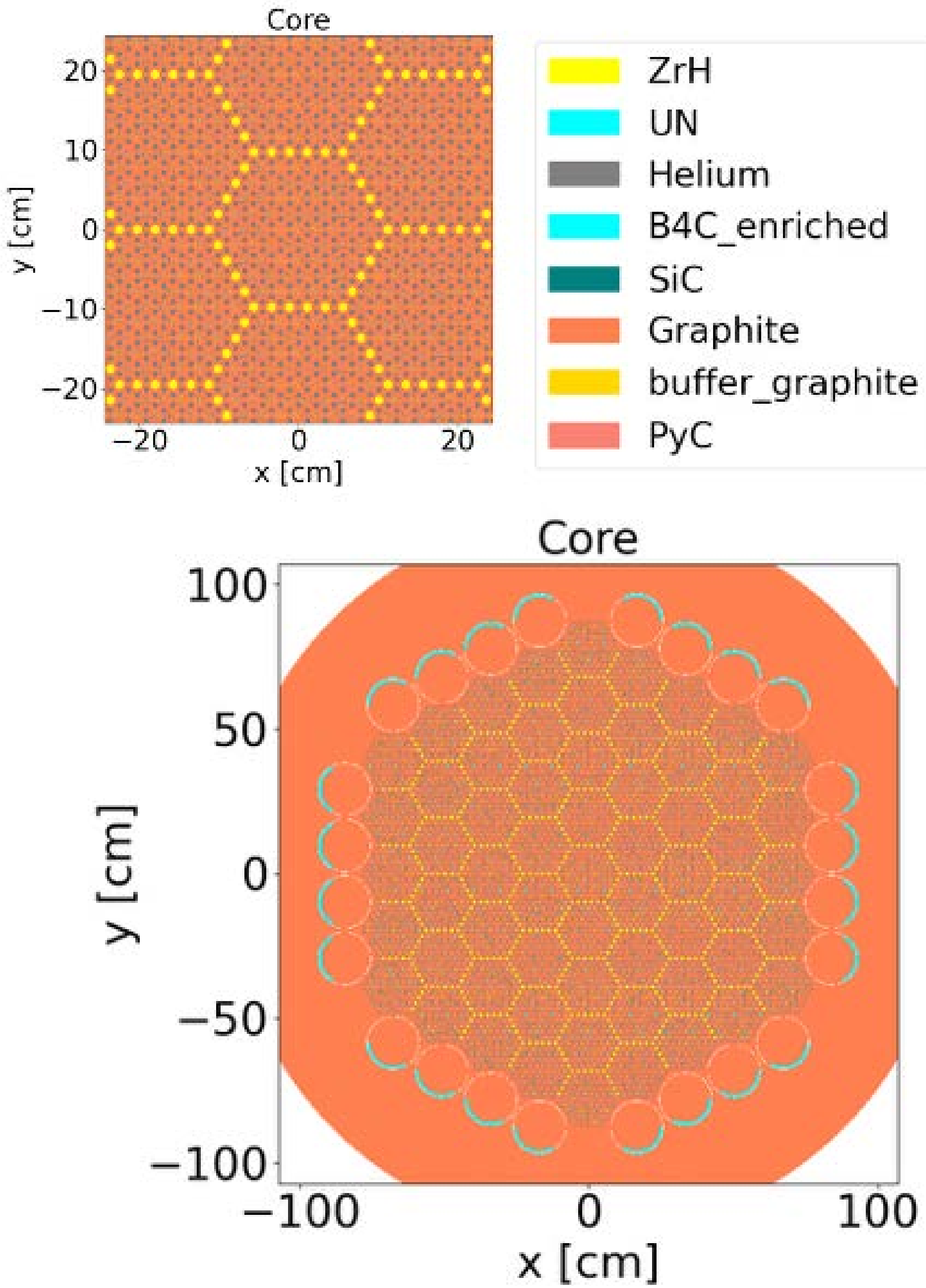

Figure 5. A zoomed-in view (*top*) and full view (*bottom*) of the GCMR core. Five assemblies are arranged along the side of the hexagonal core, which is surrounded by 24 control drums and the graphite reflector.

Table 2. GCMR design specifications.

Parameter	Value	Units
Fuel	TRISO UN	–
Enrichment	0.1975	–
Reflector	Graphite	–
Matrix Material	Graphite	–
Moderator	Graphite	–
Moderator Booster	ZrH	–
Coolant	Helium	–
Control Drum Absorber	B_4C enriched	–
Control Drum Reflector	Graphite	–
Heat Exchanger Material	SS316	–
TRISO Layers Materials (from the inside to the outside)	Uranium Nitride, Graphite, Pyrolytic Carbon, Silicon Carbide, Pyrolytic Carbon	
TRISO Particle Outer Radius	0.05	cm
Compact Fuel Radius	0.62	cm
Packing Fraction	0.3	–
Coolant Channel Radius	0.35	cm
Moderator Booster Radius	0.55	cm
Assembly Lattice Pitch	2.25	cm
Number of the Assembly Rings	6	–
Number of the Core Rings	5	–
Assembly Flat-to-Flat (FTF)	19.5	cm
Reflector Thickness	27.4	cm
Axial Reflector Thickness	27.4	cm
Core Radius	124.8	cm
Active Height	250	cm
Drum Radius	9	cm
Drum Absorber Thickness	1	cm
Drum Height	305	cm
Drum Count	24	–
All Control Drums Mass	3,270	–
Reflector Mass	9,683	kg
Axial Reflector Mass	4,559	kg
Moderator Mass	6,360	kg
Moderator Booster Mass	1,217	kg
Power MWt	15	MWt
Thermal Efficiency	0.4	–
Power MWe	6	MWe
Number of TRISO Particles per Compact Fuel	209,946	–
Total Number of TRISO Particles	1,165,410,246	–

Parameter	Value	Units
Heat Flux	0.02	MW/m^2
Fuel Lifetime	2648	Days
Mass U235	80,972	g
Mass U238	32,7919	g

2.1.3. Heat-Pipe Microreactor (HPMR)

The HPMR is a 7-MWth heat-pipe-cooled microreactor that is one of the most promising concepts due to the characteristics of heat pipes that passively extract heat from the core. Heat pipes are sealed stainless-steel or FeCrAl tubes that operate on the principle of phase change by transporting heat from the in-core evaporator section to the ex-core condenser through isothermal vapor/liquid internal flow. The advantages of HPMRs mainly arise from their compact size, the passive operation of heat pipes, and the elimination of intricate coolant pumping systems, which lead to simplifications in core design. The concept of HPMR was pioneered at Los Alamos National Laboratory (LANL) in the 1950s.

The HPMR design has a hexagonal reactor core lattice which is composed of 18 hexagonal assemblies with a central graphite monolith. Each assembly contains 72 cylindrical fuel compacts and 19 heat pipes drilled into the graphite monolith. The core is surrounded by 12 control drums with B_4C as the absorbing material.

The fuel composition for the HPMR consists of fuel compacts that contain TRISO particles with uranium dioxide (UO_2) kernels. Figure 6 shows 2D views of the HPMR core design generated with OpenMC, and Table 3 summarizes the HPMR design specifications.

The current OpenMC model is based on a 3D OpenMC model (Choi et al. 2024). Although the 3D model provides detailed and accurate calculations, performing full-core neutronics Monte Carlo simulations is computationally expensive and time-consuming, particularly for optimization studies and technoeconomic assessments. To enable efficient parametric studies and technoeconomic analysis within the MOUSE framework, a simplified 2D model was developed to reduce simulation time while preserving the key neutronic characteristics of the reactor.

The 2D model was built by simplifying the 3D homogenized model. The TRISO particles are homogenized by volume with the graphite matrix in the fuel compacts to save computational time. The axial top and bottom reflectors are removed, with the assumption of radial symmetry and periodic conditions along the axial direction. For more info on the HPMR OpenMC model, see Choi et al. (2024).

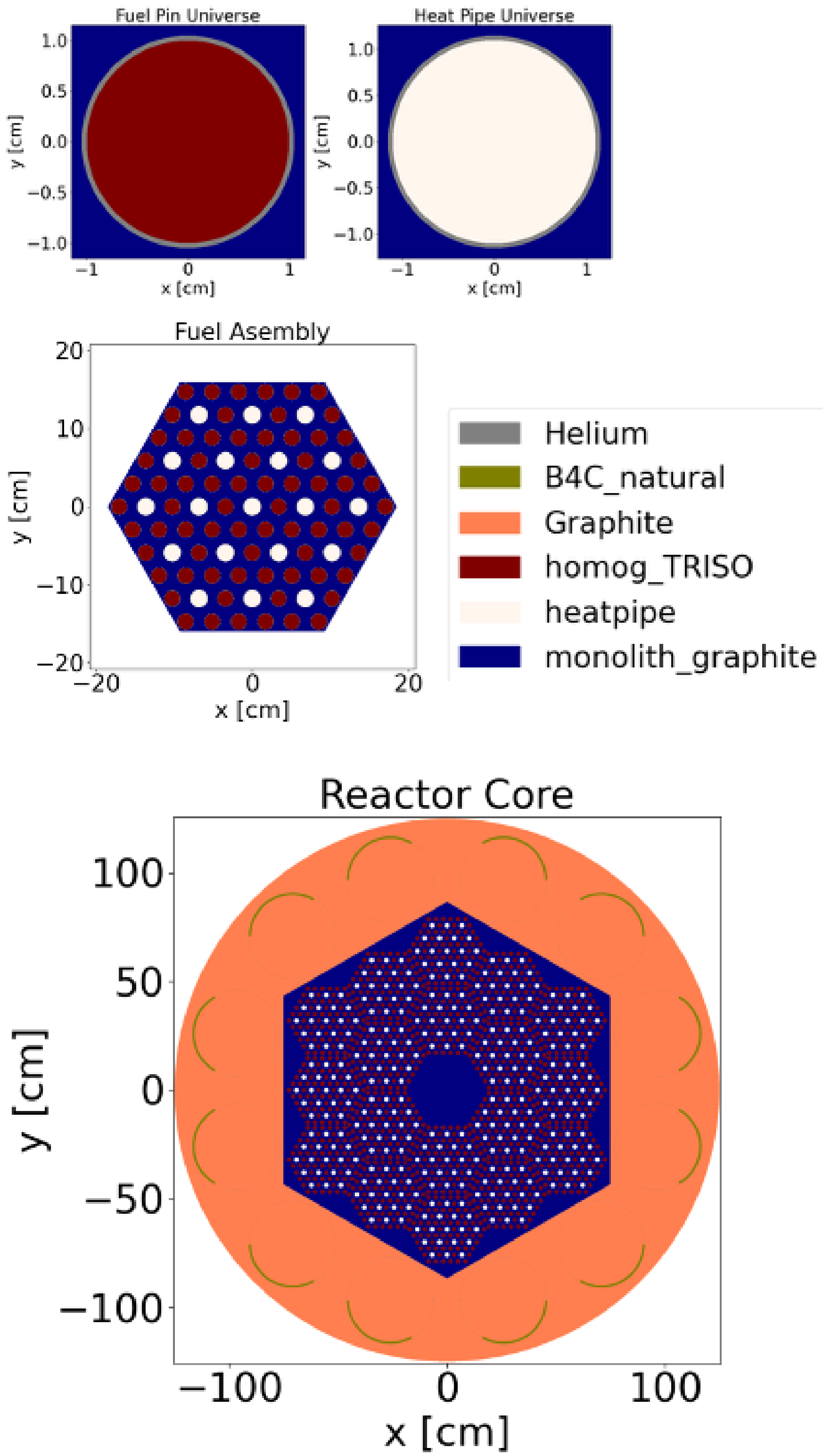

Figure 6. The HPMR reactor core. *Top*: The homogenized TRISO fuel (*left*) and the heat pipes (*right*), both surrounded by monolith graphite. *Middle*: The fuel assembly, including the TRISO fuel elements and the heat pipes. *Bottom*: The hexagonal reactor core surrounded by 12 drums and the reflector.

Table 3. HPMR design specifications.

Parameter	Value	Units
Fuel	Homogenized TRISO	–
Enrichment	0.19985	–
Reflector	Graphite	–
Moderator	Monolith graphite	–
Cooling Device	Heat pipe	–
Secondary Coolant	He	–
Control Drum Absorber	B_4C natural	–
Control Drum Reflector	Graphite	–
Fuel Pin Outer Radii	1.05	cm
Heat Pipe Outer Radii	1.15	cm
Number of Rings per Assembly	6	–
Number of Rings per Core	3	–
Assembly Lattice Pitch	3.4	cm
Assembly Flat to Flat (FTF)	32	cm
Hexagonal Core Edge Length	86.6	cm
Reflector Thickness	50	cm
Core Radius	125	cm
Active Height	250	cm
Axial Reflector Thickness	50	cm
Fuel Pin Count per Assembly	72	–
Fuel Assemblies Count	18	–
Total Fuel Pin Count	1,296	–
Number of Heat Pipes per Assembly	19	–
Total Number of Heat Pipes	342	–
Drum Radius	20	cm
Drum Absorber Thickness	1	cm
Drum Height	250	cm
Drum Count	12	–
Control Drums Mass	6505	kg
Reflector Mass	12817	kg
Axial Reflector Mass	8342	kg
Moderator Mass	5296	kg
Power MWt	7	MWt
Thermal Efficiency	0.36	–
Power MWe	2.52	MWe
Heat Flux	0.03	MW/m^2
Fuel Lifetime	1,146	Days
Mass U-235	103,245	g
Mass U-238	418,654	g

2.1.4. Correcting the Fuel Lifetime for the 2D Models

The 2D models were created to reduce simulation time. Although the 2D representation significantly improves computational performance, it does not account for axial neutron leakage, which leads to an overestimation of the effective multiplication factor k_{eff} and fuel cycle length relative to a full 3D model.

To compensate for this, a correction factor is applied based on neutron non-leakage probability estimated from diffusion theory (buckling correction). In classical reactor physics, the multiplication factor is expressed as:

$$k_{eff} = k_\infty P_{NL}$$

where k_∞ is the infinite medium multiplication factor, and P_{NL} is the probability that neutrons remain in the system without leaking. In the 2D model, there is no axial leakage due to the absence of axial geometry. Therefore, the correction targets only the axial leakage, and the corrected multiplication factor is expressed as:

$$k_{eff}^{3D} = k_{eff}^{2D} \, P_{NL}^{axial}$$

where P_{NL}^{axial} is the axial non-leakage probability, estimated using one-group diffusion theory as:

$$P_{NL}^{axial} = \frac{1}{1 + B_z^2 \, L^2}$$

where:

- $B_z^2 = (\frac{p}{\widetilde{H}})^2$ is the axial geometric buckling, based on the extrapolated total height of reactor.
- $\widetilde{H}$ = H + 2D is the extrapolated height, based on the total height and diffusion coefficient.
- D is the diffusion coefficient, calculated from tallies cross sections in OpenMC.
- $L^2 = \frac{D}{\Sigma_a}$ is the diffusion area.
- Σ_a is the macroscopic absorption cross section, tallied in OpenMC.

The diffusion coefficient is computed using P_1 approximation, which assumes the angular neutron flux is nearly isotropic with a linear anisotropic component. This gives:

$$D = \frac{1}{\Sigma_{tr}}, \text{ where } \Sigma_{tr} = \Sigma_t - \bar{\mu}_o \Sigma_s$$

where:

- Σ_t is the macroscopic total cross section, tallied in OpenMC.
- Σ_s is the macroscopic scattering cross section, tallied in OpenMC.
- $\bar{\mu}_o$ is the average cosine of the scattering angle.

All cross sections are computed using an 11-energy group structure. This 11-group energy structure was chosen due to its prior use in various microreactors.

With these mentioned parameters tallied from OpenMC, the axial non-leakage probability P_{NL}^{axial} is calculated at each depletion time step. This value is then used to correct the 2D k_{eff} values to account for the missing axial leakage. Table 4 shows how the 2D OpenMC model results compare to those of the 3D model before and after the correction. The corrected 2D model closely matches the 3D model results in terms of fuel cycle length and multiplication factor k_{eff} with less computational time.

Table 4. A comparison between the 3D, 2D, corrected 2D OpenMC models

Parameter	3D Model	2D Model	Corrected 2D Model
Computational resource usage (CPU-hours)	1008 CPU-hours	6.1 CPU-hours	6.4 CPU-hours
k_{eff} (Beginning of life)	1.06051	1.11811	1.05255
k_{eff} (End of life)	0.98425	1.04284	0.98344
Fuel Lifetime (years)	3.05	6.3	3.01
Error in estimating the fuel lifetime compared to the 3D model.	0%	107%	1.3%

2.2. Other Design Calculations

This section includes a summary of the calculations estimated in MOUSE beyond the OpenMC simulation. These calculations had to be conducted as they are prerequisites for the cost estimation.

A. Enrichment Calculations

These calculations include estimating the separative work units and the mass of the natural uranium. These estimations, which are required for estimating the fuel costs, have been presented in previous work (Hanna et al. 2024).

B. Balance-of-Plant Calculations

Back-of-envelope calculations were calculated to estimate the following

- The mass of the heat exchanger (It is assumed that the reactor-generated power is transported from the coolant to the energy conversion system via a single printed circuit heat exchanger that is made from stainless steel.)
- The primary loop mass flow rate
- The compressor power (for the GCMR)
- The pump mechanical power (for the LTMR)

More information about these calculations is in previous work (Hanna et al. 2024, Al-Dawood et al. 2025). The balance-of-plant parameters are listed in Table 5, the temperatures of which were taken from Foster et al. (2025), Shirvan et al. (2023), and Al-Dawood et al. (2025)

Table 5. Balance-of-plant parameters.

Parameter	Values			Units
	LTMR	GCMR	HPMR	
Pump Isentropic Efficiency	0.8	–	–	–
Primary Loop Inlet Temperature	703	573	923	K
Primary Loop Outlet Temperature	793	823	923	K
Secondary Loop Inlet Temperature	668	563	573	K
Secondary Loop Outlet Temperature	768	773	903	K
Primary Heat Exchanger Mass	5,208	1,567	543	kg
Primary Pump Mechanical Power	174	NA	NA	kW
Compressor Pressure Ratio	NA	4	NA	
Compressor Isentropic Efficiency	NA	0.8	NA	
Compressor Power	NA	108	NA	kW

C. Shielding Calculations

Significant uncertainty remains as to the ultimate shielding requirements for microreactors. For instance, the shielding requirements for microreactor concepts envisioned to be highly mobile would likely focus on transportation limitations, while those for less mobile reactors would likely focus on meeting more traditional regulations. Similar to the MARVEL's shielding configuration, borated water-extended polyester (B-WEP) shielding is implemented outside the reactor to achieve the required dose rate limit of 0.5 mrem/hr at 30 cm above the concrete pit structure 90 days after reactor shutdown. This limit was selected based on the recommendation of the MARVEL project (Gerstner and Arafat 2023)

The shielding calculations were performed ((Al-Dawood 2025) for a 20 MWt LTMR and a 15 MWt GCMR, but MOUSE does not yet model how changes in several design parameters affect shielding thickness.

D. Reactor Vessels

Based on previous work (Al-Dawood et al. 2025) for the reactor layout, it is assumed that there are multiple vessels around the reactor:

- The reactor inner vessel
- The guard vessel, for the LTMR, to prevent the release of sodium in case of leakage or failure
- Two vessels that comprise the reactor vessel auxiliary cooling system (RVACS).

The estimated masses of the vessels are provided in Table 6.

Table 6. Masses of vessels of the LTMR, CGMR, and HPMR.

Parameter	Values			Units
	LTMR	GCMR	HPMR	
Vessel Mass	642	3131	2972	kg
Guard Vessel Mass	340	NA	NA	kg
Cooling Vessel Mass	375	1,421	1,572	kg
Intake Vessel Mass	397	1,477	1,633	kg

E. Operation Performance and Maintenance Calculations

In MOUSE, the user can select the operation mode to be "autonomous" or "non-autonomous." A specific number of operators must be present in the control room 24/7 for non-autonomous mode, while the autonomous mode assumes that the reactors are monitored remotely and operators are required on-site only for an emergency or shutdown. The operation mode selection impacts cost. Also, the capacity factor estimate depends on the refueling period, the average number of emergency shutdowns per year, and the startup duration after each anticipated or unanticipated shutdown.

Maintenance costs will depend on how often each component is replaced. Although the exact replacement frequency is unknown, we assume that the main components (such as the vessels, reflector, moderator, and control drums) are replaced approximately every 10 years. This corresponds to a number of fuel cycles that together total close to 10 years. For example, if the fuel cycle is 3 years, the components would be replaced every 3 fuel cycles (roughly 9 years) since the replacement is assumed to be done when the reactor is shut down for refueling. This assumption is based on the replacement timeline for the Advanced Test Reactor (ATR).[a] Table 7 lists the baseline operation parameters used in the baseline cost estimation.

Table 7. Operation parameters for the baseline cost estimation.

Operation Mode	Autonomous
Number of Operators (required for an emergency or refueling)	2
Levelization Period (years)	60
Refueling Period	7
Number of Emergency Shutdowns per Year	0.2
Startup Duration after Refueling (days)	2
Startup Duration after Emergency Shutdown (days)	14
Number of Reactors Monitored per Operator	10
Number of Security Staff Per Shift	1

For the maintenance cost corresponding to the other components, an annual cost of 1–3% (relative to the direct cost) is assumed.

F. Plant Layout (Buildings)

To estimate the cost of site preparation and yard work, it is necessary to have a model for the plant layout and the included buildings. A simple plant layout was developed in previous work (Hanna et al. 2024, Al-Dawood et al. 2025). Also, CAD models from other projects that focused on the mass production of microreactors were used to estimate the dimensions of several reactor buildings. Currently, it is assumed that the dimensions of these buildings are insensitive to reactor type or design. Estimating these dimensions enables the cost estimations of several sorts of buildings that may be included in the microreactor plant. Currently, MOUSE enables concrete volumes to be estimated and hence the costs of the following buildings (if they exist):

- Reactor building
- Main function buildings
  - Energy conversion (turbine) building
  - Control building
  - Integrated heat exchanger building
- Buildings that support main functions
  - Refueling building
  - Spent fuel building
  - Emergency building
- Supply chain building
  - Storage building
  - Radwaste building.

[a] https://inl.gov/advanced-test-reactor/

2.3. Cost Estimation

2.3.1. Cost Database

A database was developed and included in MOUSE. The cost data were collected from several sources including the MARVEL project and open literature. Most of the cost data were fixed costs (independent of the design) such as licensing costs or unit costs ($/kg or $/acres, etc.). Table 8 summarizes both fixed and unit costs, some of which are not included in Table 8, such as:

- The cost of additional fuel, which is estimated based on fuel lifetime
- The decommissioning and the financing costs, which are based on specific a formula from Abou-Jaoude et al. (2024)
- The cost of maintenance, which is proportional to the CAPEX (Al-Dawood et al. 2025) and depends on the frequency of components being replaced
- The indirect costs, which are dependent on the CAPEX (see Al-Dawood et al. 2025).

Table 8. Cost database in MOUSE from several sources. The accounts are organized hierarchically and color coded by level.

Account		**Fixed Cost ($)**	**Unit Cost**		**Scaling Variable**		**Dollar Year**	**Cost Type**	**Ref**
10	**Capitalized Pre-Construction Costs**	–	–	–	–	–	–	–	–
11	Land Cost	–	3,800	$/acres	Land Area	acres	2022	General	Abou-Jaoude et al. 2024
12	Site Permits	–	10,030	$/MWe	Power MWe	MWe	2022	Labor	
13	Plant Licensing	27,025,000	–	–	–	–	2024	Labor	Nuclear Regulatory Commission n.d., Zisk 2025
14	Plant Permits	3,000,000	–	–	–	–	2009	Labor	Gandrik et al. 2011
15	Plant Studies	5,210,451	–	–	–	–	2024	Labor	MARVEL Project
20	**Capitalized Direct Costs**	–	–	–	–	–	–	–	–
21	Structures and Improvements	–	–	–	–	–	–	–	–
211	Site Preparation / Yard Work	–	–	–	–	–	–	–	–
211.1	Cleaning and Grubbing	–	5,863	$/acres	Land Area	acres	2024	Lab and Equip.	Delene 1993, GORDIAN 2024
211.2	Stripping Topsoil	–	3,412	$/acres	Land Area	acres	2024	Lab and Equip.	
211.3	Excavation	–	32	$/m^3	Excavation Volume	m^3	2024	Lab and Equip.	
212	Reactor Island Civil Structures	–	–	–	–	–	–	–	–
212.1	Reactor Building Slab Roof	–	1,836	$/m^3	Reactor Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	Delene 1993, GORDIAN 2024
212.2	Reactor Building Basement	–	1,444	$/m^3	Reactor Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
212.3	Reactor Building Walls	–	1,103	$/m^3	Reactor Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
212.4	Reactor Building Liner	–	6,492	$/m^2	Reactor Building Superstructure Area	m^2	2018	Lab and Mat. and Equip.	Stewart 2022
212.5	Reactor Building HVAC	–	1,732	$/MWt	Power MWt	MWt	2018	Lab and Mat. and Equip.	
213	Main Function Buildings	–	–	–	–	–	–	–	–
213.1	Energy Conversion Building	–	–	–	–	–	–	–	–

213.11	Energy Conversion Building Slab Roof	–	1,200	$/m^3	Turbine Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	Gordian 2024
213.12	Energy Conversion Building Basement	–	944	$/m^3	Turbine Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
213.13	Energy Conversion Building Walls	–	721	$/m^3	Turbine Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
213.2	Control Building	–	–	–	–	–	–	–	–
213.21	Control Building Slab Roof	–	1,200	$/m^3	Control Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	GORDIAN 2024
213.22	Control Building Basement	–	944	$/m^3	Control Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
213.23	Control Building Walls	–	721	$/m^3	Control Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
213.3	Integrated Heat Exchanger Building	–	–	–	–	–	–	–	–
213.31	Integrated Heat Exchanger Building Slab Roof	–	1,200	$/m^3	Integrated Heat Exchanger Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	GORDIAN 2024
213.32	Integrated Heat Exchanger Building Basement	–	944	$/m^3	Integrated Heat Exchanger Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
213.33	Integrated Heat Exchanger Building Walls	–	721	$/m^3	Integrated Heat Exchanger Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
213.34	Integrated Heat Exchanger Building Liner	–	6,492	$/m^2	Integrated Heat Exchanger Building Superstructure Area	m^2	2018	Lab and Mat. and Equip.	Stewart and Shirvan 2021
214	Buildings to Support Main Function	–	–	–	–	–	–	–	–
214.1	Fuel Management Buildings	–	–	–	–	–	–	–	–
214.11	Refueling Building	–	–	–	–	–	–	–	–
214.111	Refueling Building Slab Roof	–	1,836	$/m^3	Refueling Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	Delene 1993, GORDIAN 2024
214.112	Refueling Building Basement	–	1,444	$/m^3	Refueling Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
214.113	Refueling Building Walls	–	1,103	$/m^3	Refueling Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
214.12	Spent Fuel Building	–	–	–	–	–	–	–	–
214.121	Spent Fuel Building Slab Roof	–	1,836	$/m^3	Spent Fuel Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	Delene 1993, GORDIAN 2024
214.122	Spent Fuel Building Basement	–	1,444	$/m^3	Spent Fuel Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
214.123	Spent Fuel Building Walls	–	1,103	$/m^3	Spent Fuel Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
214.7	Emergency and Startup Power Systems Building	–	–	–	–	–	–	–	–
214.71	Emergency Building	–	–	–	–	–	–	–	–
214.711	Emergency Building Slab Roof	–	1,200	$/m^3	Emergency Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	GORDIAN 2024
214.712	Emergency Building Basement	–	944	$/m^3	Emergency Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
214.713	Emergency Building Walls	–	721	$/m^3	Emergency Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
214.72	Diesel Generator	–	2,717,312	$/MWt	Power MWt	MWt	2024	Equipment	MARVEL Project
214.8	Auxiliary Building	–	–	–	–	–	–	–	–
214.81	Manipulator Building	–	–	–	–	–	–	–	–
214.811	Manipulator Building Slab Roof	–	1,200	$/m^3	Manipulator Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	GORDIAN 2024

214.812	Manipulator Building Basement	–	944	$/m^3	Manipulator Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
214.813	Manipulator Building Exterior Walls	–	721	$/m^3	Manipulator Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
215	Supply Chain Buildings	–	–	–	–	–	–	–	–
215.1	Storage Building	–	–	–	–	–	–	–	–
215.11	Storage Building Slab Roof	–	1,200	$/m^3	Storage Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	GORDIAN 2024
215.12	Storage Building Basement	–	944	$/m^3	Storage Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
215.13	Storage Building Walls	–	721	$/m^3	Storage Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
215.4	Radwaste Building	–	–	–	–	–	–	–	–
215.41	Radwaste Building Slab Roof	–	1,836	$/m^3	Radwaste Building Slab Roof Volume	m^3	2024	Lab and Mat. and Equip.	Delene 1993, GORDIAN 2024
215.42	Radwaste Building Basement	–	1,444	$/m^3	Radwaste Building Basement Volume	m^3	2024	Lab and Mat. and Equip.	
215.43	Radwaste Building Walls	–	1,103	$/m^3	Radwaste Building Exterior Walls Volume	m^3	2024	Lab and Mat. and Equip.	
22	Reactor System	–	–	–	–	–	–	–	–
221	Reactor Components	–	–	–	–	–	–	–	–
221.1	Reactor Vessel and Accessories	–	–	–	–	–	–	–	–
221.11	Reactor Support	–	312	$/kg	Total Vessels Mass	kg	2018	Lab and Mat. and Equip.	MARVEL Project
221.12	Outer Vessel Structure (Stainless Steel)	–	757	$/kg	Guard Vessel Mass	kg	2017	Lab and Mat. and Equip.	MARVEL Project
221.12	Outer Vessel Structure (Low-Alloy Steel)	–	154	$/kg	Guard Vessel Mass	–	2017	Lab and Mat. and Equip.	Ganda et al. 2019
221.12	Outer Vessel Structure (Incoloy)	–	444	$/kg	Guard Vessel Mass	–	2017	Lab and Mat. and Equip.	Ganda et al. 2019
221.13	Inner Vessel Structure (Stainless Steel)	3,369,445	1,768	$/kg	Vessel Mass	–	2017	Lab and Mat. and Equip.	MARVEL Project
221.13	Inner Vessel Structure (Low-Alloy Steel)	–	154	$/kg	Vessel Mass	–	2017	Lab and Mat. and Equip.	Ganda et al. 2019
221.13	Inner Vessel Structure (Incoloy)	–	444	$/kg	Vessel Mass	–	2017	Lab and Mat. and Equip.	Ganda et al. 2019
221.2	Reactor Control Devices	–	–	–	–	–	–	–	–
221.21	Reactivity Control System	–	–	–	–	–	–	–	–
221.211	Reactivity Control System Fabrication	–	347,890	$/Drum	Drum Count	–	2024	Lab and Mat. and Equip.	MARVEL Project
221.212	Installation	–	80,666	$/Drum	Drum Count	–	2024	Lab and Equip.	MARVEL Project
221.213	Control Drums Materials (Absorber): B_4C natural	–	14,286	$/kg	Control Drum Absorber Mass	kg	2024	Material	MARVEL Project
221.213	Control Drums Materials (Absorber): B_4C enriched	–	10,064	$/kg	Control Drum Absorber Mass	–	2023	Material	Prosser et al. 2024
221.214	Control Drums Materials (Reflector): Beryllium Oxide (BeO)	–	10,063	$/kg	Control Drum Reflector Mass	kg	2024	Material	MARVEL Project
221.214	Control Drums Materials	–	44,737	$/kg	Control Drum Reflector Mass	kg	2024	Material	MARVEL Project

	(Reflector): Beryllium (Be)								
221.214	Control Drums Materials (Reflector): Graphite	–	80	$/kg	Control Drum Reflector Mass	–	2022	Material	De Candido and Shirvan 2022
221.215	Control System Drive Mechanism	–	74,759	$/Drum	Drum Count	–	2023	Lab and Mat. and Equip.	MARVEL Project
221.3	Non-Fuel Core Internals	–	–	–	–	–	–	–	–
221.31	Reflector	–	–	–	–	–	–	–	–
221.311	Radial Reflector (BeO)	120,231	10,063	$/kg	Reflector Mass	kg	2024	Material	MARVEL Project
221.312	Axial Reflector (BeO)	120,231	10,063	$/kg	Axial Reflector Mass	kg	2024	Material	
221.311	Radial Reflector (Be)	–	44,737	$/kg	Reflector Mass	kg	2024	Material	
221.312	Axial Reflector (Be)	–	44,737	$/kg	Axial Reflector Mass	kg	2024	Material	
221.311	Radial Reflector (Graphite)	–	80	$/kg	Reflector Mass	–	2022	Material	De Candido and Shirvan 2022
221.312	Axial Reflector (Graphite)	–	80	$/kg	Axial Reflector Mass	–	2022	Material	De Candido and Shirvan 2022
221.311	Radial Reflector: Al_2O_3	–	134	$/kg	Reflector Mass	–	2017	Material	Ganda, Taiwo, and Kim 2018
221.312	Axial Reflector: Al_2O_3	–	134	$/kg	Axial Reflector Mass		2017	Material	
221.32	Shield	–	–	–	–	–	–	–	–
221.321	In-Vessel Shield Materials (B4C_natural)	647,991	14,286	$/kg	In-Vessel Shield Mass	kg	2024	Material	MARVEL Project
221.322	Out-The-Vessel Shield Materials (WEP)	–	20	$/kg	Out-of-Vessel Shield Mass	kg	2024	Material	
221.33	Moderator (Graphite)	–	80	$/kg	Moderator Mass	kg	2022	Material	De Candido and Shirvan 2022
221.33	Moderator (Monolith Graphite)		160	$/kg	Moderator Mass	kg	2022	Material	
221.33	Moderator (ZrH)		1,520	$/kg	Moderator Mass	kg	2017	Material	Abou-Jaoude et al. 2024
221.34	Moderator (Booster) (Graphite)		80	$/kg	Moderator Booster Mass	kg	2022	Material	De Candido and Shirvan 2022
221.34	Moderator (Booster) (ZrH)		1,520	$/kg	Moderator Booster Mass	kg	2017	Material	Abou-Jaoude et al. 2024
222	Main Heat Transport System	–	–	–	–	–	–	–	–
222.1	Fluid Circulation Drive System	–	–	–	–	–	–	–	–
222.11	Primary Pump	–	8,819	$/(kg.sec)	Primary Pump Mechanical Power	–	2003	Lab and Mat. and Equip.	Roosen 2003, Ganda et al. 2019
222.12	Secondary Pump	–	705	$/(kg.sec)	Secondary Pump Mechanical Power	–	2003	Lab and Mat. and Equip.	Roosen 2003
222.13	Compressor	–	7,100,000	Unitless	–	–	2020	Lab and Mat. and Equip.	Hoffman, Abou-Jaoude, and Foss 2020
222.2	Reactor Heat Transfer Piping System (regular piping)	–	20,000	$/MWe	Power MWe		2017	Equipment	Ganda et al. 2019
222.2	Reactor Heat Transfer Piping System (heat pipes)	–	10,000	$/heat pipe	Number of Heat Pipes		2017	Equipment	Abou-Jaoude et al. 2021
222.3	Heat Exchangers	–	–	–	–	–	–	–	–
222.31	Primary Heat Exchanger (SS316)	–	50	$/kg	Primary HX Mass	kg	2004	Equipment	Gezelius 2004
222.31	Primary Heat Exchanger (Incoloy 800H)	–	120	$/kg	Primary HX Mass	kg	2013	Equipment	Yoon, Sabharwall, and Kim 2013
222.32	Secondary Heat Exchanger (SS316)	–	50	$/kg	Secondary HX Mass	kg	2004	Equipment	Gezelius 2004
222.32	Secondary Heat Exchanger (Incoloy 800H)	–	120	$/kg	Secondary HX Mass	kg	2013	Equipment	Yoon, Sabharwall, and Kim 2013

222.5	Initial Coolant Inventory (Helium)	–	170	$/kg	On-site Coolant Inventory	kg	2024	Material	De Losada 2024
222.5	Initial Coolant Inventory (NaK)	–	118	$/kg	On-site Coolant Inventory	kg	2023	Material	MARVEL Project
222.6	Integrated Heat Transfer Vessel	–	–	–	–	–	–	–	–
222.61	Integrated Heat Transfer Vessel		50	$/kg	Integrated Heat Transfer Vessel Mass	kg	2004	Lab and Mat. and Equip.	Gezelius 2004
222.62	Integrated Heat Transfer System Support		**8**	$/kg	Integrated Heat Transfer Vessel Mass	kg	2018	Lab and Mat. and Equip.	
223	Safety Systems	–	–	–	–	–	–	–	–
223.2	Reactor Cavity Cooling System (RVACS)	–	–	–	–	–	–	–	–
223.21	RVACS (Cooling Vessel)	–	**757**	$/kg	Cooling Vessel Mass	–	2017	Lab and Mat. and Equip.	Ganda, Taiwo, and Kim 2018
223.22	RVACS (Intake Vessel)	–	**757**	$/kg	Intake Vessel Mass	–	2017	Lab and Mat. and Equip.	
226	Other Reactor Plant Equipment (based on MARVEL)	456,297	–	–	–	–	2024	Equipment	MARVEL Project
226	Other Reactor Plant Equipment (Helium purification)	–	118,208	Unitless	Primary Loop Mass Flow Rate	kg/s	2023	Lab and Mat. and Equip.	United Engineers and Constructors 1980
227	Reactor Instrumentation and Control (I&C)	8,500,000	–	–	–	–	2023	Lab and Equip.	Shirvan et al. 2023
228	Reactor Plant Miscellaneous Items	30,960	–	–	–	–	2024	Lab and Mat. and Equip.	MARVEL Project
23	Energy Conversion System	–	–	–	–	–	–	–	–
232	Energy Applications	–	–	–	–	–	–	–	–
232.1	Electricity Generation Systems		12,504	$/kWe	Balance of plant Power kWe		2023	Lab and Mat. and Equip.	Hanna et al. 2024
236	Common Instrumentation & Controls	1,000,000	–	–	–	–	2023	Lab and Mat. and Equip.	Shirvan et al. 2023
24	Electrical Equipment	–	–	–	–	–	–	–	–
241	Switchgear	–	12,609	$/MWe	Power MWe	MWe	2018	Lab and Mat. and Equip.	Stewart and Shirvan 2022
242	Station Service Equipment	–	10,483	$/MWe	Power MWe	MWe	2018	Lab and Mat. and Equip.	
243	Switchboards	–	3,404	$/MWe	Power MWe	MWe	2018	Lab and Mat. and Equip.	
244	Protective Equipment	–	9,776	$/MWe	Power MWe	MWe	2018	Lab and Mat. and Equip.	
245	Electrical Structure & Wiring Container	–	52,721	$/MWe	Power MWe	MWe	2018	Lab and Mat. and Equip.	
246	Power & Control Wiring	–	39,872	$/MWe	Power MWe	MWe	2018	Lab and Mat. and Equip.	
25	Initial Fuel Inventory	–	–	–	–	–	–	–	–
251	First Core Mining	–	184	$/kg	Natural Uranium Mass	–	2022	Material	Abou-Jaoude et al. 2024
252	First Core Conversion	–	15.1	$/kg	Natural Uranium Mass	–	2022	Material	
253	First Core Enrichment[b]	–	184.2	$/SWU	SWU	–	2022	Material	
254	First Core Fuel Assembly Fabrication (UZrH Fuel)	–	1520	$/kg	Uranium Mass	–	2023	Material	

[b] The cost of uranium enrichment does not increase linearly with the number of Separative Work Units (SWU). Instead, there is a premium for achieving higher enrichment levels. Specifically, an SWU premium multiplier of 1.15 is applied when the enrichment level exceeds 10% (Dixon et al., 2017).

254	First Core Fuel Assembly Fabrication (UO_2)	–	250	\$/kg	Uranium Mass	–	2023	Material	
254	First Core Fuel Assembly Fabrication (TRISO)	–	10,000	\$/kg	Uranium Mass	–	2009	Material	
26	Miscellaneous Equipment (Cranes)	1,000,000	–	–	–	–	2021	Equipment	Abou-Jaoude et al. 2023
30	**Capitalized Indirect Services Cost**	–	–	–	–	–	–	–	–
33	Startup Costs	2,407,166	–	–	–	–	2024	Lab and Equip.	MARVEL Project
34	Shipping and Transportation Costs	832,641	–	–	–	–	2024	Lab and Equip.	
35	Engineering Services	620,314					2024	Labor	
36	PM/CM Services	416,959	–	–	–	–	2024	Labor	
40	**Capitalized Training Costs**		**–**	**–**	**–**	**–**	**–**	**–**	**–**
41	Staff Recruitment and Training	300,000	–	–	–	–	2024	Labor	Al-Dawood et al. 2025
70	**Annualized O&M Cost**	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**–**
71	O&M Staff	–	–	–	–	–	–	–	–
711	Operators	–	178,500	\$/FTE	Number of Operators		2024	Labor	De Candido et al. 2024
712	Remote Monitoring Technicians (for Autonomous Operation)	–	178,500	\$/FTE	Reactors Monitored per Operator	–	2024	Labor	
713	Security Staff	–	178,500	\$/FTE	Security Staff per Shift	–	2024	Labor	
72	Variable Non-Fuel Costs	–	–	–	–	–	–	–	–
721	Coolant (Helium)	–	170	\$/kg	Replacement Coolant Inventory	kg	2024	Material	De Losada 2024
721	Coolant (NaK)	–	118	\$/kg	Replacement Coolant Inventory	kg	2023	Material	MARVEL Project
73	Regulatory Costs	107,180	–	–	–	–	2024	Labor	Nuclear Regulatory Commission 2025
80	**Annualized Fuel Cost**	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**–**
81	Refueling Operations		178,500	\$/FTE	Number of Operators	–	2024	Labor	De Candido et al. 2024
83	Spent Fuel Management	–	–1	\$/MWeHour	Annual Electricity Production	–	2024	Lab and Mat. and Equip.	Abou-Jaoude et al. 2024

2.3.2. Cost Escalation

MOUSE includes inflation multipliers for materials, labor, and equipment to escalate the costs to any dollar year. The inflation multipliers are based on Abou-Jaoude et al. (2024). In Table 8, the “dollar year” and the “cost type” determine which inflation multiplier is used.

2.3.3. Uncertainty Propagation

The uncertainty of the fixed costs, unit costs, and the scaling exponents were incorporated and propagated. Most of the costs are assumed to be a Class-3 cost estimated with an error between -10% and +30%.

2.3.4. Cost Scaling

The cost is scaled, for each account, from the reference cost (e.g., from MARVEL) to the cost of the cost of interest, using the scaling variables in Table 8. For most of the accounts, the cost was scaled as follows:

$$C = C_{fixed} + C_{ref}\left(\frac{X}{X_{ref}}\right)^{n}$$

where C is the estimated cost, C_{fixed} is the fixed cost, C_{ref} is the reference cost, X is the scaling variable, X_{ref} is the reference value of this scaling variable, and n is the scaling exponent. The value of the scaling exponent is typically 1 if the scaling variable is the mass of any component, and it is around $0.6 - 0.8$ when the scaling variable is the thermal or electric power.

While that method was used to scale the cost for most of the accounts, some costs were scaled using specific scaling equations from the literature. These specific scaling equations were applied for the costs of the pumps, compressors, heat exchangers, and fuel enrichment.

2.3.5. FOAK to NOAK

It is expected that microreactor economic competitiveness will be improved through mass production. The cost reduction from the FOAK to the NOAK cost is typically represented by the learning rate equation:

$$\text{NOAK cost} = \text{FOAK cost} \times (1 - \text{LR})^{\log_2 N}$$

Based on previous work (Abou-Jaoude et al. 2023) on the mass production and factory fabrication of microreactors, the reduction in costs of different accounts and the corresponding learning rates were estimated. Table 9 details how the cost of each account is impacted. It is assumed that building more units will not significantly reduce some costs in Table 9 since they do not benefit from mass production or they are already mass produced. Also, based on Abou-Jaoude et al. (2023), the costs of on-site activities are not expected to be reduced as much as factory activities. For components in Table 9 made of beryllium (Be) or beryllium oxide (BeO), a huge cost reduction is expected based on comparing the cost of Be from MARVEL versus the ATR (Abou-Jaoude et al. 2021). Finally, when using the learning rate equation, it is assumed that there are no further costs after 100 reactor units have been built.

Table 9. The FOAK to NOAK cost reduction.

Account Titles	FOAK to NOAK Cost Reduction
Costs that are not expected to decrease significantly when building more units Land Cost, Permits, Plant Studies, Initial Coolant, First Core (Mining, Conversion, Enrichment), Staff Recruitment and Training (Operators, Technicians, Security), Coolant, Refueling, Spent Fuel Management.	None
On-site activities Site Preparation (Cleaning, Grubbing, Topsoil Stripping, Excavation), Building Construction (Slab Roof; Basement; Walls; Liner; Heating, Ventilation, and Air Conditioning [HVAC]), Energy Conversion Building, Control Building, Integrated Heat Exchanger Building, Refueling Building, Spent Fuel Building, Emergency Building, Manipulator Building, Storage Building, Radwaste Building, Startup, Shipping, Engineering, and Project Management / Construction Management (PM/CM) Services, Plant Licensing, Regulatory Costs	Cost is reduced assuming a learning rate of 8%
Reactor primary structure Reactor Support, Outer Vessel Structure, Inner Vessel Structure	Cost is reduced assuming a learning rate of 18%
Reactivity Control System Fabrication, Installation, Control System Drive Mechanism	Cost is reduced assuming a learning rate of 24%

Account Titles	FOAK to NOAK Cost Reduction
Control Drum Materials (Absorber, Reflector), Shield Materials (In Vessel, Out Vessel), Moderator (Booster), Pumps (Primary, Secondary), Compressor, Heat Transfer Systems (Reactor Piping, Primary Exchanger, Secondary Exchanger, Integrated Vessel, System Support), RVACS (Cooling, Intake), Reactor Plant Equipment, Instrumentation and Control (I&C), Miscellaneous Items (Cranes, Common I&C), First Core Fuel Assembly Fabrication.	Cost is reduced assuming a learning rate of 23%
Any components made of Be or BO	Cost is reduced assuming a learning rate of 40%

2.4. Opportunities for Enhancing MOUSE

MOUSE integrates reactor core design and economics, allowing for the cost of microreactors to be estimated and the economic impact of design changes to be assessed. However, significant room for improvement remains in several areas, including the following.

1. User Experience

MOUSE is a Python-based tool that may not suit all users. Therefore, a more user-friendly web-based app is being developed. However, there is a complexity versus usability tradeoff: a simpler web app will not have all the Python tool's capabilities.

2. Software Versatility

Currently, MOUSE includes models for an LTMR, a GCMR, and an HPMR. Other microreactor designs, such as light-water reactors and organic-cooled microreactors, are not included.

3. Accuracy

- The shielding calculations for the LTMR and GCMR were performed, but MOUSE does not yet model how changes in other design parameters affect shielding thickness.
- To ensure that the designs are realistic, other design parameters need to be checked, such as the peak heat flux, shutdown margin, transient limits, reactivity coefficients and passive heat removal capabilities
- Some costs were missing due to the lack of data (e.g., the cost of yttrium hydride).

3. MOUSE TOOL RESULTS

In this section, the results that can be obtained by MOUSE are presented to demonstrate its capability. Section 3.1 presents bottom-up cost estimates generated by MOUSE for three types of microreactors; these estimates include the uncertainty of the low-level costs propagated to the high-level figures of merit such as overnight construction cost (OCC) and levelized cost of energy (LCOE). For a microreactor to be "economic by design," the influence of design characteristics on the capital and LCOE should be accounted for, and MOUSE can also be used to study the impact of design characteristics on the economics, as shown in Section 3.2. Section 3.2 gives insight into the trade-offs in cost when the materials or dimensions of several components, such as the reflector, moderator, and fuel, are changed.

3.1. Baseline Costs

The results from using MOUSE to generate bottom-up cost estimates for a UzrH-fueled 20-MWt LTMR, a TRISO-fueled 15-MWt GCMR, and a TRISO-fueled 7-MWt HPMR for both the FOAK and NOAK reactors are presented in Table 10 and Table 11 respectively. The NOAK cost estimate was developed assuming that 100 units are built. The results in Table 10 and Table 11 are dependent on the design specifics and also sensitivity to the data in the cost database in MOUSE. However, based on these results, we can draw several conclusions.

- There are several accounts that are insensitive to reactor design such as pre-construction costs, training costs, and operations and maintenance (O&M) staff.
- The LCOE of the LTMR is significantly lower than that of the GCMR due to the high cost of the GCMR's TRISO fuel. Also, the low fuel density of the TRISO particles leads to the need for more fuel and an increase in reactor size, which also increase the cost.
- The HPMR has the highest LCOE compared to the LTMR and GCMR, which can be explained by the low power (7 MWt), the relatively short fuel lifetime (3 years), the high cost of the TRISO fuel, and the large amount of uranium (~30% more than the GCMR and 54% more than the LTMR). None of the designs have been optimized, so there is room to adjust the design and reduce the cost. However, it is also notable that Shirvan et al. (2023) estimated that the levelized cost of the fuel for the HPMR is two to three times higher than that of other microreactor types, and the cost of its major equipment is approximately twice that of other microreactor types as well.
- The cost differences between the three reactor types are more significant for the FOAK unit compared to the NOAK unit. For example, the LCOE for the FOAK LTMR is 25% cheaper compared to the GCMR, but it is only 6% cheaper when comparing the NOAK cost.

Table 10. Detailed bottom-up FOAK cost estimate for the UzrH-fueled 20-MWt LTMR, TRISO-fueled 15-MWt GCMR, and TRISO-fueled 7-MWt HPMR. The accounts are organized hierarchically and color coded by level. "Rel. std." denotes the relative standard deviation.

		20-MWt LTMR		**15-MWt GCMR**		**7-MWt HPMR**	
Account	**Account Title**	**FOAK Estimated Cost ($2024)**	**Rel. Std.**	**FOAK Estimated Cost ($2024)**	**Rel. Std.**	**FOAK Estimated Cost ($2024)**	**Rel. Std.**
10.00	Capitalized Pre-Construction Costs	37,700,000	10%	37,800,000	10%	37,900,000	11%
11.00	Land Cost	77,000	16%	78,000	15%	77,000	14%
12.00	Site Permits	71,000	17%	68,000	15%	29,000	16%
13.00	Plant Licensing	26,900,000	13%	26,900,000	12%	27,000,000	13%
14.00	Plant Permits	4,700,000	23%	4,900,000	22%	4,900,000	22%
15.00	Plant Studies	5,900,000	25%	5,900,000	22%	5,900,000	25%
20.00	Capitalized Direct Costs	100,000,000	19%	108,600,000	12%	85,600,000	10%
21.00	Structures and Improvements	14,500,000	43%	12,300,000	41%	8,100,000	36%
211.00	Site Preparation / Yard Work	190,000	11%	190,000	10%	190,000	11%
211.10	Cleaning and Grubbing	110,000	15%	110,000	15%	110,000	15%
211.20	Stripping Topsoil	64,000	15%	65,000	15%	66,000	15%
211.30	Excavation	14,000	14%	14,000	13%	14,000	15%

212.00	Reactor Island Civil Structures	1,700,000	22%	1,700,000	23%	1,700,000	25%
212.10	Reactor Building Slab Roof	190,000	15%	190,000	14%	180,000	16%
212.20	Reactor Building Basement	150,000	15%	150,000	14%	150,000	15%
212.30	Reactor Building Walls	150,000	15%	150,000	15%	150,000	14%
212.40	Reactor Building Liner	1,000,000	36%	1,100,000	34%	1,100,000	38%
212.50	Reactor Building HVAC	170,000	65%	140,000	63%	73,000	70%
213.00	Main Function Buildings	73,000	7%	73,000	6%	73,000	8%
213.10	Energy Conversion Building	49,000	9%	48,000	9%	48,000	10%
213.11	Energy Conversion Building Slab Roof	15,000	17%	15,000	15%	15,000	18%
213.12	Energy Conversion Building Basement	12,000	14%	12,000	15%	12,000	15%
213.13	Energy Conversion Building Walls	21,000	14%	22,000	14%	21,000	16%
213.20	Control Building	24,000	9%	24,000	9%	25,000	9%
213.21	Control Building Slab Roof	7,700	14%	7,500	15%	7,900	15%
213.22	Control Building Basement	5,900	14%	6,100	15%	5,900	15%
213.23	Control Building Walls	11,000	15%	11,000	15%	11,000	15%
214.00	Buildings to Support Main Function	12,500,000	51%	10,300,000	50%	6,100,000	46%
214.70	Emergency and Startup Power Systems Building	12,400,000	52%	10,300,000	50%	6,100,000	46%
214.72	Diesel Generator	12,400,000	52%	10,300,000	50%	6,100,000	46%
214.80	Auxiliary Building	36,000	9%	36,000	10%	36,000	9%
214.81	Manipulator Building	36,000	9%	36,000	10%	36,000	9%
214.81	Manipulator Building Slab Roof	6,000	16%	6,100	14%	6,200	14%
214.81	Manipulator Building Basement	18,000	14%	18,000	14%	17,000	16%
214.81	Manipulator Building Exterior Walls	12,000	17%	12,000	17%	12,000	17%
215.00	Supply Chain Buildings	39,000	10%	39,000	9%	40,000	11%
215.10	Storage Building	39,000	10%	39,000	9%	40,000	11%
215.11	Storage Building Slab Roof	15,000	15%	15,000	17%	15,000	18%
215.12	Storage Building Basement	12,000	16%	12,000	14%	12,000	19%
215.13	Storage Building Walls	12,000	14%	12,000	15%	12,000	16%
22.00	Reactor System	48,100,000	11%	56,100,000	7%	43,800,000	8%
221.00	Reactor Components	33,400,000	13%	35,600,000	7%	27,900,000	8%
221.10	Reactor Vessel and Accessories	8,300,000	14%	14,000,000	13%	13,900,000	14%
221.11	Reactor Support	810,000	17%	2,300,000	19%	2,300,000	17%
221.12	Outer Vessel Structure	490,000	19%	-	-	-	-
221.13	Inner Vessel Structure	7,000,000	17%	11,700,000	15%	11,600,000	16%
221.20	Reactor Control Devices	6,900,000	10%	16,700,000	8%	11,000,000	11%
221.21	Reactivity Control System	6,900,000	10%	16,700,000	8%	11,000,000	11%
221.21	Reactivity Control System Fabrication	4,300,000	16%	9,000,000	13%	4,500,000	16%
221.21	Installation	1,000,000	16%	2,100,000	15%	1,000,000	15%

221.21	Control Drums Materials (Absorber)	620,000	15%	3,400,000	16%	4,000,000	20%
221.21	Control Drums Materials (Reflector)	42,000	16%	250,000	16%	530,000	16%
221.22	Control System Drive Mechanism	960,000	13%	1,900,000	18%	990,000	16%
221.30	Non-Fuel Core Internals	18,200,000	25%	4,900,000	9%	3,000,000	9%
221.31	Reflector	44,000	11%	1,100,000	11%	1,800,000	11%
221.31	Radial Reflector	27,000	16%	790,000	15%	1,100,000	15%
221.31	Axial Reflector	17,000	14%	350,000	15%	710,000	17%
221.32	Shield	17,400,000	25%	330,000	22%	370,000	25%
221.32	In-Vessel Shield Materials	17,300,000	25%	-	-	-	-
221.32	Out-the-Vessel Shield Materials	77,000	17%	330,000	22%	370,000	25%
221.33	Moderator	760,000	16%	530,000	16%	860,000	15%
221.34	Moderator (Booster)	-	-	2,900,000	14%	-	-
222.00	Main Heat Transport System	3,600,000	27%	3,000,000	9%	2,300,000	52%
222.10	Fluid Circulation Drive System	1,800,000	54%	1,500,000	15%	-	-
222.11	Primary Pump	1,800,000	54%	-	-	-	-
222.13	Compressor	-	-	1,500,000	15%	-	-
222.20	Reactor Heat Transfer Piping System	190,000	14%	360,000	18%	1,900,000	63%
222.30	Heat Exchangers	640,000	17%	380,000	15%	340,000	16%
222.31	Primary Heat Exchanger	640,000	17%	380,000	15%	340,000	16%
222.50	Initial Coolant Inventory	910,000	16%	730,000	15%	73,000	15%
223.00	Safety Systems	870,000	11%	3,200,000	12%	3,600,000	10%
223.20	Reactor Cavity Cooling System (RVACS)	870,000	11%	3,200,000	12%	3,600,000	10%
223.21	RVACS (Cooling Vessel)	420,000	16%	1,600,000	19%	1,800,000	14%
223.22	RVACS (Intake Vessel)	450,000	16%	1,600,000	14%	1,800,000	16%
226.00	Other Reactor Plant Equipment	520,000	21%	4,700,000	45%	10,000,000	21%
227.00	Reactor Instrumentation and Control (I&C)	9,700,000	25%	9,600,000	21%	36,000	24%
228.00	Reactor Plant Miscellaneous Items	34,000	22%	34,000	24%	-	-
23.00	Energy Conversion System	20,600,000	80%	16,300,000	67%	9,000,000	63%
232.00	Energy Applications	19,400,000	85%	15,200,000	72%	7,900,000	71%
232.10	Electricity Generation Systems	19,400,000	85%	15,200,000	72%	7,900,000	71%
236.00	Common I&C	1,100,000	22%	1,100,000	23%	1,100,000	23%
24.00	Electrical Equipment	10,100,000	30%	10,000,000	29%	6,800,000	44%
241.00	Switchgear	910,000	49%	980,000	56%	560,000	54%
242.00	Station Service Equipment	870,000	59%	950,000	86%	540,000	87%
243.00	Switchboards	250,000	56%	300,000	50%	190,000	79%
244.00	Protective Equipment	790,000	56%	800,000	59%	510,000	84%
245.00	Electrical Structure & Wiring Container	4,200,000	52%	3,900,000	56%	2,900,000	83%
246.00	Power & Control Wiring	3,100,000	58%	3,000,000	53%	2,200,000	73%

25.00	Initial Fuel Inventory	5,300,000	16%	12,500,000	12%	16,400,000	13%
251.00	First Core Mining	2,800,000	15%	3,300,000	17%	4,100,000	14%
252.00	First Core Conversion	230,000	16%	260,000	14%	340,000	18%
253.00	First Core Enrichment	1,800,000	43%	1,700,000	48%	2,500,000	44%
254.00	First Core Fuel Assembly Fabrication	560,000	14%	7,300,000	15%	9,500,000	17%
26.00	Miscellaneous Equipment (Cranes)	1,400,000	20%	1,300,000	22%	1,400,000	24%
30.00	Capitalized Indirect Services Cost	12,000,000	18%	11,400,000	12%	9,600,000	11%
31.00	Factory & Field Indirect Costs	5,400,000	22%	5,500,000	15%	4,000,000	13%
32.00	Factory and Construction Supervision	1,700,000	59%	1,300,000	50%	750,000	41%
33.00	Startup Costs	2,700,000	22%	2,600,000	19%	2,700,000	23%
34.00	Shipping and Transportation Costs	950,000	24%	910,000	20%	970,000	25%
35.00	Engineering Services	720,000	25%	690,000	22%	710,000	24%
36.00	Project Management / Construction Management (PM/CM) Services	480,000	25%	490,000	22%	470,000	21%
40.00	Capitalized Training Costs	350,000	21%	330,000	21%	340,000	22%
41.00	Staff Recruitment and Training	350,000	21%	330,000	21%	340,000	22%
60.00	Capitalized Financial Costs	2,600,000	14%	2,700,000	10%	2,300,000	8%
62.00	Interest	2,600,000	14%	2,700,000	10%	2,300,000	8%
70.00	Annualized Operations and Maintenance (O&M) Cost	5,600,000	7%	7,300,000	6%	5,700,000	7%
71.00	O&M Staff	1,100,000	13%	1,100,000	13%	1,100,000	15%
711.00	Operators	6,400	19%	6,100	16%	6,700	18%
712.00	Remote Monitoring Technicians	120,000	25%	120,000	22%	120,000	19%
713.00	Security Staff	950,000	15%	930,000	14%	950,000	17%
73.00	Regulatory Costs	120,000	23%	120,000	24%	120,000	23%
75.00	Capital Plant Expenditures	4,300,000	9%	6,100,000	7%	4,500,000	8%
751.00	Annualized Reactor Pressure Vessel (RPV) Replacements	110,000	20%	-	-	-	-
752.00	Annualized Core Barrel Replacements	1,600,000	17%	2,100,000	15%	1,700,000	16%
753.00	Annualized Moderator Replacements	170,000	16%	95,000	16%	310,000	15%
754.00	Annualized Reflector Replacements	10,000	11%	200,000	11%	260,000	12%
755.00	Annualized Reactivity Control Replacements	1,600,000	10%	3,000,000	8%	1,600,000	11%
759.00	Annualized Misc. Replacements	820,000	23%	760,000	17%	580,000	13%
78.00	Annualized Decommissioning Cost	65,000	14%	69,000	10%	58,000	8%
80.00	Annualized Fuel Cost	1,300,000	15%	2,300,000	12%	6,000,000	12%
81.00	Refueling Operations	2,500	17%	1,900	14%	4,300	15%
82.00	Additional Nuclear Fuel	1,200,000	16%	2,200,000	12%	6,000,000	12%
83.00	Spent Fuel Management	56,000	15%	57,000	15%	23,000	16%
OCC	Overnight Capital Cost	150,100,000	14%	158,200,000	10%	133,400,000	8%
OCC per kW	Overnight Capital Cost per kW	24,000	15%	26,000	10%	53,000	8%

OCC excl. fuel	Overnight Capital Cost Excluding Fuel	144,700,000	15%	145,600,000	11%	117,000,000	9%
OCC excl. fuel per kW	Overnight Capital Cost Excluding Fuel per kW	23,000	15%	24,000	11%	46,000	9%
TCI	Total Capital Investment	152,700,000	14%	160,900,000	10%	135,700,000	8%
TCI per kW	Total Capital Investment per kW	25,000	14%	27,000	10%	54,000	8%
AC	Annualized Cost	6,800,000	6%	9,600,000	5%	11,700,000	7%
AC per MWh	Annualized Cost per MWh	130	6%	190	5%	540	7%
LCOE	Levelized Cost of Energy ($/MWh)	330	10%	410	7%	980	6%

Table 11. Detailed bottom-up NOAK cost estimate for a UZrH-fueled 20-MWt LTMR, a TRISO-fueled 15-MWt GCMR, and a TRISO-fueled 7-MWt HPMR. The accounts are organized hierarchically and color coded by level. “Rel. std.” denotes the relative standard deviation.

		20-MWt LTMR		**15-MWt GCMR**		**7-MWt HPMR**	
Account	**Account Title**	**NOAK Estimated Cost ($2024)**	**Rel. Std.**	**NOAK Estimated Cost ($2024)**	**Rel. Std.**	**NOAK Estimated Cost ($2024)**	**Rel. Std.**
10.00	Capitalized Pre-Construction Costs	26,200,000	10%	26,400,000	9%	26,400,000	11%
11.00	Land Cost	77,000	16%	78,000	15%	77,000	14%
12.00	Site Permits	71,000	17%	68,000	15%	29,000	16%
13.00	Plant Licensing	15,500,000	12%	15,400,000	12%	15,500,000	13%
14.00	Plant Permits	4,700,000	23%	4,900,000	22%	4,900,000	22%
15.00	Plant Studies	5,900,000	25%	5,900,000	22%	5,900,000	25%
20.00	Capitalized Direct Costs	39,500,000	31%	39,300,000	21%	30,600,000	15%
21.00	Structures and Improvements	3,400,000	32%	3,000,000	30%	2,200,000	25%
211.00	Site Preparation / Yard Work	110,000	10%	110,000	10%	110,000	11%
211.10	Cleaning and Grubbing	65,000	15%	64,000	15%	65,000	15%
211.20	Stripping Topsoil	37,000	15%	37,000	16%	38,000	16%
211.30	Excavation	7,800	14%	8,000	13%	8,000	15%
212.00	Reactor Island Civil Structures	980,000	21%	970,000	23%	970,000	26%
212.10	Reactor Building Slab Roof	110,000	15%	110,000	15%	110,000	15%
212.20	Reactor Building Basement	87,000	14%	85,000	14%	84,000	15%
212.30	Reactor Building Walls	87,000	15%	88,000	15%	88,000	14%
212.40	Reactor Building Liner	600,000	35%	610,000	34%	650,000	37%
212.50	Reactor Building HVAC	97,000	63%	79,000	65%	42,000	71%
213.00	Main Function Buildings	42,000	7%	42,000	6%	42,000	8%
213.10	Energy Conversion Building	28,000	9%	28,000	9%	28,000	10%
213.11	Energy Conversion Building Slab Roof	8,700	17%	8,700	14%	8,700	18%
213.12	Energy Conversion Building Basement	6,900	14%	6,700	15%	6,900	16%

213.13	Energy Conversion Building Walls	12,000	15%	12,000	15%	12,000	16%
213.20	Control Building	14,000	9%	14,000	9%	14,000	9%
213.21	Control Building Slab Roof	4,400	15%	4,300	14%	4,500	15%
213.22	Control Building Basement	3,400	14%	3,500	15%	3,400	14%
213.23	Control Building Walls	6,200	15%	6,200	16%	6,300	16%
214.00	Buildings to Support Main Function	2,200,000	50%	1,800,000	50%	1,100,000	45%
214.70	Emergency and Startup Power Systems Building	2,200,000	50%	1,800,000	50%	1,100,000	45%
214.72	Diesel Generator	2,200,000	50%	1,800,000	50%	1,100,000	45%
214.80	Auxiliary Building	21,000	10%	21,000	10%	21,000	9%
214.81	Manipulator Building	21,000	10%	21,000	10%	21,000	9%
214.81	Manipulator Building Slab Roof	3,500	16%	3,500	14%	3,600	14%
214.81	Manipulator Building Basement	10,000	15%	10,000	15%	10,000	16%
214.81	Manipulator Building Exterior Walls	7,100	15%	7,100	15%	7,000	16%
215.00	Supply Chain Buildings	23,000	10%	22,000	9%	23,000	10%
215.10	Storage Building	23,000	10%	22,000	9%	23,000	10%
215.11	Storage Building Slab Roof	8,700	15%	8,600	17%	8,700	17%
215.12	Storage Building Basement	6,800	16%	6,800	15%	7,000	19%
215.13	Storage Building Walls	7,100	14%	7,100	15%	7,000	16%
22.00	Reactor System	9,800,000	9%	11,400,000	7%	8,800,000	8%
221.00	Reactor Components	6,500,000	12%	7,200,000	8%	5,900,000	9%
221.10	Reactor Vessel and Accessories	2,100,000	15%	3,600,000	13%	3,600,000	14%
221.11	Reactor Support	210,000	17%	600,000	18%	590,000	17%
221.12	Outer Vessel Structure	130,000	18%	-	-	-	-
221.13	Inner Vessel Structure	1,800,000	17%	3,000,000	15%	3,000,000	16%
221.20	Reactor Control Devices	1,100,000	10%	2,700,000	9%	1,800,000	11%
221.21	Reactivity Control System	1,100,000	10%	2,700,000	9%	1,800,000	11%
221.21	Reactivity Control System Fabrication	690,000	16%	1,400,000	14%	720,000	17%
221.21	Installation	160,000	16%	330,000	15%	160,000	15%
221.21	Control Drums Materials (Absorber)	110,000	15%	610,000	16%	700,000	20%
221.21	Control Drums Materials (Reflector)	7,400	16%	44,000	16%	93,000	16%
221.22	Control System Drive Mechanism	150,000	13%	310,000	18%	160,000	16%
221.30	Non-Fuel Core Internals	3,200,000	25%	870,000	9%	530,000	9%
221.31	Reflector	7,800	11%	200,000	11%	310,000	11%
221.31	Radial Reflector	4,700	16%	140,000	15%	190,000	16%
221.31	Axial Reflector	3,000	14%	62,000	15%	120,000	18%
221.32	Shield	3,100,000	25%	59,000	22%	66,000	24%
221.32	In-Vessel Shield Materials	3,100,000	25%	-	-	-	-
221.32	Out-the-Vessel Shield Materials	14,000	16%	59,000	22%	66,000	24%

221.33	Moderator	140,000	16%	94,000	16%	150,000	15%
221.34	Moderator (Booster)	-	-	520,000	14%	-	-
222.00	Main Heat Transport System	1,400,000	16%	1,100,000	11%	470,000	45%
222.10	Fluid Circulation Drive System	320,000	53%	260,000	15%	-	-
222.11	Primary Pump	320,000	53%	-	-	-	-
222.13	Compressor	-	-	260,000	15%	-	-
222.20	Reactor Heat Transfer Piping System	33,000	14%	64,000	19%	340,000	62%
222.30	Heat Exchangers	110,000	17%	67,000	15%	60,000	16%
222.31	Primary Heat Exchanger	110,000	17%	67,000	15%	60,000	16%
222.50	Initial Coolant Inventory	910,000	16%	730,000	15%	73,000	15%
223.00	Safety Systems	150,000	11%	570,000	12%	630,000	10%
223.20	Reactor Cavity Cooling System (RVACS)	150,000	11%	570,000	12%	630,000	10%
223.21	RVACS (Cooling Vessel)	74,000	16%	280,000	19%	310,000	15%
223.22	RVACS (Intake Vessel)	79,000	16%	290,000	14%	320,000	16%
226.00	Other Reactor Plant Equipment	92,000	22%	830,000	45%	1,800,000	21%
227.00	Reactor Instrumentation and Control (I&C)	1,700,000	25%	1,700,000	21%	6,300	25%
228.00	Reactor Plant Miscellaneous Items	6,000	22%	6,000	25%	-	-
23.00	Energy Conversion System	14,000,000	84%	11,000,000	70%	5,800,000	69%
232.00	Energy Applications	13,800,000	85%	10,800,000	71%	5,600,000	71%
232.10	Electricity Generation Systems	13,800,000	85%	10,800,000	71%	5,600,000	71%
236.00	Common I&C	200,000	21%	200,000	22%	200,000	22%
24.00	Electrical Equipment	7,200,000	29%	7,100,000	28%	4,800,000	44%
241.00	Switchgear	650,000	49%	700,000	56%	400,000	53%
242.00	Station Service Equipment	620,000	58%	680,000	85%	380,000	87%
243.00	Switchboards	180,000	56%	210,000	48%	130,000	85%
244.00	Protective Equipment	560,000	55%	570,000	58%	360,000	86%
245.00	Electrical Structure & Wiring Container	3,000,000	53%	2,800,000	57%	2,000,000	85%
246.00	Power & Control Wiring	2,200,000	59%	2,100,000	52%	1,500,000	80%
25.00	Initial Fuel Inventory	4,900,000	17%	6,500,000	15%	8,600,000	15%
251.00	First Core Mining	2,800,000	15%	3,300,000	17%	4,100,000	14%
252.00	First Core Conversion	230,000	16%	260,000	14%	340,000	18%
253.00	First Core Enrichment	1,800,000	43%	1,700,000	48%	2,500,000	44%
254.00	First Core Fuel Assembly Fabrication	99,000	14%	1,300,000	15%	1,700,000	17%
26.00	Miscellaneous Equipment (Cranes)	250,000	20%	240,000	22%	250,000	23%
30.00	Capitalized Indirect Services Cost	5,200,000	23%	4,800,000	15%	4,200,000	13%
31.00	Factory & Field Indirect Costs	1,800,000	43%	1,700,000	31%	1,100,000	25%
32.00	Factory and Construction Supervision	630,000	60%	440,000	48%	280,000	39%
33.00	Startup Costs	1,600,000	21%	1,500,000	19%	1,600,000	22%

34.00	Shipping and Transportation Costs	550,000	24%	520,000	19%	560,000	25%
35.00	Engineering Services	410,000	24%	400,000	22%	410,000	24%
36.00	Project Management / Construction Management (PM/CM) Services	270,000	25%	280,000	21%	270,000	22%
40.00	Capitalized Training Costs	350,000	21%	330,000	21%	340,000	22%
41.00	Staff Recruitment and Training	350,000	21%	330,000	21%	340,000	22%
60.00	Capitalized Financial Costs	1,200,000	19%	1,200,000	14%	1,100,000	9%
62.00	Interest	1,200,000	19%	1,200,000	14%	1,100,000	9%
70.00	Annualized Operations and Maintenance (O&M) Cost	2,300,000	9%	2,600,000	7%	2,200,000	9%
71.00	O&M Staff	1,100,000	13%	1,100,000	13%	1,100,000	15%
711.00	Operators	6,400	19%	6,100	16%	6,700	18%
712.00	Remote Monitoring Technicians	120,000	25%	120,000	22%	120,000	19%
713.00	Security Staff	950,000	15%	930,000	14%	950,000	17%
73.00	Regulatory Costs	69,000	23%	70,000	24%	70,000	23%
75.00	Capital Plant Expenditures	1,100,000	13%	1,400,000	9%	1,100,000	8%
751.00	Annualized RPV Replacements	29,000	19%	-	-	-	-
752.00	Annualized Core Barrel Replacements	410,000	17%	540,000	15%	440,000	16%
753.00	Annualized Moderator Replacements	31,000	16%	17,000	15%	55,000	15%
754.00	Annualized Reflector Replacements	1,800	11%	36,000	11%	46,000	11%
755.00	Annualized Reactivity Control Replacements	260,000	10%	480,000	9%	270,000	11%
759.00	Annualized Misc. Replacements	360,000	33%	330,000	25%	250,000	18%
78.00	Annualized Decommissioning Cost	31,000	19%	31,000	14%	27,000	10%
80.00	Annualized Fuel Cost	1,200,000	16%	1,200,000	14%	3,200,000	15%
81.00	Refueling Operations	2,500	17%	1,900	14%	4,300	15%
82.00	Additional Nuclear Fuel	1,100,000	17%	1,200,000	14%	3,100,000	15%
83.00	Spent Fuel Management	56,000	15%	57,000	15%	23,000	16%
OCC	Overnight Capital Cost	71,300,000	19%	70,800,000	14%	61,500,000	10%
OCC per kW	Overnight Capital Cost per kW	12,000	18%	12,000	13%	24,000	10%
OCC excl. fuel	Overnight Capital Cost Excluding Fuel	66,500,000	20%	64,200,000	15%	52,900,000	11%
OCC excl. fuel per kW	Overnight Capital Cost Excluding Fuel per kW	11,000	20%	11,000	15%	21,000	11%
TCI	Total Capital Investment	72,600,000	19%	72,000,000	14%	62,600,000	10%
TCI per kW	Total Capital Investment per kW	12,000	18%	12,000	13%	25,000	10%
AC	Annualized Cost	3,400,000	9%	3,800,000	7%	5,400,000	9%
AC per MWh	Annualized Cost per MWh	60	8%	70	7%	250	9%
LCOE	Levelized Cost of Energy ($/MWh)	160	13%	170	9%	450	8%

The cost drivers for the three reactor types can be determined using the detailed cost estimates, as shown in Figure 7 and Figure 8. For the FOAK LTMR, the main cost drivers are capital plant expenditure (the annualized cost of replacing the reactor vessel, the reflector, the drums, etc.), the cost of the reactor system, the cost of plant licensing, the cost of the energy conversion system, and the annualized cost of the fuel. Similar cost drivers were found for the GCMR and HPMR, except that the contribution of the annualized cost of fuel is higher for the GCMR and much more significant for the HPMR since both are fueled by TRISO fuel. The cost drivers for the NOAK reactors are those that do not benefit much from the building of more units. These include the cost of capital plant expenditure, the cost of the plant licensing, the cost of the energy conversion system, the annualized cost of the fuel, and the cost of the O&M staff.

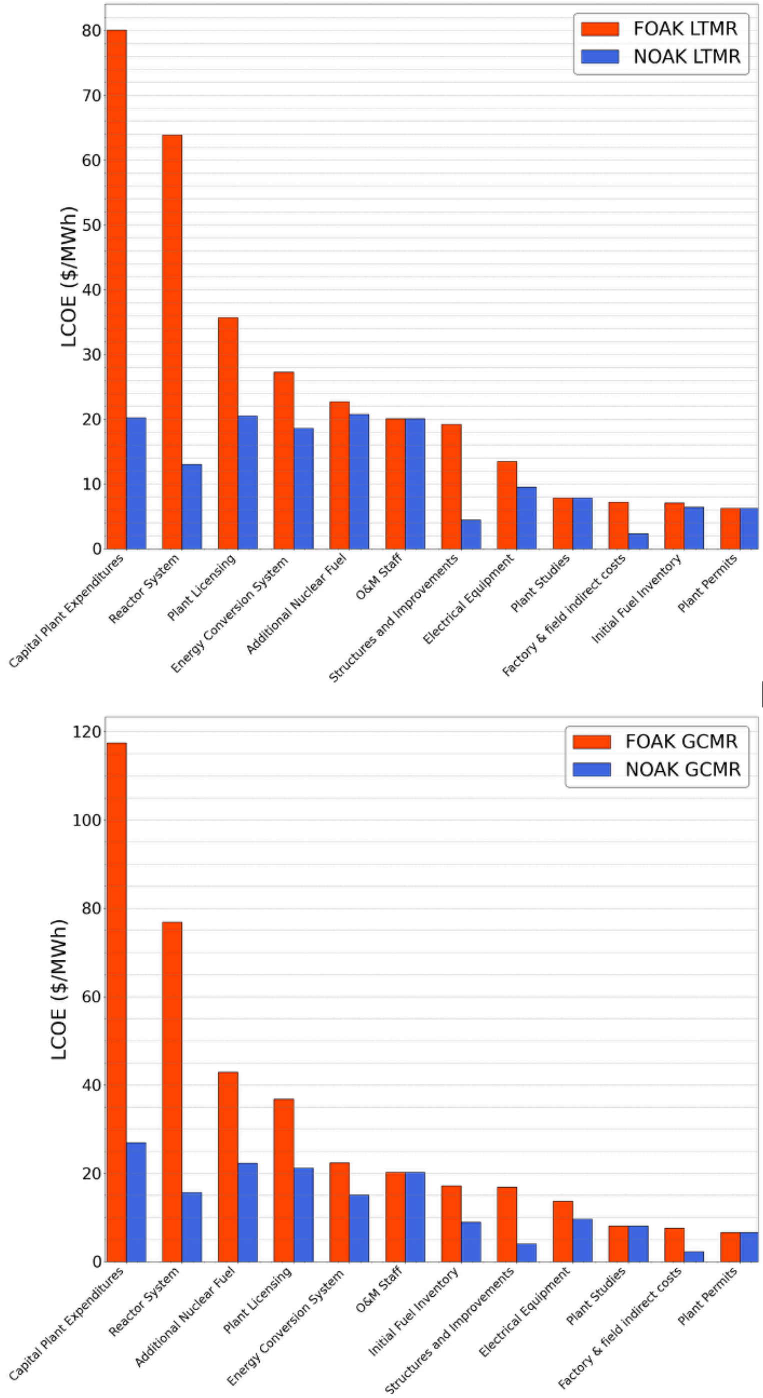

Figure 7. Cost drivers for a UzrH-fueled 20-MWt LTMR and a TRISO-fueled 15-MWt GCMR.

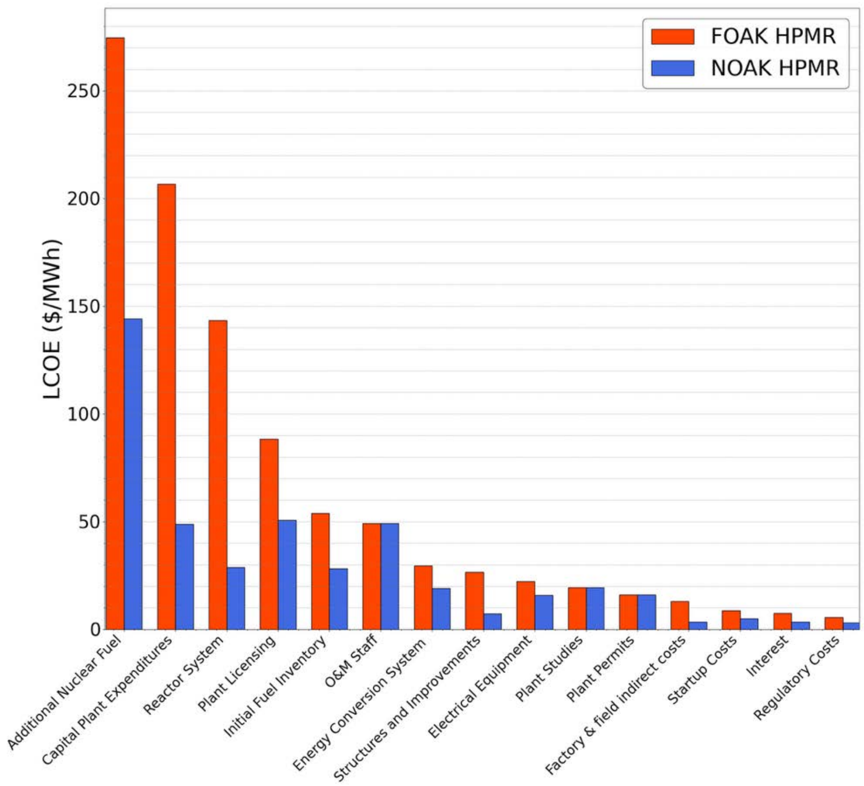

Figure 8. Cost drivers for a 7-MWt TRISO-fueled HPMR.

3.2. Parametric Studies

This section demonstrates MOUSE's capabilities in helping researcher understand how changing reactor design specifications, such the geometry or materials, can impact reactor economics. Typically, design principles originate from first-principle physics best practices (e.g., utilizing high-power-density fuels to increase cycle length or utilizing hydride as a solid moderator to increase the compactness of the core), but their impact in terms of technoeconomic performance has not been quantified. While these principles draw inspiration from years of experience and engineering expertise, their impact must be understood to make better-informed decisions and capture trade-offs between inherent neutronics performance, cost, and supply chain availability.

The following subsections provide details about parametric studies we performed using MOUSE to look at the economic impact of design parameters such as the reflector's composition and thickness, the moderator's composition and radius, fuel composition, core size, and power. A summary of the lessons learned is presented at the end.

For these studies, it is assumed that the stakeholders are interested in minimizing the LCOE for an FOAK and NOAK reactor, maximizing the fuel lifetime and minimizing the reactor size for transportability. Significant design metrics (peaking factors, temperature coefficients, control drum worth) were overlooked in this work. Therefore, the following studies should only be used to gain insights into narrow economic considerations and cost tradeoffs of several design choices. They are not sufficient to make complete design decisions.

3.2.1. Impact of the Reflector's Composition and Thickness

In large water reactors, the water-baffle-barrel structure constitutes the radial reflector, but for smaller designs in which leakage becomes substantial, it is common practice to include radial reflectors to improve the neutron economy of the reactor and flatten the power profile. This approach has already been utilized for small modular reactors, including the use of heavy reflectors (i.e., heavy metal blocks) with stainless-steel slabs in the NuScale design (Halimi 2024). For microreactors with a thermal spectrum, a reflector that exhibits good moderation properties, such as Be, BeO, and graphite, is preferable. These three reflectors are compared in this section

The number of collisions necessary to thermalize a neutron for Be is the smallest compared to BeO and graphite due to its low atomic number. This results in a high macroscopic slowing-down power, and consequently, the smallest core size, which is beneficial for total LCOE. However, Be (and hence BeO) is difficult to manufacture and poses health hazards, making it challenging to handle Shirvan et al. (2023) and resulting in high costs compared to its graphite counterparts, as reported in Table 12. Additionally, Be has large uncertainties related to its behavior at high temperature and under irradiation (Shirvan et al. 2023). Moreover, owing to the small neutron absorption cross section of graphite, its moderating ratio is higher, which could result in better fuel economy (see Table 12):

Table 12. Cost and moderation properties of the reflectors reported on in this section.

	Cost ($/kg)	**Macroscopic Slowing-Down Power ($\xi \times \sigma_s$)**	**Moderating Ratio ($\frac{\xi \Sigma_s}{\Sigma_a}$)**
Graphite	80 (2022 USD)	0.063	200
BeO	10,063 (2024 USD)	0.11	180
Be	44,737 (2024 USD)	0.16	150

For all these reasons, it may be preferable to prioritize graphite. However, this would incur a penalty on the fuel lifetime, but its lower cost and resulting neutron economy would beneficially impact the LCOE. Similarly, a smaller fuel thickness would also penalize the fuel lifetime but would result in a lower capital cost and a more transportable reactor core. All these considerations are of great interest to microreactor designers and can be assessed using the MOUSE tool. The trade-offs related to changing the reflector's composition and thickness for the LTMR and GCMR are discussed next. Since the reflector and the control drum's reflector are made from the same material, both reflectors were modified in this study.

Impact of the Reflector's Composition and Thickness on the GCMR

Due to the large cost differences between graphite, Be, and BeO, the LCOE for an FOAK reactor using a graphite reflector is significantly lower, and the difference increases with increasing reflector thickness, as shown in Figure 9. While the fuel lifetime can substantially improve with a Be-based reflector, it does not offset the higher reflector cost. At low thickness, it might seem that the LCOE (using BeO reflector) is close to the LCOE when using a Graphite reflector, making BeO an acceptable option for more compact cores.

Although the cost of transportation to and from the site is not accounted for, it is very unlikely that increasing fuel lifetime by 300–400 days or a year (see Figure 9A) would compensate for such a high difference in total LCOE for an FOAK reactor (Figure 9B). However, the differences are significantly smaller for the LCOE of the NOAK unit, where the costs of BeO are assumed to drop. For instance, if the thickness is reduced to 2 cm, the fuel lifetime for the BeO reflector is 8 years, with an LCOE of $732/MWh and $201/MWh for the FOAK and NOAK scenarios, respectively, compared to 7.3 years and $432/MWh and $200/MWh for the FOAK and NOAK scenarios, respectively, forr the graphite case.

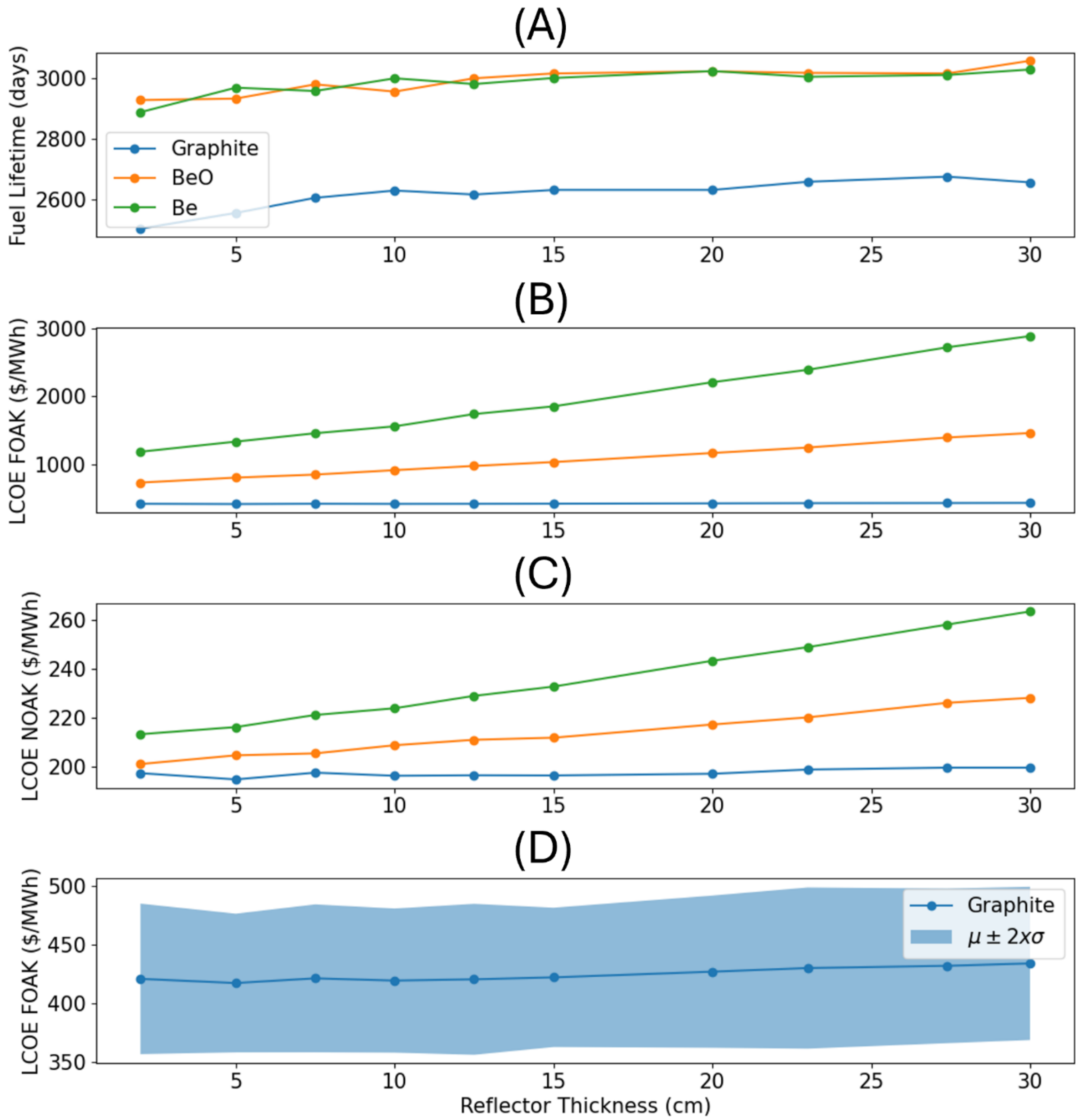

Figure 9. Impact of the reflector's composition and thickness for the GCMR measured in terms of (A) fuel lifetime, (B) FOAK's LCOE, (C) NOAK's LCOE, and (D) FOAK's LCOE for the graphite (cheapest) option.

Last, the impact of reflector thickness for graphite is limited, ranging from $420/MWh to $434/MWh for 2 cm and 30 cm, respectively, on average for the FOAK's LCOE, with virtually no impact on the NOAK unit. Additionally, these values are well within the bounds of cost uncertainties for graphite. This can be explained by the very low cost of graphite (see Table 12). The gain in fuel lifetime ranges from 6.8 to 7.3 years. The core size limit underscored by Shirvan et al. (2023) is 2.4 m by 2.4 m, which is exceeded by our two greater thicknesses (including the nominal case), which amount to a radius of 124.8 and 127.4

cm, respectively. It could be beneficial to reduce that thickness to lower the LCOE and improve the transportability without a significant penalty on fuel lifetime.

Impact of the Reflector's Composition and Thickness on the LTMR

The results for the LTMR are given in Figure 10. The trends are similar to those of the GCMR but less pronounced. The cost difference between the smaller thickness for graphite and BeO is about \$200/MWh, rising to \$500/MWh (see Figure 10), with a fuel lifetime difference of less than 100 days, or less than 5%. Another difference lies in the reactor thickness worth: the benefit of increasing the thickness from 2 cm to 50 cm is less than 100 days for graphite, as seen in Figure 10, with an inconsequential impact on cost. Last, unlike for the GCMR, there may be no benefit to using BeO for the LTMR. With the nominal reflector thickness, the LCOE is \$538/MWh and \$182/MWh for the FOAK and NOAK scenarios, respectively, reaching about 5.7 years in fuel lifetime. In contrast, for the nominal case with graphite, the LCOE is \$330/MWh and \$176/MWh for the FOAK and NOAK scenarios, respectively, with a fuel lifetime of 5.3 years.

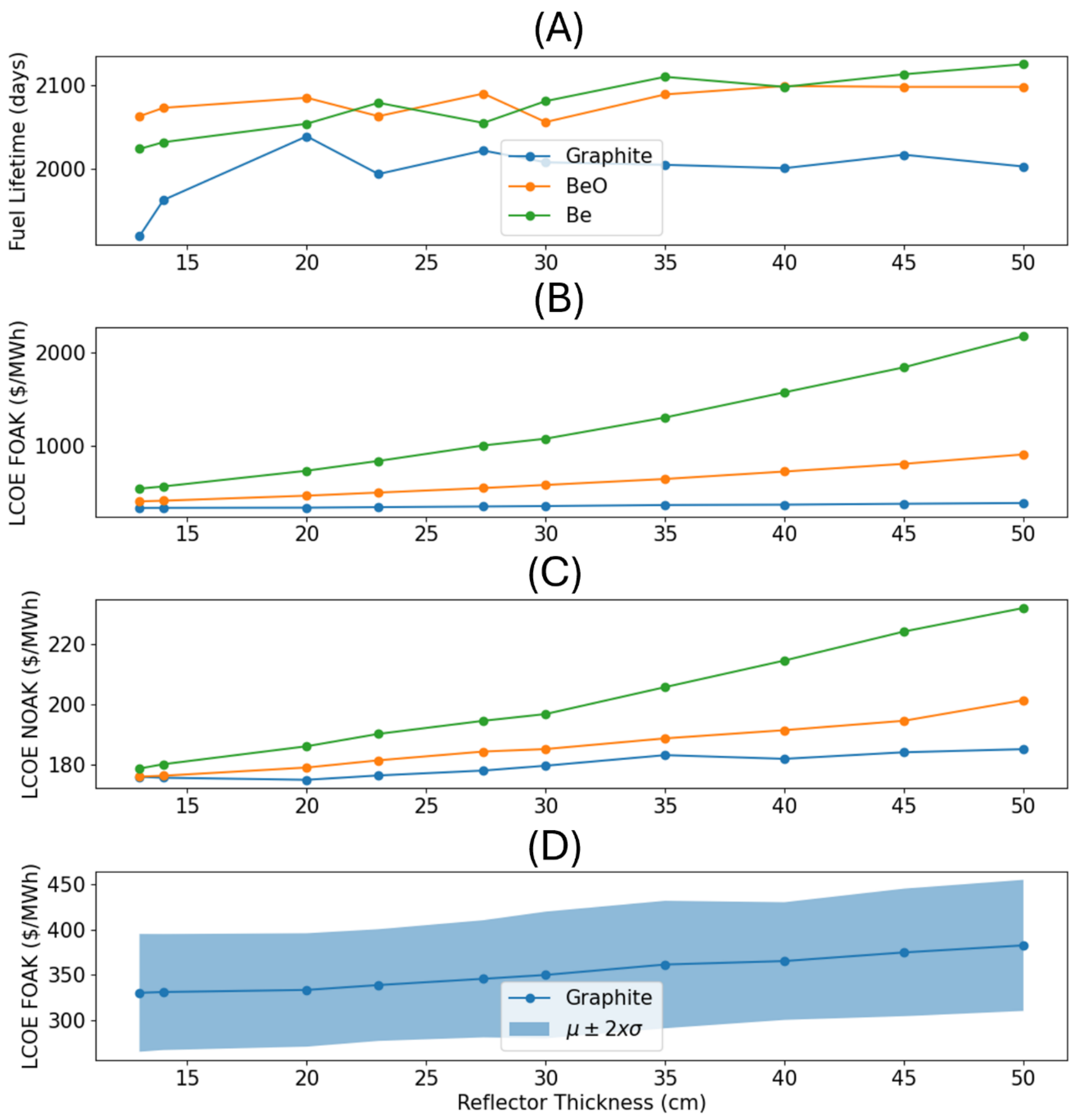

Figure 10. Impact of the reflector's composition and thickness for the LTMR measured in terms of (A) fuel lifetime, (B) LCOE FOAK, (C) LCOE NOAK, and (D) LCOE FOAK for the graphite (cheapest) case with uncertainties.

To sum up, the benefit of using a Be-based reflector in terms of fuel lifetime (and hence core size) is outperformed by the very low cost of graphite and the minimal impact of reflector composition and thickness on fuel lifetime. The advantage of graphite is even more transformative in the case of the LTMR, where the neutronics performance is more comparable, especially at thicknesses above 20 cm. In both systems, the "reflector worth," or the impact of increasing the reflector thickness in terms of operating lifetime, is too small, and the LCOE increases with it.

Be-based reflectors (in particular BeO) are often chosen due to their superior moderation properties to reduce core size, thereby improving compactness and transportability, a pivotal aspect of microreactor design. However, they are often deemed unfeasible because of their handling difficulty and associated cost uncertainties (Shirvan et al. 2023). In this section, it was demonstrated that graphite is superior, especially for the LTMR, and the potential for BeO is only realized with the NOAK unit, particularly for a smaller reflector thickness. It is worth noting that the LTMR core is relatively small. Therefore, even if with a thick graphite reflector, the LTMR should still remain within the size restrictions.

Therefore, the use of graphite for both the GCMR (a larger microreactor) and the LTMR (a smaller one) might be recommended. The cost of increasing or decreasing the thickness of the graphite is inconsequential, and only questions of fuel lifetime and transportability need to be addressed. Other parameters MOUSE cannot natively capture include peaking factors flattening (which may be achieved with thicker reflectors) and potentially control drum worth (higher neutron flux at the periphery with thicker reflectors). Thus, further study is needed.

3.2.2. Impact of Moderator Booster Radius and Composition

Achieving a thermal neutron spectrum is a unique challenge for these microreactors as they need to remain compact to ensure transportability and neutron economy, and/or to minimize the payload for long-term space travel. Solid moderator elements or moderator boosters, which consist of metal hydrides (zirconium hydride [ZrH] and yttrium hydride [YH]) and claddings, are a cornerstone of their designs. By adding pellets of moderators adjacent to fuel assemblies, fuel lifetime can be significantly improved while keeping the reactor compact due to the good neutron moderation properties of these moderator systems. Moreover, due to the low fuel per unit volume in TRISO- or UZrH-based fuel, achieving a desired design may not be possible without them.

In the vast array of potential hydrides, ZrHx and YHx (where *x* is the atomic ratio of hydrogen to yttrium) are favored due to their low absorption cross section, resulting in a high moderating ratio (see Table 13), negative prompt temperature coefficients, and favorable thermophysical properties compared to their metallic counterparts (Sprouster et al. 2025). They can also maintain high hydrogen density at elevated temperatures and have played historical roles in several reactor designs, including the Systems Nuclear Auxiliary Power (SNAP) Program reactors, Aircraft Nuclear Propulsion (ANP) program reactors, Nuclear Thermal Propulsion (NTP) reactors, and Training, Research, Isotopes, General Atomic (TRIGA) research reactors (Sprouster et al. 2025). ZrH and YHx can retain a high hydrogen density up to 500°C, with yttrium di-hydride (YH2) being stable up to 1350°C (Sprouster et al. 2025).

Using Yttrium in microreactors (Evans et al. 2025, Hu et al. 2020) has recently gained attention due to its superior thermal stability, with several orders of magnitude lower equilibrium hydrogen partial pressure for the same hydrogen-to-metal ratio at the same temperature, and higher attainable hydrogen content compared to zirconium-based hydrides. In other words, the hydrogen stays bound to the yttrium at much higher temperatures and for a longer time, reducing the risk of internal gas overpressurization and stress-rupture of the cladding. Moreover, ZrH requires specific consideration due to hydrogen desorption at the elevated temperatures achieved in many microreactor designs, which necessitates cladding or self-protecting layers in the hydride itself. On the other hand, YHx requires high-purity grade (99.9%) yttrium, which was not available as an affordable commercial product until recently.

Due to the strategic nature of these moderator systems, we decided to study the impact of booster composition, as well as of its volume through its radius. While ZrH exhibits superior neutronics properties (see Table 13), the superior hydrogen stability of YHx makes it more appealing, especially for systems with temperatures that can exceed 650°C (e.g., the GCMR). The MOUSE tool was used to understand the actual impact of replacing ZrH with YHx in terms of fuel lifetime and cost, which can inform research and development campaigns for YHx.

Table 13. Cost and moderation properties of the moderators discussed in this section. Due to the lack of data on the cost of YHx, its cost is parameterized to be 1 to 10 times the cost of ZrH.

	Cost ($/kg)	**Macroscopic Slowing-Down Power ($\xi\sigma_s$)**	**Moderating Ratio $\frac{\xi\Sigma_s}{\Sigma_a}$ ***
ZrH2*	1,520 (2017 USD)	1.45	55
YH2*	[1× to 10×] 1,520 (2017 USD)	1.2	25
* Hu 2020			

Due to the lack of knowledge about the cost of the YHx, the same fabrication cost was used for both boosters (Table 13), but we also looked at the impact on the total LCOE of increasing this cost up to 10-fold.

Impact of Moderator Booster Radius and Composition on the GCMR

The results of the impact of the booster's composition and radius for the GCMR are shown in Figures 11A through 11C, and the impact of the cost of YHx in Figures 11D and 11E.

First, in Figure 11A we can observe that the larger the radius, the higher the fuel lifetime, owing to the increased moderation. The benefit of ZrH is about 930 days, or 2.5 years, for the base booster radius. This benefit is overestimated for the GCMR as we did not add stainless-steel cladding around the ZrH (this was done for the LTMR), which is necessary to limit hydrogen loss due to its dissociation into the gas gap and permeation through the cladding and into the coolant (Hu et al. 2020, Shirvan et al. 2023, Evans et al. 2025). However, austenitic stainless steel loses strength rapidly at temperatures above 600°C (Evans and Parisi 2024, Evans et al. 2025), providing an additional reason why ZrH can be challenging to deploy in such a system (substantial insulation would be necessary). Unlike the reflector case study discussed in Section 3.2.1, the benefit of increasing fuel lifetime decreases the total LCOE for ZrH. The two competing effects on the LCOE are the increase in cost by replacing graphite with metal hydrides while increasing the radius (which increases the total cost) and the benefit in fuel lifetime (which decreases the annualized cost). For ZrH, the latter always surpasses the former. For YHx, there are trade-offs due to the lower fuel lifetime achieved with it. In our study, the optimal fuel radius for YHx in terms of LCOE is the nominal one at 0.55 cm with $418/MWh and $202/MWh for FOAK and NOAK, respectively, compared to $452/MWh and $206/MWh for the radius of 0.65 cm. The fuel lifetime difference is about 300 days, or 0.8 years. The (LCOE) remains similar up to a radius of 0.55 cm, despite the significantly higher fuel lifetime of ZrH. This is due to the density difference between the two moderator boosters: 4.28 g/cc for YHx and 5.6 g/cc for ZrH. Since ZrH is denser, it is heavier for the same volume, leading to higher initial costs based on $/kg. Consequently, both the direct and annualized replacement costs for ZrH are higher. Therefore, the cost savings from ZrH's increased fuel lifetime are offset by its higher costs. Therefore, despite the higher fuel lifetime, the LCOE remains the same. However, for larger radii, the benefit of higher fuel lifetime on the LCOE outweighs the mass differences

Figure 11(D) and Figure 11(E) showcase the impact of the cost of YHx on the LCOE for the FOAK and NOAK scenarios, respectively. Even if we increase the cost of YHx tenfold, the total LCOE only increases by about 9%, and the cost remains within the uncertainty bounds of the original one.

Considering the reasonable cost of commercial high-purity-grade yttrium, the cost of fabrication compared to that of ZrH must be evaluated, but we do not anticipate that it would substantially affect the result. The real difference lies in the difference in fuel lifetime, and increasing other parameters, including the packing fraction (which is possible up to 44% compared to the 30% nominal case [Brown, Hernandez, and Nelson 2022]), might be necessary when switching to yttrium. Increasing the moderator radius is also desirable, but yttrium hydrides have a known potential to exhibit positive temperature coefficients due to the loss of neutron absorption of yttrium when the temperature decreases (Ade et al. 2022), which prompted their evaluation in this instance.

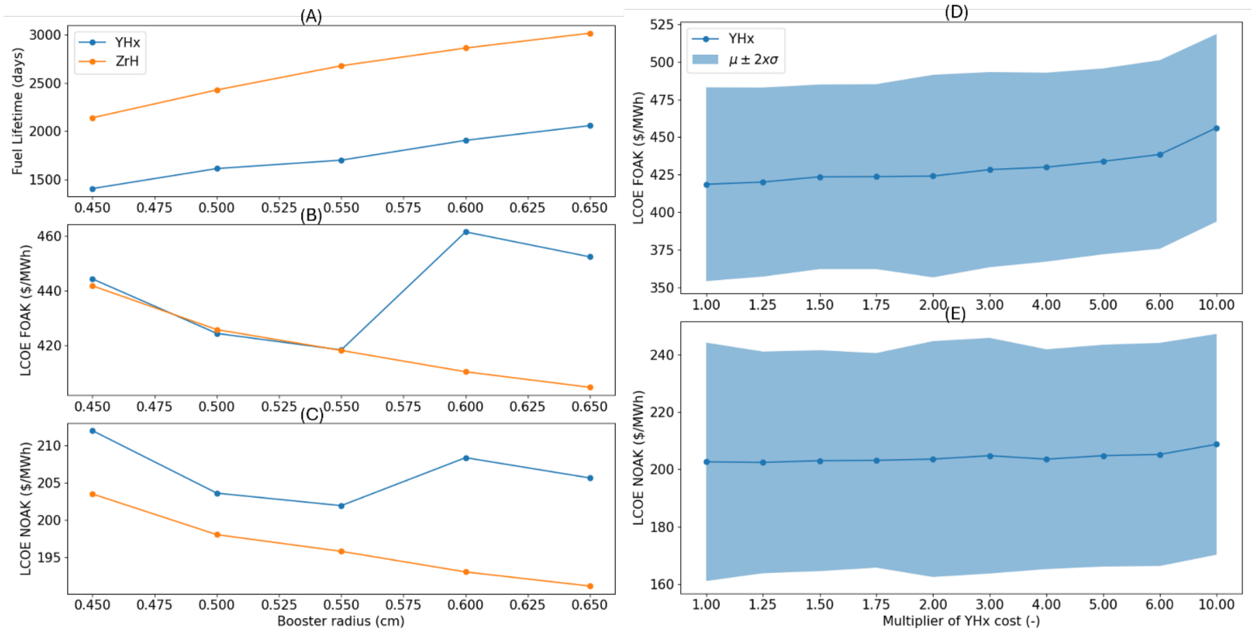

Figure 11. Impact of the solid moderator's composition and radius for the GCMR (A through C), and impact on the cost of YHx (D and E) for a fixed radius of 0.55 cm.

<u>Impact of Moderator Booster Radius and Composition on the LTMR</u>

The results for the LTMR are given in Figure 12. The trends are similar to those of the GCMR, but the differences between ZrH and YHx are smaller, with a difference in fuel lifetime of about 150 days for the nominal booster radius. Again, a thicker booster increases the fuel lifetime and reduces the LCOE more effectively for ZrH. The sweet spot is 1.75 cm for YHx, with an LCOE of $309/MWh and $312/MWh for the FOAK and NOAK scenarios, respectively, with a fuel lifetime of 4.93 years, compared to $333/MWh and $177/MWh and 4.98 years for the nominal case (these differences in fuel lifetime are within the error margin).

Figures 12D and 12E show the evolution of the LCOE with the cost of YHx, where the impact of the YHx cost is again minimal (4% LCOE increase for the FOAK with a tenfold cost increase).

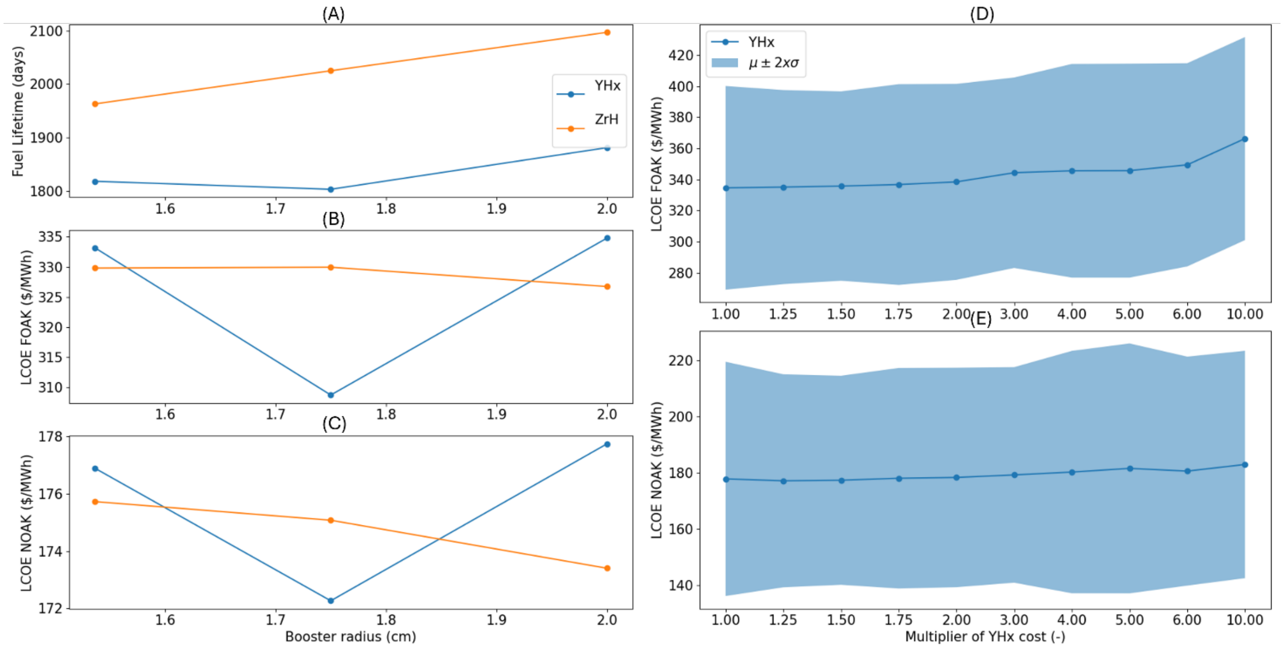

Figure 12. Impact of the solid moderator's composition and radius for the LTMR (A through C), and impact on the cost of YHx (D and E) for a fixed radius of 1.5367 cm.

For the impact of booster radius and composition, we demonstrated that ZrH surpasses YHx in terms of the fuel lifetime and LCOE, especially for the GCMR. However, it is very challenging for a ZrH-based system to retain all of its hydrogen by the expected operation life of the GCMR, considering it is anticipated to operate for 7.5 years at a high temperature (e.g. 650°C). As alluded to earlier, it is possible to insulate the moderator hydrides to decrease its temperature. However, this increases the complexity of the design, which was not modeled here. Moreover, increasing the operating temperature of the GCMR by using YHx will increase its thermal efficiency, thereby enhancing the overall economic competitiveness of the reactor (though this must be compared to the increased material costs resulting from harsher conditions in the secondary side). Therefore, it is suggested to use YHx for GCMR and ZrH for LTMR, considering the previously mentioned caveats. This suggestion may change based on fuel lifetime, operating temperature, and whether the moderator hydride is insulated.

To mitigate the penalty on fuel lifetime when YHx is chosen, it was proposed to increase the moderator radius. The minimal cost involved with increasing the volume of hydride, and the improvement in fuel lifetime, has a net positive effect on the overall LCOE for ZrH. However, a sweet spot must be found for YHx. Unfortunately, the improvement is small. Further work will need to be done to evaluate the temperature coefficient to ensure that increasing the radius does not lead to a positive temperature coefficient (Ade 2022). Other limitations include the chemical energy stored from gamma absorption, which must be accounted for in hypothetical release scenarios during accidents (Shirvan et al. 2023), and the loss of moderation caused by hydrogen redistribution and losses outside its boundary over time, accelerated by irradiation (Evans and Parisi 2024, Evans et al. 2025, Sprouster et al. 2025). Another avenue for cost improvement that can be explored with the MOUSE tool is to increase the power output, reactor size, and/or the amount of uranium loaded (see Section 3.2.3).

3.2.3. Impact of Fuel Composition, Enrichment, Size of the Core, and Power Level

The use of TRISO fuel by many vendors is motivated by its robustness under irradiation, which allows for high-temperature operation and a high fission product retention capability. However, due to the low fuel loading per unit volume, high-assay low-enriched uranium (HALEU) must be used. Domestic TRISO capabilities are being developed, with the goal of transforming the nuclear energy supply chain.

Despite government efforts to kickstart a domestic supply chain, a mature supply chain for HALEU fuel does not exist yet. It is worth noting that the use of TRISO fuel does not always necessitate the use of HALEU. For example, the High-Temperature Gas-Cooled Reactor–Pebble-Bed Module (HTR-PM) in China is operating with TRISO-based UO_2 enriched to 8.5% (Jaradat, Schunert, and Ortensi 2023). Similarly, other popular forms of fuel, including metallic fuels (e.g., uranium oxycarbide [UCO], uranium nitride [UN], uranium carbide [UC]), may face similar shortcomings.

In this section, we discuss the results of using the MOUSE tool to study the impact of changing the fuel and switching to low-enrichment fuel using readily available fuel forms. Note that in MOUSE, the cost of TRISO fuel manufacturing is independent of the fuel type.

Impact of Fuel Composition, Enrichment, Size of the Core, and Power Level on the TRISO-Fueled GCMR

The first question we posed is whether it is possible to reduce the fuel enrichment and increase the reactor size without significantly increasing the LCOE (if obtaining HALEU fuel is challenging). To increase the core size, the number of rings per assembly was increased from 6 to 8, resulting in an increase in the core diameter from 2.4 to 3.3 meters. When lowering the enrichment to 10%, it is found that using UN with 8 rings resulted in a fuel lifetime of 7.2 years (comparable to the nominal 7.3 years) with a total Uranium-235 mass of 85 kg, compared to about 81 kg in the nominal case. Therefore, the lower-enrichment core utilizes its uranium less efficiently, resulting in a total LCOE of $504/MWh and $203/MWh for the FOAK and NOAK scenarios, respectively, compared to $432/MWh and $200/MWh in the nominal case. Consequently, we hypothesize that it is preferable to utilize HALEU for a TRISO-fueled reactor rather than LEU+.

The second set of results is presented in Figure 13. Panels *A*, *B*, and *C* provide the distribution of fuel lifetime, LCOE (FOAK), and LCOE (NOAK) for two types of fuel (UO_2 and UN) at different enrichment levels for two power levels, 15 and 17.5 MWth. The first observation is that increasing the fuel lifetime through enrichment (and thus the amount of uranium-235 loaded) is beneficial not only for fuel lifetime but also for LCOE. The two competing mechanisms are the increase in enrichment cost due to higher enrichment levels and the increase in fuel lifetime, which reduces the annualized cost and enhances the energy extracted from the fuel. The latter phenomena outweighing the former may be attributed to the significantly high cost of the TRISO fuel.

Additionally, the difference in fuel lifetime between UN and UO_2 can be significant, amounting to about 0.8 to 1.1 years. However, the FOAK's LCOE is significantly lower for UO_2. For instance, at enrichment of 10%, with 7 assembly rings, and power level of 17.5 MWth (i.e., the cheapest scenario with the highest fuel lifetime), the FOAK's LCOE with UO_2 is approximately $40/MWh cheaper the UN ones, which translates to about $6.1 million/year/plant. The difference between the UN-based TRISO and UO_2-based TRISO fuel arises from uranium loading; While UN exhibits a higher fuel loading, this characteristic alone does not enable it to compete effectively with UO2 kernels. The cost of UN is higher than the cost of UO2 since UN has a higher proportion of uranium.

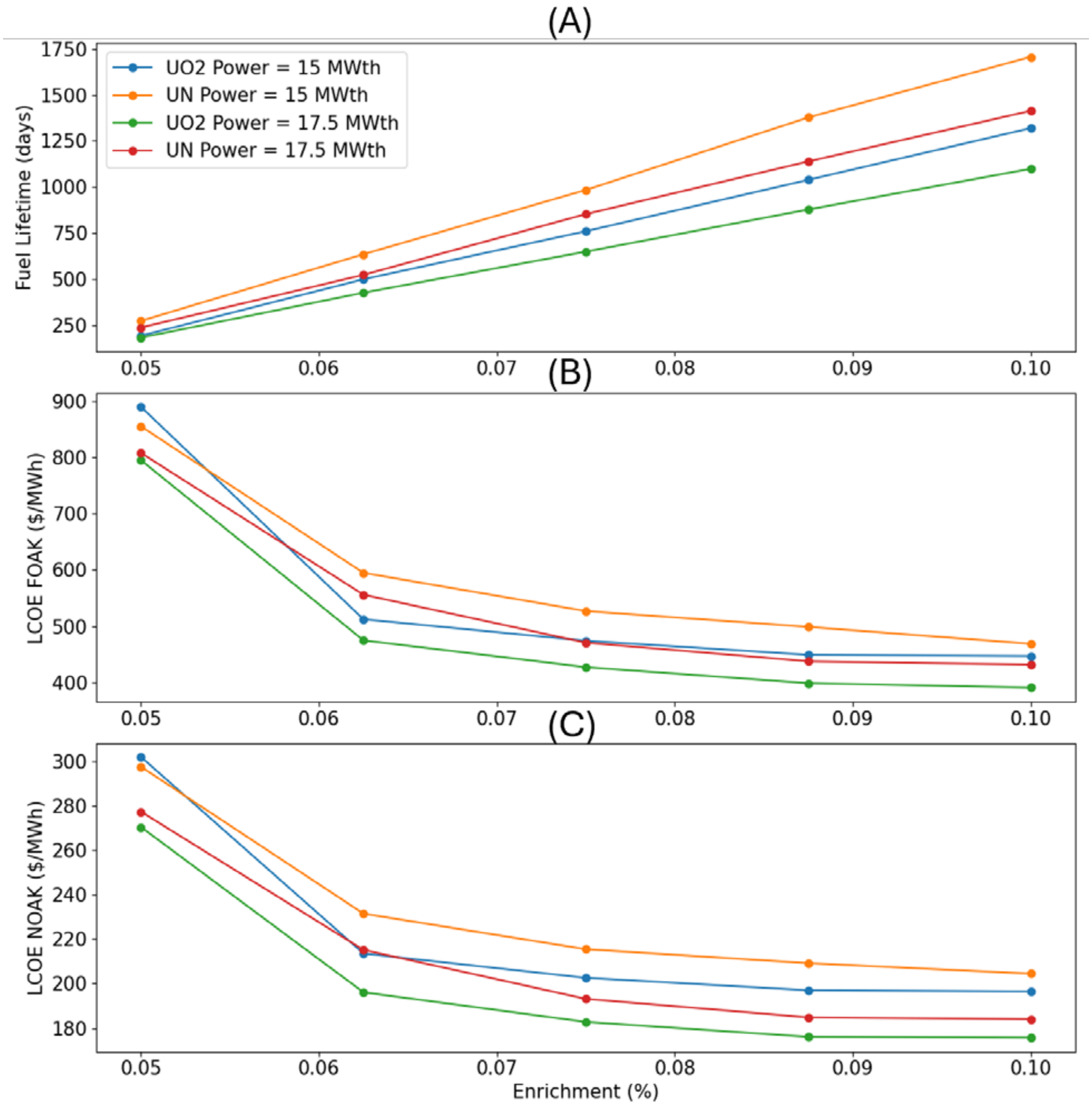

Figure 13. Impact of fuel composition, enrichment, size of the core, and power level for the GCMR measured in terms of (A) fuel lifetime, (B) LCOE FOAK, and (C) LCOE NOAK for a reactor with seven rings per fuel assembly.

This result also warrants more detailed technoeconomic studies, especially regarding transportation costs, to understand whether the substantial difference in fuel lifetime justifies a penalty for FOAK. As in the reflector study, the NOAK differences are inconsequential. For the best scenario described in the previous paragraph, the difference in NOAK's LCOE is only 8$/MWh, remaining within the bounds of cost uncertainties. Depending on the use case, if the long-term projected NOAK can be justified, UN might be the superior choice.

Considering the challenge of obtaining HALEU fuel, and considering the different combinations of fuel enrichment, core size, and fuel material, we opted for a 10%-enriched UO_2-loaded TRISO, targeting a power output of 17.5 MWth. For seven rings, the resulting fuel lifetime reached 3.1 years, with LCOE values of $391/MWh and $176/MWh for the FOAK and NOAK scenarios, respectively. Assuming the availability of HALEU increases in the future, it might be feasible to replace that LEU fuel core with 19.75% UO_2 to achieve a long fuel lifetime of 7.8 years and associated LCOE values of $364/MWh and $169/MWh for the FOAK and NOAK scenarios, respectively.

Considering the different scenarios of the HALEU availability, and also accounting for the issue of losing the moderating power of ZrH (as explained in previous section), if the core fuel lifetime is long (e.g., 7 years), it is hypothesized that specific reactor designs may be more suitable for specific scenarios, as Table 14 shows.

Table 14. Different TRISO-fueled GCMR design characteristics for different scenarios. The costs in this table are in 2024 USD.

Scenario	HALEU Unavailability (Low Enrichment Is Preferred)	Second Generation (HALEU Supply Chain Is Mature)	Second Generation (HALEU) and ZrH Is Replaced with YHx)
FOAK LCOE ($/MWh) **NOAK LCOE ($/MWh)**	391 ± 33 176 ± 21	364 ± 26 169 ± 16	397 ± 28 186 ± 17
Fuel Lifetime (years)	3.1	7.8	7.1
Power Output (MWth)	17.5	17.5	17.5
Size (diameter × height) in cm	2.88 × 2.88	2.88 × 2.88	2.88 × 2.88
Composition (packing fraction [%] / fuel type [-])	30/UO_2	30/UO_2	44*/UO_2
Fuel Enrichment (wt%)	10	19.75	19.75

<u>Impact of Enrichment, Uranium Content, and Power Level on the LTMR</u>

For the LTMR, we conducted a similar study but decided to retain the TRIGA-based fuel. Indeed, U-ZrH fuels are particularly well suited for use in advanced microreactors. While solid moderators are widely adopted, a more elegant approach to improving compactness is to incorporate the metal hydride directly into the fuel. The U-ZrH form has been used in TRIGA fuel and is particularly advantageous for advanced reactors: this fuel configuration exhibits excellent fission product retention, high-temperature stability, and strong negative feedback under large prompt-reactivity insertions (Evans 2024).

Increasing the fuel content (ratio of uranium weight to total fuel weight) may be beneficial by enhancing uranium loading, but this would come at the cost of reducing moderation. In this section, we discuss increasing the fuel content from 30% to 45%, which is consistent with the bound set by the Nuclear Regulatory Commission (1987). These trade-offs were interesting to quantify, especially at low enrichment.

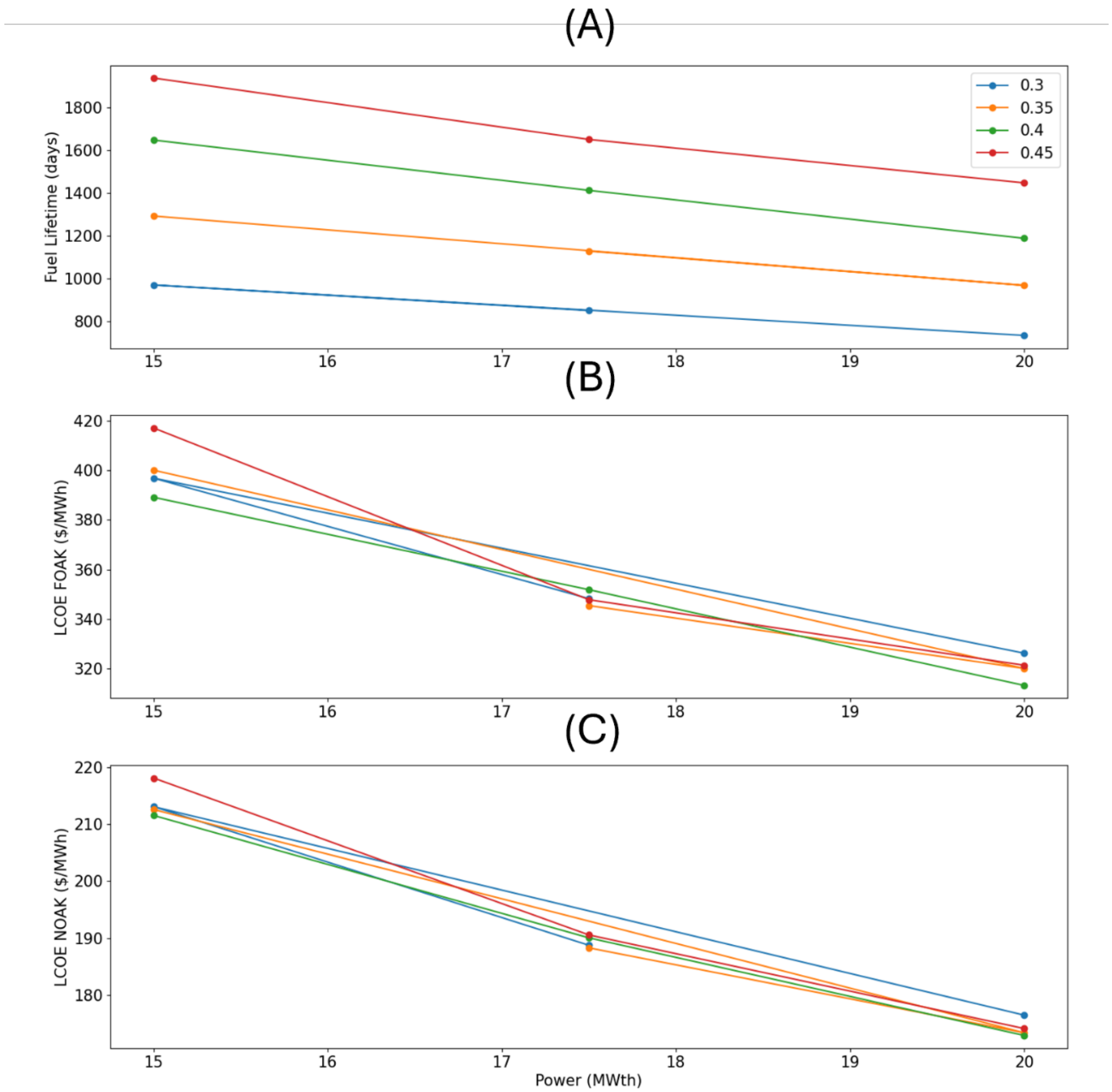

Figure 14. Impact of the fuel's composition, size of the core, and power level for the LTMR measured in terms of (A) fuel lifetime, (B) LCOE FOAK, and (C) LCOE NOAK. The fuel composition was changed by adjusting the ratio of uranium weight to total fuel weight, which takes the values 0.3, 0.35, 0.4, and 0.45. The enrichment was set at 10%.

The first observation is that increasing the uranium weight percent had a relatively linear effect on fuel lifetime, regardless of the power level (Figure 14A). Thus, the loss of moderation is outweighed by the benefits of higher uranium content. Interestingly, the effect on the LCOE is quite small, with all values remaining within the uncertainty bounds of each other. Therefore, increasing the uranium weight percent has an overall positive effect. However, it was not possible to achieve a comparable fuel lifetime at 20 MW_{th} at high enrichment levels. The optimal design was 10% enrichment and 45% weight percent uranium with a 14-cm reflector, which yielded a fuel lifetime of 5.3 years and an LCOE of $417/MWh and $218/MWh for the FOAK and NOAK scenarios, respectively.

Similar to the GCMR, when considering the different scenarios of HALEU availability and also accounting for the issue of losing the moderating power of ZrH if the core fuel lifetime is long, we hypothesize that specific reactor designs may be more suitable for specific scenarios, as Table 15 shows.

Table 15. Different TRIGA-fueled LTMR design characteristics for different scenarios. The costs in this table are in 2024 USD.

Scenario	HALEU Unavailability (Low Enrichment Is Preferred)	Second Generation (HALEU Supply Chain Is Mature)	Second Generation (HALEU) and ZrH Is Replaced with YHx
FOAK LCOE ($/MWh) NOAK LCOE ($/MWh)	319 ± 30 173 ± 19	317 ± 30 179 ± 20	312 ± 32 181 ± 21
Fuel Lifetime (years)	3.96	9.1	8.1
Power Output (MWth)	20	20	20
Size (diameter × height) in cm	1.06 × 1.06	1.06 × 1.06	1.06 × 1.06
Uranium Weight Percent (%)	45	45	45
Fuel Enrichment (wt%)	10	19.75	19.75

3.2.4. Summary of the Studies Conducted, and Lessons Learned

In this section, we summarize the hypotheses of our study and the lessons learned from the previous three sections.

Impact of Reflector Thickness and Composition

- Be-based reflectors are often utilized to reduce the size of microreactors and improve neutron economy. However, uncertainties related to cost and behavior at high temperatures might compel designers to switch to graphite-based reflectors, which exhibit inferior moderation properties. While the benefits in terms of fuel lifetime for BeO are substantial, the FOAK LCOE for Be-based reflectors is significantly greater than that of graphite. Even decreasing the reflector thickness by 90% does not compensate for this difference. BeO could potentially be superior in scenarios involving long-term projected NOAK LCOE for the GCMR, which would necessitate a reduction in reflector thickness (e.g., a 90% reduction in the GCMR case), or in designs that require more compact cores. This warrants further feasibility studies to determine the actual NOAK as well as the impact of smaller thickness and BeO on other factors, including power flattening and control drum worth.
- Increasing the reflector thickness will always increase the cost due to the larger volume occupied by the reactor vessel, even though fuel lifetime increases (which positively impacts fuel utilization and hence the LCOE). However, if transportability constraints are satisfied (i.e., keeping the reactor height and width below a certain threshold), the benefits of increased fuel lifetime outweigh the increase in cost.

Impact of Booster Radius and Composition

- The desired level of fuel residence time for LTMR and GCMR, as well as the operating temperature in the case of the GCMR, exceeds the hydrogen stability of ZrH. This compels designers to consider alternative solid moderators or moderator boosters in future work, including YHx, which exhibits higher stability and the capacity to attain high hydrogen content at elevated temperatures over longer periods. While the cost of YHx is currently unknown, we found that even if it were ten times that of ZrH, the impact on LCOE would be minimal. Moreover, the higher operating temperatures attainable (approximately 200°C more) would increase the thermal efficiency, thereby enhancing the overall economic competitiveness of the reactor (though this must be compared to the increased material costs resulting from harsher conditions in the secondary side).
- ZrH exhibits favorable moderation properties, and both fuel lifetime and LCOE were better in the ZrH case. To mitigate the differences, we proposed increasing the radius of the booster. The benefits in terms of fuel lifetime exceed the penalties of replacing (less expensive) graphite with hydrides in the ZrH case, but a sweet spot must be found for the YHx case. Due to the poor performance of YHx compared to ZrH, we recommend maximizing this radius, even if it may lead to a slightly higher LCOE. However, the hydrides may exhibit positive reactivity coefficients, and the radius must not exceed a threshold to maintain a negative coefficient.

Impact of Fuel Composition, Enrichment, Core Size, and Power Level

- It is found that regardless of power and reactor size, we found that increasing enrichment (for the TRISO-fueled GCMR) decreases the total LCOE, despite the increasing contribution of enrichment costs. The benefits of increasing fuel lifetime is found to outweigh these additional costs. This finding was less pronounced for the UZrH-fueled LTMR but still valid, and it was attributed to the high cost of the TRISO and UzrH fuels. For the TRISO-fueled GCMR, using UO_2 (in the TRISO particles) reduced the fuel lifetime by around a year, compared to using UN. However, the benefit in terms of LCOE FOAK of using UO_2 is about $40/MWh to $60/MWh, depending on the amount of uranium loaded.
- Considering the immaturity of the HALEU supply chain, we attempted to find a design in the LEU+ realm (5–10% uranium loaded) that is comparable to the baseline HALEU-based design. The penalty in terms of LCOE for the FOAK is about $70/MWh, which is also substantial. Therefore, we conclude that it is preferable to utilize HALEU for a TRISO design rather than LEU+, as the penalty on core size from using lower-enrichment fuel is too high.
- For the LTMR, we decreased the enrichment to LEU+ and studied the impact of increasing uranium content in U-ZrH, which is the fuel of choice for many LTMRs due to its inherent safety features and compatibility with the coolant. We found that it is preferable to maximize power output while increasing uranium content to achieve a smaller LCOE and significantly higher fuel lifetime.

Finally, many design decisions will depend on whether the stakeholders are focused on the short-term FOAK cost or the long-term plan for the NOAK cost. Indeed, most costs tend to flatten out at the NOAK unit and lie within the uncertainty ranges of one another.

4. REFERENCES

Abou-Jaoude, A., Y. Arafat, C. Bolisetti, B. Hanna, J. Belvedere, J. Blocker, B. Cooper, S. Harmon, and D. McCarthy. 2023. “Assessment of Factory Fabrication Considerations for Nuclear

Microreactors." *Nuclear Technology* 209 (11): 1697–1732. https://doi.org/10.1080/00295450.2023.2206779.

Abou-Jaoude, A., Y. Arafat, A. W. Foss, and B. W. Dixon. 2021. *An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept*. Report No. INL/EXT-21-63067, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1811894.

Abou-Jaoude, A., C. S. Lohse, L. M. Larsen, N. Guaita, I. Trivedi, F. C. Joseck, E. Hoffman, N. Stauff, K. Shirvan, and A. Stein. 2024. *Meta-Analysis of Advanced Nuclear Reactor Cost Estimations*. Report No. INL/RPT-24-77048, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/2371533.

Ade, B. J., B. R. Betzler, J. R. Burns, C. W. Chapman, and J. Hu. 2022. "Reactor Physics Considerations for Use of Yttrium Hydride Moderator." *Nuclear Science and Engineering* 196 (12): 1539–1558. https://doi.org/10.1080/00295639.2022.2035157.

Al-Dawood, K., B. Hanna, S. P. Balla, R. de Oliveira, S. Garcia, D. McCarthy, C. Bolisetti, B. Lindley, and A. Abou-Jaoude. 2025. "Open-Source Microreactor Design Models for Technoeconomic Assessments." *Nuclear Engineering and Design* 442: 114210. https://doi.org/10.1016/j.nucengdes.2025.114210.

Brown, N. R., R. Hernandez, and A. T. Nelson. 2022. "High Volume Packing Fraction TRISO-Based Fuel in Light Water Reactors." *Progress in Nuclear Energy* 146: 104151. https://doi.org/10.1016/j.pnucene.2022.104151.

Choi, N., M. K. Mohammad Jaradat, V. Laboure, J. A. Christensen, and S. Terlizzi. 2024. *Advancements in Multiphysics Microdepletion Analysis of an eVinciTM-like Microreactor Leveraging OpenMC-CRAB Workflow*. Report No. INL/RPT-24-77346, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/2341461.

De Candido, I. N., A. Al Rashdan, A. Abou-Jaoude, and J. Buongiorno. 2024. "Assessment of Technoeconomic Opportunities in Automation for Nuclear Microreactors." *Nuclear Science and Engineering* 1–20. https://doi.org/10.1080/00295639.2024.2372511.

De Candido, N., and K. Shirvan. 2022. "Graphite Life-Cycle Cost Model for HTGRs," Paper presented at the International High-Level Radioactive Waste Management Conference, Phoenix, AZ, November 13–17, 2022.

De Losada, L. J. F., J. Buongiorno, and A. Manera 2024. *Assessment of the Lifecycle Cost of Nuclear-Grade Coolants for Advanced Reactors*. Report No. MIT-ANP-TR-203, Cambridge, MA: Massachusetts Institute of Technology. https://47278698.fs1.hubspotusercontent-na1.net/hubfs/47278698/Lucas%20report%20203%20ANP-TR%20MIT%20CANES.pdf.

Delene, J. G., and C. R. Hudson, II. 1993. *Cost Estimate Guidelines for Advanced Nuclear Power Technologies*. Report No. ORNL/TM–10071/R3, Oak Ridge, TN: Oak Ridge National Laboratory. https://doi.org/10.2172/10176857.

Dixon, B., F. Ganda, K. Williams, E. Hoffman, and J. Hanson. 2017. *Advanced Fuel Cycle Cost Basis.*

Evans, J. A., and C. Parisi. 2024. "Optimizing Hydride Stability in U-ZrHx Nuclear Fuel: The 'Goldilocks Radius.'" *Nuclear Science and Engineering*, 1–20. https://doi.org/10.1080/00295639.2024.2383111.

Evans, J. A., C. N. Taylor, A. R. Wagner, R. T. Sweet, T. L. Lange, and N. E. Woolstenhulme. 2025. "Sensitivity Study of Hydrogen Soret Transport in Yttrium Hydride-Based Nuclear Fuel." *Nuclear Engineering and Design* 438: 114030. https://doi.org/10.1016/j.nucengdes.2025.114030.

Foster, C. H., I. W. Jentz, T. A. Moreira, T. J. Morton, G. F. Nellis, and M. H. Anderson. 2025. "Printed Circuit Primary Heat Exchanger for Power Conversion in Heat Pipe Microreactor Applications." *Applied Thermal Engineering* 275: 126879. https://doi.org/10.1016/j.applthermaleng.2025.126879.

Ganda, F., E. Hoffman, T. A. Taiwo, T. K. Kim, and J. Hansen. 2019. *Report on the ACCERT Cost Algorithms Tool*. Report No. ANL/NSE-19/10, Lemont, IL: Argonne National Laboratory.

Ganda, F., T. A. Taiwo, and T. K. Kim. 2018. Report on the Update of Fuel Cycle Cost Algorithms. Report No. NTRD-FCO-2018-000439, Lemont, IL: Argonne National Laboratory.

Gandrik, A., Wallace, B., Demick, L., Melancon, S., & Patterson, M. (2011). Assessment of high temperature gas-cooled reactor (HTGR) capital and operating costs. Idaho National Laboratory, TEV-1196, Idaho Falls, ID.

Gerstner, D., and Y. Arafat. 2023. MARVEL 90% Final Design Report. Report No. INL/RPT-23-74280-Rev000, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/2208844.

Gezelius, K. 2004. "Design of Compact Intermediate Heat Exchangers for Gas Cooled Fast Reactors." BS and MS thesis, Massachusetts Institute of Technology. https://dspace.mit.edu/bitstream/handle/1721.1/26911/56504354-MIT.pdf?sequence=2&isAllowed=y.

GORDIAN. 2024. "RSMeans Data." https://www.rsmeans.com/.

Halimi, A., and K. Shirvan. 2024. "Scale Effects on Core Design, Fuel Costs, and Spent Fuel Volume of Pressurized Water Reactors." *Annals of Nuclear Energy* 209: 110847. https://doi.org/10.1016/j.anucene.2024.110847.

Hanna, B. N., R. G. Gonzaga de Oliveira, K. A. Mohammed Al Dawood, M. D. Patterson, A. Abou-Jaoude, S. Garcia, and B. Lindley. 2024. *Technoeconomic Evaluation of Microreactor Using Detailed Bottom-up Estimate*. Report No. INL/RPT–24-80433-Rev001, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/2447366.

Hoffman, E., A. Abou-Jaoude, and A. Foss. 2020. *Improvement of ACCERT Algorithm - FY20*. Report No. ANL/NSE-20/28, Lemont, IL: Argonne National Laboratory.

Hu, X., D. Schappel, C. M. Silva, and K. A. Terrani. 2020. "Fabrication of Yttrium Hydride for High-Temperature Moderator Application." *Journal of Nuclear Materials* 539: 152335. https://doi.org/10.1016/j.jnucmat.2020.152335.

Jaradat, M., S. Schunert, and J. Ortensi. 2023. *Gas-Cooled High-Temperature Pebble-Bed Reactor Reference Plant Model*. Report No. INL/RPT-23-72192, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1984239.

Nuclear Regulatory Commission. n.d. "General Questions About NRC Fees." Accessed August 27, 2025. https://www.nrc.gov/about-nrc/regulatory/licensing/general-fee-questions.pdf.

Nuclear Regulatory Commission. Proposed Rule. "Fee Schedules; Fee Recovery for Fiscal Year 2025." *Federal Register* 90, no. 32 (February 19, 2025): 9848. https://nst.inl.gov/pubs/SitePages/2023-CMOS%20Reference%20Diagrams.pdf.

Nuclear Regulatory Commission. 1987. *Safety Evaluation Report on High-Uranium Content, Low-Enriched Uranium-Zirconium Hydride Fuels for TRIGA Reactors*. Report No. NUREG-1282, U.S. Nuclear Regulatory Commission.

Prosser, J. H., M. Graham, Y. Acevedo, M. Jensen, B. D. James, and A. Abou-Jaoude. 2024. *First-Principles Cost Estimation of a Sodium Fast Reactor Nuclear Plant*. Report No. INL/RPT-23-74316, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/2007008.

Romano, P. K., N. E. Horelik, B. R. Herman, A. G. Nelson, B. Forget, and K Smith. 2015. "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development." *Annals of Nuclear Energy* 82: 90–97. https://doi.org/10.1016/j.anucene.2014.07.048.

Romano, P. K.., N. E. Stauff, Z. J. Ooi, Y. Miao, A. Lund, and L. Zou. 2022. "WATTS: Workflow and Template Toolkit for Simulation." *Journal of Open Source Software* 7 (79): 4735. https://doi.org/10.21105/joss.04735.

Roosen, P., S. Uhlenbruck, and K. Lucas. 2003. "Pareto Optimization of a Combined Cycle Power System as a Decision Support Tool for Trading Off Investment Vs. Operating Costs." *International Journal of Thermal Sciences* 42 (6): 553–560. https://doi.org/10.1016/S1290-0729(03)00021-8.

Shirvan, K., J. Buongiorno, R. MacDonald, B. Dunkin, S. Cetiner, E. Saito, T. Conboy, and C. Forsberg. 2023. "UO_2-Fueled Microreactors: Near-Term Solutions to Emerging Markets." *Nuclear Engineering and Design* 412: 112470. https://doi.org/10.1016/j.nucengdes.2023.112470.

Sprouster, D. J., M. Ouyang, N. Cetiner, P. Negi, A. Sharma, D. Bhardwaj, Y. Huang, X. Hu, K. Shirvan, and L. L. Snead. 2025. "Low Temperature Neutron Irradiation Stability of Zirconium Hydride and Yttrium Hydride." *Journal of Nuclear Materials* 609: 155770. https://doi.org/10.1016/j.jnucmat.2025.155770.

Stewart, W. R., and K. Shirvan. 2022. "Capital Cost Estimation for Advanced Nuclear Power Plants." *Renewable and Sustainable Energy Reviews* 155: 111880. https://doi.org/10.1016/j.rser.2021.111880.

United Engineers and Constructors. 1980. *1170 MW/sub t/ HTGR Steamer Cogeneration Plant: Design and Cost Study*. Report No. DOE/ET/34222-T1, Philadelphia, PA: United Engineers and Constructors. https://doi.org/10.2172/5084245.

Yoon, S.-J., P. Sabharwall, and E.-S. Kim. 2013. *Analytical Study on Thermal and Mechanical Design of Printed Circuit Heat Exchanger*. Report No. INL/EXT-13-30047, Idaho Falls, ID: Idaho National Laboratory. https://doi.org/10.2172/1116746.

Zisk, R. 2025. "The NRC Passes New Rules for Advanced Reactor Companies." Ignition. June 6. https://ignition-news.com/the-nrc-passes-new-rules-for-advanced-reactor-companies.