# Aligning Design Costs with Market Constraints for Microreactors

## Market-Specific Design Selection and Economic Assessment Using MOUSE

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# ABSTRACT

Microreactor markets differ in their access to high-assay low-enriched uranium (HALEU), transportation limitations, required operating lifetime, power demand, and available capital. These requirements can change both the cost of a reactor, and the set of reactor designs capable of serving a market. This study uses the Microreactor Optimization Using Simulation and Economics (MOUSE) tool to quantify these effects for liquid-metal thermal microreactor (LTMR), gas-cooled microreactor (GCMR), and heat-pipe microreactor (HPMR) concepts. A broad design space was explored using enrichments of 4.95%, 9.9%, 15%, and 19.75% U-235 and nominal thermal powers of 2, 15, 30, and 50 MWt. Designs were screened using a shutdown margin, temperature coefficient, and fuel lifetimes between two and six years. First-of-a-kind (FOAK) and nth-of-a-kind (NOAK) levelized costs of electricity (LCOEs) were then evaluated without tax credits. This analysis constitutes design-space exploration rather than formal design optimization.

When HALEU is unavailable, the LTMR provides the lowest identified LCOE at 15–50 MWt, with FOAK/NOAK values decreasing from $530/$303 per MWh at 15 MWt to $263/$149 per MWh at 50 MWt. When HALEU is available, the LTMR generally provides the lowest FOAK LCOE, while the GCMR provides a low NOAK LCOE. Across 15–50 MWt, the resulting minimum FOAK/NOAK values decrease from $453/$243 per MWh to $226/$121 per MWh. The TRISO-fueled GCMR and HPMR configurations are generally larger and have a greater FOAK fuel-cost contribution in the current models; however, the GCMR becomes competitive under NOAK manufacturing and learning assumptions.

Of 2,144 technically eligible designs, 761 satisfy the defined standard-road transportation limits. This filter removes most GCMR designs and all evaluated HPMR designs but produces almost no increase in the minimum LCOE because several low-cost LTMR and GCMR configurations remain available. Requiring irradiated-module take-back is more restrictive: GCMR options remain only at 2 MWt, LTMR options remain at 2–30 MWt, and no evaluated 50-MWt or HPMR design qualifies. Longer operating cycles can also increase LCOE, although three- and four-year cycles are frequently available with little penalty. Markets limited to low total capital are restricted to smaller reactors with substantially higher LCOEs. The results indicate that tailoring a microreactor to a market requires considering both the LCOE of qualifying designs and the reactor options eliminated by the market’s technical and financial constraints.

These findings are intended solely to provide comparative insights for research and early-stage screening. The LTMR, GCMR, and HPMR models represent pre-conceptual designs that have not been fully optimized and do not represent final or licensed reactor configurations. MOUSE necessarily uses simplifying assumptions and incomplete engineering, procurement, manufacturing, and cost information. Significant uncertainty therefore remains across the estimates, particularly for novel and FOAK components. The reported minimum LCOEs are the lowest values identified within the sampled design space, not proven economic optima or investment-grade estimates. They should not be used as the sole basis for financial, investment, procurement, licensing, or project-development decisions.

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# ACRONYMS

| | |
|---|---|
| CFR | Code of Federal Regulations |
| DOE | U.S. Department of Energy |
| DOT | U.S. Department of Transportation |
| FHWA | Federal Highway Administration |
| FOAK | first-of-a-kind |
| GCMR | gas-cooled microreactor |
| HALEU | high-assay low-enriched uranium |
| HPMR | heat-pipe microreactor |
| INL | Idaho National Laboratory |
| ISO | International Organization for Standardization |
| LCOE | levelized cost of electricity |
| LEU | low-enriched uranium |
| LEU+ | low-enriched uranium plus |
| LTMR | liquid-metal thermal microreactor |
| MOUSE | Microreactor Optimization Using Simulation and Economics |
| MRP | Microreactor Program |
| MWe | megawatt electric |
| MWh | megawatt-hour |
| MWt | megawatt thermal |
| N+1 | number of units required to serve the load plus one reserve unit |
| NEI | Nuclear Energy Institute |
| NOAK | nth-of-a-kind |
| OpenMC | open-source Monte Carlo particle-transport code |
| pcm | per cent mille |
| PNNL | Pacific Northwest National Laboratory |
| TCI | total capital investment |
| TRISO | tristructural isotropic |
| WATTS | Workflow and Template Toolkit for Simulation |

# Aligning Design Costs with Market Constraints for Microreactors

Market-Specific Design Selection and Economic Assessment Using MOUSE

## 1. INTRODUCTION

### 1.1 Background

Microreactors are being developed to provide electricity and heat for applications that may not be well served by conventional large-scale generation. Potential applications include remote communities, mines, military and federal installations, isolated grids, industrial facilities, and other customers that place a high value on reliable, locally available energy. The attractiveness of microreactors for these applications is associated not only with their relatively small power output, but also with potential characteristics such as factory fabrication, transportability, long operating cycles, limited onsite staffing, modular deployment, and operation independently from a large electrical grid (Shropshire et al. 2021; Black et al. 2022).

These potential customers do not, however, require the same reactor product. A remote community with a small electrical load may prioritize low initial capital investment, long fuel life, and limited onsite staffing. A permanent military installation may require firm power and redundancy, while a mobile or austere military application may impose strict transportation limits. A large remote mine may require considerably more power but could still face restrictions on fuel availability, site access, and the frequency with which the reactor can be refueled. Consequently, the reactor design with the lowest unrestricted levelized cost of electricity (LCOE) may not be the lowest-cost design capable of meeting a particular customer's requirements.

Previous market studies have identified potential microreactor applications and examined the technical, economic, infrastructure, and institutional conditions affecting their deployment. Shropshire et al. (2021) developed microreactor deployment indicators and used them to characterize potential profile markets, including isolated operations, distributed energy systems, resilient urban applications, marine propulsion, and disaster relief. Black et al. (2022) reviewed the technology, economic, market, regulatory, and safety considerations associated with microreactor deployment. The Nuclear Energy Institute evaluated the potential cost competitiveness of stationary microreactors in remote communities, mining operations, and military installations, among other remote applications (Nuclear Energy Institute 2019). Collectively, these studies provide a literature basis for identifying relevant markets and understanding their potential requirements.

Other studies have focused more directly on the relationship between market requirements and reactor design. Forsberg et al. (2022) introduced an economics-by-design framework in which market needs are translated into design and economic requirements early in reactor development. This approach recognizes a fundamental tradeoff between product standardization, which supports factory production and cost reduction, and customization, which may be necessary to

serve customers with different power, temperature, transportation, fuel-cycle, reliability, and economic requirements. Forsberg (2023) further examined the economic requirements of fission batteries across applications such as off-grid electricity, industrial heat, hydrogen production, biofuels, and maritime markets. Buongiorno et al. (2021) similarly emphasized that standardized, factory-fabricated nuclear batteries could serve distributed electricity and heat markets, provided that their capital and operating costs are compatible with the energy services being supplied.

The Microreactor Optimization Using Simulation and Economics (MOUSE) tool (Hanna et al. 2025) provides a means of quantifying these relationships. MOUSE integrates OpenMC-based reactor-physics calculations, simplified balance-of-plant calculations, and bottom-up cost estimation for three representative microreactor classes: a liquid-metal-cooled thermal microreactor (LTMR), a gas-cooled microreactor (GCMR), and a heat-pipe microreactor (HPMR). The tool calculates technical and economic outputs, including reactor dimensions, material quantities, fuel lifetime, capital costs, operating costs, and FOAK and NOAK LCOE. MOUSE can therefore be used to examine how restrictions on enrichment, power, fuel lifetime, transportability, capital investment, and site configuration change the feasible design space and the cost of the lowest-LCOE design (Hanna et al. 2025).

The objective of this report is to quantify the design and economic consequences of selected market requirements using MOUSE. Rather than assigning a particular reactor technology to an entire market in advance, the analysis begins with literature-supported requirements and determines which simulated LTMR, GCMR, and HPMR designs remain feasible after those requirements are imposed. The minimum LCOE among the remaining designs is then compared with an appropriate reference case. This comparison measures the LCOE penalty associated with satisfying a market requirement and identifies the physical or economic constraint responsible for that penalty.

The report addresses the following research questions:

1. How does the availability or unavailability of high-assay low-enriched uranium (HALEU) affect reactor feasibility, design characteristics, fuel lifetime, and minimum LCOE?
2. How do market-specific transportability requirements affect the number and types of reactor designs that remain available, and what LCOE penalty results from eliminating designs that do not satisfy the applicable transportation envelope?
3. How does requiring a longer fuel lifetime affect reactor size, fuel loading, enrichment, feasible power range, and minimum LCOE?
4. How do small- and large-power requirements affect the feasible reactor technologies and the minimum LCOE available within each power range?
5. How does limiting the capital available for an individual project or site affect reactor selection and the tradeoff between initial capital investment and LCOE?

## 1.2 Scope

This work tailors reactor design and cost estimates to user-specified market constraints, including HALEU availability, refueling frequency, and the differing needs of applications such

as U.S. military installations and remote Arctic communities. MOUSE is used to assess the design and cost implications of these requirements and to identify the lowest-LCOE feasible design for each evaluated set of constraints. In this report, “optimal reactor design” means the lowest-LCOE technically feasible design within the evaluated MOUSE design space; it does not mean the optimal design among all existing or proposed commercial microreactors.

The quantitative analysis considers principal market requirements:

1. Availability or unavailability of HALEU
2. Reactor transportability
3. Long fuel lifetime
4. Small- or large-power requirements
5. Limited project or site capital

HALEU availability is treated as a fuel-supply constraint because enrichment affects fuel lifetime, fuel inventory, reactor size, and the range of achievable power levels. DOE identifies smaller reactor designs and longer operating cycles as important motivations for using HALEU while recognizing that gaps in domestic supply could delay advanced-reactor deployment. The analysis therefore compares conventional-LEU designs with designs for which the evaluated HALEU enrichment levels are available.

Transportability is defined as compatibility with a specified logistics envelope, rather than the general ability to move a reactor using specialized equipment. The analysis distinguishes permanent applications, which require initial delivery of the fresh reactor module, from temporary, mobile, or vendor take-back applications that also require removal of the irradiated module. Transportability is evaluated primarily using module mass and dimensions, with shielding and packaging effects included for irradiated-return cases.

Fuel-lifetime and power requirements also differ among markets. Applications with difficult site access, limited fuel-handling capability, or a strong need to avoid refueling outages may place greater value on long operating cycles. Other applications may accept more frequent refueling if it reduces reactor size, fuel inventory, or cost. Required power also varies substantially: a small remote community may need relatively little energy, whereas a military installation, mine, or industrial facility may require a much higher output. This report evaluates how these different fuel-lifetime and power requirements affect the feasible reactor designs and their LCOE.

Capital-constrained applications are evaluated by limiting allowable initial capital investment and identifying the minimum LCOE achievable under that limit. If the literature does not support a single capital ceiling, a range of limits is evaluated.

Before market requirements are imposed, candidate designs are screened using the technical feasibility criteria applicable to each MOUSE reactor model. These criteria include successful completion of the required calculations, achievement of the required critical lifetime, adequate shutdown margin, and acceptable reactivity feedback. Heat-flux and power-peaking limits are included where consistently available.

The analysis does not attempt to reproduce the complete conditions of every military installation, Arctic community, mine, or other customer. These markets vary in load, transportation access, capital availability, reliability needs, fuel-management arrangements, and operating life. The selected requirements are therefore evaluated individually, and their design and cost implications are interpreted in relation to the markets for which each requirement is relevant. Values based on engineering judgment rather than a cited source are identified as study assumptions. The results demonstrate how MOUSE can support market-informed design decisions but should not be interpreted as evaluations of complete market profiles or as universal reactor recommendations for an entire market.

# 2 FROM MICROREACTOR MARKETS TO QUANTITATIVE REQUIREMENTS

## 2.1 Microreactor Markets

Several studies have evaluated potential markets for microreactors and the characteristics that could make these reactors attractive to customers. These studies describe a range of applications that differ in energy demand, infrastructure, fuel access, operating conditions, and ability to support a conventional nuclear facility.

Shropshire et al. (2021) developed a global market assessment that matched microreactor characteristics with potential use cases and profile markets. The study identified applications involving isolated operations, distributed energy, resilient urban systems, marine propulsion, and disaster relief. It also incorporated previous work on remote and Arctic communities, islands, mining operations, and U.S. government facilities. Black et al. (2022) reviewed many of the same markets while emphasizing the potential value of transportability, resilience, grid independence, long refueling intervals, and the ability to supply both electricity and heat.

The principal markets, identified in the literature, are summarized in Table 1.

Table 1. Microreactor markets identified in the literature (Shropshire et al. 2021; NEI 2019, Black et al. 2022, Forsberg et al. 2022; Forsberg and Foss 2023).

| Market | Principal reasons for considering microreactors |
|---|---|
| Remote and Arctic communities: villages, rural hubs, isolated community systems | Local electricity and heat, reduced dependence on delivered fuel, long operating cycles |
| Military and government installations | Resilient onsite power, grid independence, possible mobility |
| Mining sites and resource extraction | Continuous energy demand, limited grid access, possible temporary deployment |
| Island utilities and isolated grids | Reduced dependence on imported fuel and isolated-grid operation |

| | |
|---|---|
| Industrial applications: Manufacturing, process heat, hydrogen, biofuels | Continuous electricity and heat demand |
| Critical infrastructure, microgrids and critical government facilities | Firm onsite power and continued operation during grid disruptions |

The literature on microreactor markets can be interpreted in terms of the underlying requirements Forsberg et al. (2022) organize market considerations around market size, profitability, operating objectives, and nuclear-specific requirements. Shropshire et al. (2021,) similarly translate microreactor deployment indicators into reactor-design characteristics. Based on these frameworks, the principal requirements can be summarized as follows:

- **Energy service and required power.** A small community may primarily require electricity and district heat, while a mine or industrial facility may require considerably more power or higher-temperature process heat. The required power influences reactor size, fuel inventory, balance-of-plant capacity, number of modules, and capital investment. (Shropshire et al. 2021).
- **Fuel availability and enrichment.** Reactor developers and customers may not have assured access to the same fuel supply. HALEU can support smaller cores and longer operating cycles for many advanced-reactor concepts, but its availability remains a deployment concern. Restricting a design to conventional LEU can affect core size, fuel mass, achievable lifetime, and power output (DOE 2026).
- **Fuel lifetime and refueling frequency.** Applications with difficult site access, limited fuel-handling capabilities, or a high cost of outages may prefer long operating cycles. A long lifetime may reduce the frequency of fuel deliveries and refueling outages, but it can require additional fuel, higher enrichment, or a larger core. The preferred cycle length is therefore market-dependent rather than an inherent characteristic of all microreactor applications (Black et al. 2022; Forsberg et al. 2022).
- **Transportability and site access.** Transportability is especially relevant where the customer has limited road, port, rail, air, or heavy-lift infrastructure. The meaningful requirement is not whether a reactor can be transported by any conceivable specialized method, but whether the reactor module fits the logistics system available to the customer. Permanent applications may require only initial delivery of the fresh reactor. Temporary, mobile, or vendor take-back applications may also require removal of the irradiated module, including any shielding and packaging needed for transportation.
- **Capital availability**. Customers differ in their ability to finance a project. A design with the lowest LCOE may require a larger initial investment than a customer can support. Conversely, minimizing initial capital may result in a smaller plant, a greater number of modules, or a higher LCOE. Remote communities and small industrial customers may be particularly sensitive to initial project cost, while larger government or industrial customers may be able to accept greater capital investment in exchange for lower long-term energy costs or improved reliability (NEI 2019, Shropshire et al. 2021).

## 2.2 Requirements Selected for Quantitative Analysis

The literature identifies more market considerations than can currently be represented quantitatively in MOUSE. The present study therefore focuses on requirements that satisfy four conditions:

- The requirement is relevant to one or more markets identified in the literature.
- It can be represented using a MOUSE input, calculated output, fleet calculation, or post-processing screen.
- It can materially affect reactor feasibility, design, or LCOE.
- It can be evaluated using the available LTMR, GCMR, and HPMR simulation datasets.

Based on these criteria, six requirements are selected for quantitative analysis:

1. **HALEU availability:** Designs are evaluated with and without access to the modeled HALEU enrichment levels. The analysis determines how the fuel constraint affects feasible power and cycle-length combinations, reactor characteristics, and minimum LCOE.
2. **Transportability:** Reactor mass and dimensions are compared with defined transportation envelopes. Permanent road applications require transport of the fresh reactor module. Vendors take-back and mobile defense cases also evaluate transportation of the irradiated module after a specified cooldown period.
3. **Long fuel lifetime:** Minimum operating-cycle requirements are applied to determine which designs can operate for the required period without refueling and how progressively longer cycles affect design and LCOE.
4. **Required power:** Designs are grouped according to the power needs of different applications. The analysis identifies the feasible reactor concepts and minimum LCOE within the selected power ranges.
5. **Available capital:** A maximum allowable capital investment is imposed to determine which designs remain available and how limiting initial capital changes the minimum achievable LCOE.

Other requirements, including heat-delivery temperature, seasonal demand, black-start capability, detailed load following, autonomous operation, staffing, security, licensing difficulty, and quantified resilience value, may be relevant to particular markets but are not included as quantitative constraints in this analysis. They are discussed qualitatively where appropriate and identified as areas for future MOUSE development.

The selected requirements do not independently define complete markets. Instead, each requirement is evaluated separately to determine its effect on the feasible design space, reactor selection, and minimum LCOE. The results are then interpreted in the context of the markets for which each requirement is relevant.

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# 3 MOUSE ANALYSIS FRAMEWORK

The Microreactor Optimization Using Simulation and Economics tool (MOUSE) is a Python-based framework that connects early-stage microreactor design decisions with technical performance and economic outcomes. It integrates reactor-physics simulations, simplified engineering calculations, balance-of-plant models, and bottom-up cost estimation within a common workflow. A detailed description of the original MOUSE methodology is provided by Hanna et al. (2025,). Therefore, this chapter provides only the information needed to understand its application in the present analysis.

As shown in Figure 1, a MOUSE analysis begins with user-defined technical and economic inputs, including reactor materials, geometry, control systems, balance-of-plant configuration, shielding and vessel characteristics, operating assumptions, and financial parameters. MOUSE uses the Workflow and Template Toolkit for Simulation (WATTS) to coordinate the calculations and support parametric, sensitivity, and uncertainty analyses.

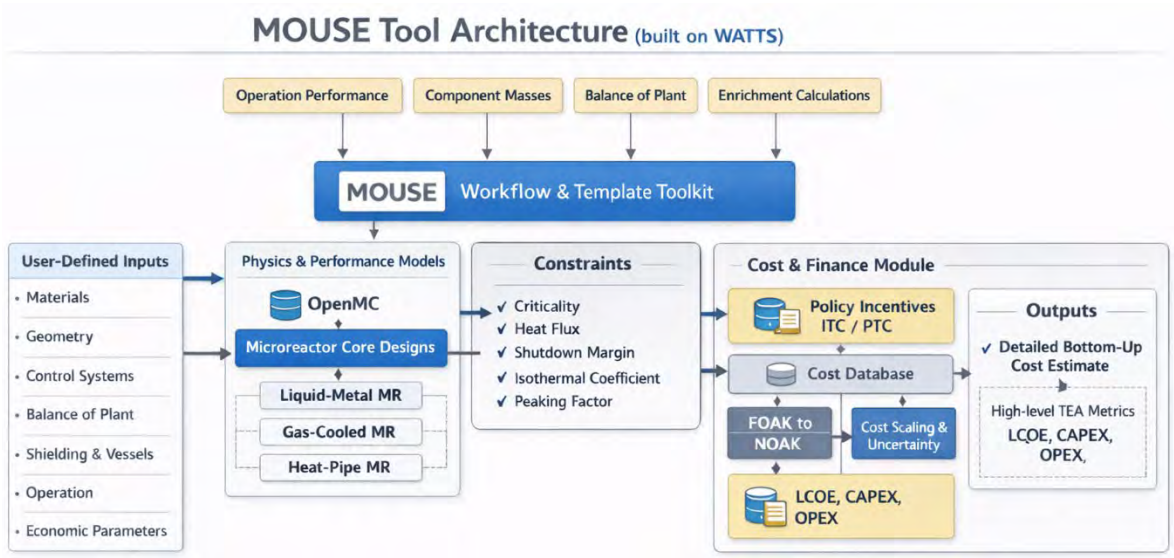



Figure 1. MOUSE tool architecture and the relationship among user-defined inputs, reactor-physics and performance models, technical constraints, and economic outputs.

The physics and performance portion of the workflow uses OpenMC to evaluate the reactor core. MOUSE currently includes preconceptual models representing three reactor classes:

- A liquid-metal thermal microreactor (LTMR);
- A gas-cooled microreactor (GCMR); and
- A heat-pipe microreactor (HPMR).

Supporting calculations estimate operating performance, component masses, balance-of-plant requirements, and fuel enrichment. The resulting designs can then be evaluated against technical constraints, including criticality, heat flux, shutdown margin, isothermal temperature coefficient, and power-peaking limits.

Designs are evaluated using the MOUSE cost and finance module. The module develops detailed bottom-up estimates of capital, fuel, operations and maintenance, replacement, and decommissioning costs. It can also represent cost scaling, uncertainty, policy incentives, and the transition from first-of-a-kind to nth-of-a-kind deployment. Principal outputs include capital expenditure, operating expenditure, overnight capital cost, total capital investment, and levelized cost of electricity.

The complete MOUSE research code is publicly available through the MOUSE GitHub repository. Users who do not require a new OpenMC calculation can explore precomputed results through the MOUSE web application.

Detailed descriptions of the current LTMR, GCMR, and HPMR models, links to the MOUSE repository and web application, and the principal economic and operating assumptions used in this analysis are provided in Appendix A. Appendix B summarizes the shielding methods used for both the reactor site and the transportation of an irradiated reactor module

# 4 QUANTITATIVE EVALUATION OF MARKET REQUIREMENTS

The analysis varies selected MOUSE design inputs to generate a broad set of candidate reactor designs. Variations in parameters such as fuel enrichment, fuel loading, core geometry, reflector dimensions, control-system characteristics, and reactor power produce designs with different operating lifetimes, physical dimensions, material requirements, and costs. The purpose is to identify multiple technically plausible designs across the ranges of power and operating lifetime relevant to the markets considered in this report.

The candidate designs are not evaluated on cost alone. Additional attention is given to designs that satisfy two design constraints:

- **Shutdown margin:** MOUSE simulates the reactor with its shutdown control elements fully inserted. The shutdown margin is calculated from the effective multiplication factor in this shutdown configuration. The minimum shutdown margin calculated over the reactor operating cycle must exceed 1,000 pcm. This requirement provides confidence that the modeled control system can maintain the reactor sufficiently subcritical after shutdown.
- **Isothermal temperature coefficient:** MOUSE performs paired calculations at the reference temperature and at a uniformly elevated temperature. The most limiting coefficient over the operating cycle must be negative. A negative value means that an increase in reactor temperature introduces negative reactivity, providing an inherent stabilizing response.

For both constraints, MOUSE evaluates the reactor at beginning, middle, and end of life and applies the criterion to the most limiting result. These two criteria do not constitute a complete assessment of reactor feasibility or safety. Additional constraints could include power-peaking limits, fuel and material temperature limits, transient response, passive decay-heat removal, structural margins and coolant behavior. The present analysis uses shutdown margin and the isothermal temperature coefficient as an initial screening step to make the designs carried forward into the cost analysis more realistic; passing these criteria should not be interpreted as demonstrating a complete or licensable reactor design.

Following this technical screening, the remaining designs are evaluated against the selected market requirements. All economic results presented in this chapter exclude federal investment and production tax credits.

## 4.1 HALEU Availability

The availability of high-assay low-enriched uranium (HALEU) is an important market constraint for microreactor deployment because enrichment affects fuel loading, core dimensions, attainable operating lifetime, and fuel cost. Although many advanced reactor designs rely on HALEU to obtain smaller cores and longer operating cycles, a mature domestic commercial supply is not yet broadly available. DOE is addressing this limitation through enrichment contracts, material allocations, and limited initial production under the HALEU Availability Program (DOE 2026a, DOE 2026b). Consequently, a reactor designed around upper-end HALEU may provide favorable technical performance but face greater fuel-supply and deployment risk.

This analysis evaluates four enrichment values: 4.95%, 9.9%, 15%, and 19.75% U-235. These values are not intended to represent four formal regulatory categories. Instead, they span four plausible fuel-availability scenarios and allow the technical and economic value of increasing enrichment to be quantified:

- **4.95% U-235:** This case represents conventional-assay fuel just below 5% enrichment. It is relevant when HALEU is unavailable or when a project prioritizes compatibility with the established commercial fuel supply. Nearly all current commercial reactor fuel is enriched between 3% and 5% U-235 (DOE 2025). This case establishes the design and LCOE consequences of avoiding dependence on HALEU.
- **9.9% U-235 (lower-assay HALEU case):** DOE defines LEU+ as uranium enriched between 5% and 10% U-235. The 9.9% case therefore represents a real lower-assay HALEU design pathway. It is relevant to microreactors designed specifically around enrichment near 10%
- **15% U-235 (**representative mid-assay HALEU case): Fifteen percent is included as a representative intermediate assay within the HALEU range to determine how reactor performance and cost change between the lower-assay 9.9% case and the upper-end 19.75% case. This case is relevant to reactor designs that require more fissile material than lower-assay HALEU can provide but do not require enrichment near the maximum HALEU level. Accordingly, the 15% case should be interpreted as a design-sensitivity case rather than as a distinct market or fuel-supply scenario.

- **19.75% U-235:** This case represents access to upper-end HALEU and provides a benchmark for the greatest enrichment considered in the study. It is relevant to a more mature HALEU supply scenario or to applications that place a high value on compactness, long operating cycles, or reduced fuel volume. DOE currently describes the HALEU range as extending from above 5% through 19.75% U-235.

The four subsections that follow evaluate the technically screened reactor designs available at each enrichment level and compare their economic performance. The objective is not to assume that higher enrichment is always preferable, but to determine when its technical benefits compensate for its additional fuel cost and supply constraints.

### 4.1.1 4.95% U-235: Conventional LEU

The 4.95% U-235 case evaluates the consequences of designing microreactors using conventional low-enriched uranium (LEU), thereby avoiding dependence on the emerging HALEU supply chain. Rather than optimizing a single reactor configuration, the analysis explored a broad range of LTMR, GCMR, and HPMR design cases. Input parameters were varied to identify combinations capable of providing the desired power and operating lifetime while satisfying two principal design constraints: a shutdown margin greater than 1,000 pcm and a limiting temperature coefficient below 0 pcm/K. This approach constitutes a design-space exploration, not a formal optimization. Consequently, the lowest LCOEs identified here are the lowest values found within the explored design space and should not be interpreted as the theoretical minimum achievable for each reactor type.

The principal variables explored for each reactor model are summarized in Table 2. The design process was conducted through successive simulation campaigns, with later campaigns targeting regions that were insufficiently represented or unsuccessful in the initial calculations.

Table 2. Principal design variables explored in the 4.95% U-235 simulation campaigns.

| Reactor model | Design variables and explored values or ranges |
|---|---|
| LTMR | Core rings: 8–23; active height: 26.7–197.7 cm; moderator arrangement: fuel-rich, baseline, and moderator-rich; equal radial and axial reflector thickness: 20–50 cm; shutdown rods: 6 or 12; shutdown-rod absorber radius: 1.30 or 1.35 cm; shutdown-rod cladding radius: 1.50 or 1.55 cm; control-drum absorber arc: 120°, 135°, or 150° |

| | |
|---|---|
| GCMR | Core rings: 3–16; active height: 93.5–771.6 cm; target aspect-ratio families: 0.6, 1.0, 1.4, and 1.8, with realized aspect ratios of approximately 0.62–2.65 in the follow-up study; TRISO packing fraction: 11.1–40%; uranium inventory: 600–5,255.5 kg; equal radial and axial reflector thickness: 20–50 cm; shutdown-system size: 24, 48, 84, or 120 rods; central shutdown-rod absorber radius: 0.85 or 0.90 cm; surrounding shutdown-rod absorber radius: 0.45, 0.70, or 0.90 cm; control-drum absorber arc: 120° or 150° |
| HPMR | Core rings: 3–14; active height: approximately 120–868 cm; target core aspect ratio: 0.6–1.8; TRISO packing fraction: 12.9–40%; fuel-compact meat radius: 1.15, 1.30, or 1.40 cm; fuel-compact outer radius: 1.20, 1.35, or 1.45 cm; lattice pitch: 3.0, 3.2, or 3.4 cm; assembly configuration: 72 fuel compacts with 19 heat pipes or 78 fuel compacts with 13 heat pipes; equal radial and axial reflector thickness: approximately 35–112 cm; central shutdown-rod absorber radius: 2–5 cm; shutdown-rod cladding radius: 2.2–5.2 cm; control-drum absorber arc: 120° or 150° |

Figure 2 presents the LCOE results for the LTMR and GCMR cases that satisfied both design constraints. The minimum LCOEs identified at each power level are summarized in Table 3.

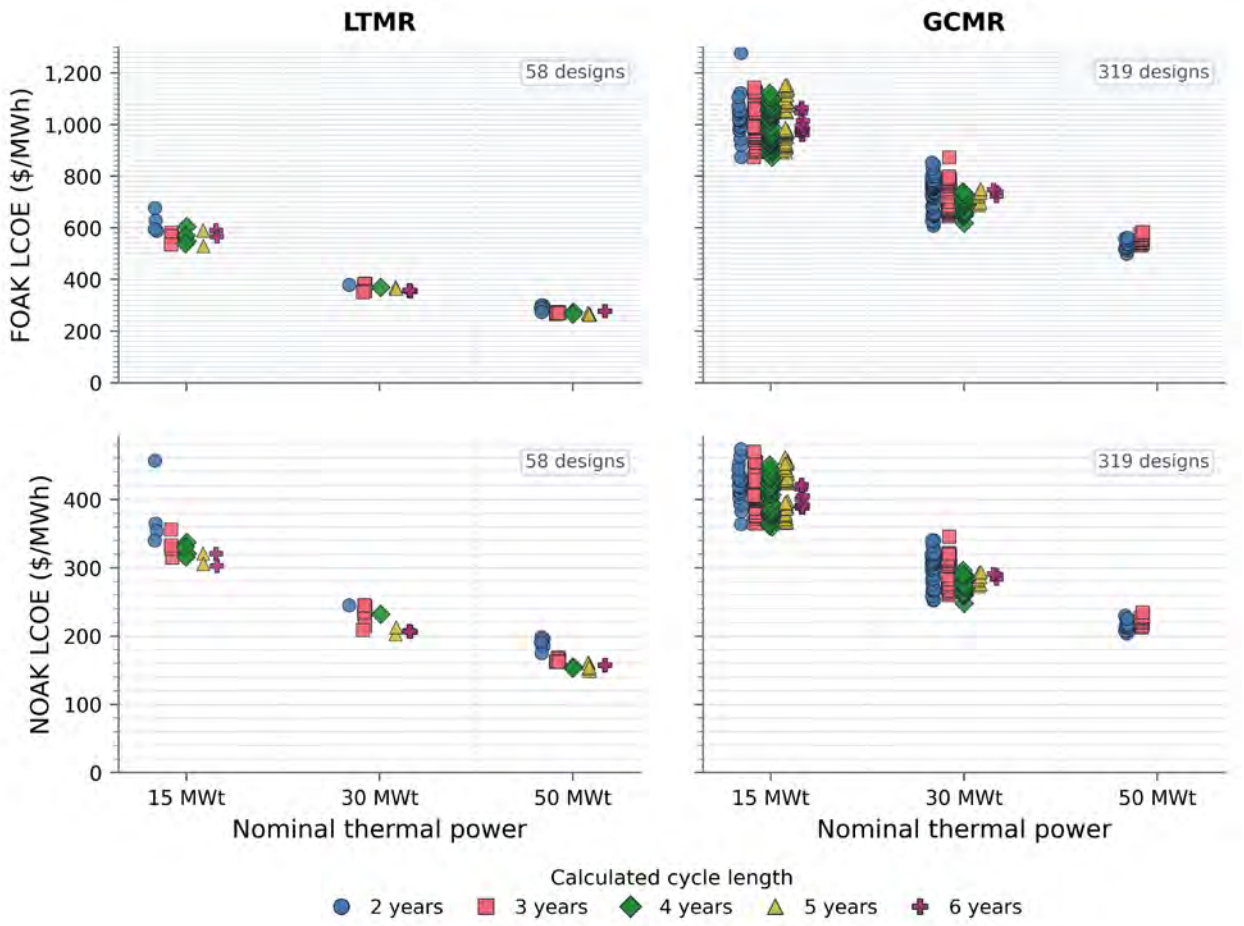



Figure 2. FOAK and NOAK LCOE for constraint-satisfying LTMR and GCMR designs using 4.95% U-235 fuel. Only designs at nominal thermal power levels of 15, 30, and 50 MWt are included. A design is included only when its most limiting shutdown margin is greater than 1,000 pcm and its most limiting temperature coefficient is less than 0 pcm/K. The analysis limited to cases for which the fuel lifetime of 2–6 years. The thermal-power axis is categorical: the horizontal separation of cycle lengths within each group is included only to improve readability. The labels “58 designs” and “319 designs” report the numbers of LTMR and GCMR design cases, respectively, included in each corresponding FOAK or NOAK panel.

Table 3. Minimum calculated LCOE among the constraint-satisfying 4.95% U-235 designs shown in Figure 2.

| Thermal power | LTMR FOAK | LTMR NOAK | GCMR FOAK | GCMR NOAK |
|---|---|---|---|---|
| 15 MWt | $530/MWh (5 years) | $303/MWh (6 years) | $873/MWh (4 years) | $360/MWh (4 years) |
| 30 MWt | $351/MWh (3 years) | $203/MWh (5 years) | $609/MWh (2 years) | $248/MWh (4 years) |
| 50 MWt | $263/MWh (5 years) | $149/MWh (5 years) | $500/MWh (2 years) | $204/MWh (2 years) |

The clearest trend is the reduction in LCOE as reactor power increases. Many reactor, site, instrumentation and control, and operational costs do not increase proportionally with thermal output.

Within the explored cases, the LTMR produces a lower minimum LCOE than the GCMR at each displayed power level. These differences should not be interpreted as a general conclusion. The two models have different fuel forms, material inventories, component requirements, and sampled design spaces. The results therefore compare the designs found in the current exploration rather than fully optimized versions of the two technologies.

The results do not show a uniformly monotonic relationship between cycle length and LCOE. A longer cycle can reduce the frequency of refueling and fuel-handling activities, but it generally requires additional fissile inventory, a larger core, or changes to the reflector and control systems. Consequently, the lowest-cost design is not always the design with the longest cycle.

HPMR results are not included because a constraint-satisfying 4.95% U-235 HPMR dataset was not available for the economic comparison. Achieving an LEU HPMR is particularly challenging because the current MOUSE HPMR model uses TRISO fuel and was originally anchored to a reference design containing 19.75% enriched fuel at a 36% packing fraction. Reducing the enrichment to 4.95%, even while increasing the packing fraction to 40%, provides only approximately 28% of the reference U-235 loading per unit homogenized fuel volume when considering enrichment and packing fraction alone. Furthermore, heat pipes and structural materials displace fuel and introduce neutron absorption. Increasing the core dimensions can reduce leakage, but it cannot fully compensate for a large reduction in fissile-material density without adding substantial fuel and material inventory. Thus, the absence of an HPMR curve should not be interpreted as proof that an LEU heat-pipe reactor is impossible. It indicates that a feasible and economically assessable HPMR was not identified within the design space and modeling assumptions evaluated to date.

### 4.1.2 9.9% U-235

The 9.9% U-235 case evaluates the cost implications of increasing enrichment above the conventional LEU limit while remaining substantially below 19.75% U-235. The design-space

exploration method and the two design constraints are the same as those described for the 4.95% case and are not repeated here. The simulation campaigns instead focused on identifying how the additional fissile loading available at 9.9% enrichment affected the range and cost of feasible LTMR and GCMR designs.

The principal variables and ranges explored in the 9.9% simulation campaigns are summarized in Table 4.

Table 4. Principal design variables explored in the 9.9% U-235 simulation campaigns.

| Reactor model | Design variables and explored values or ranges |
|---|---|
| LTMR | Core rings: 8–17; active height: approximately 23.7–150.7 cm; moderator arrangement: fuel-rich, baseline, and moderator-rich; reflector thickness: 20–50 cm; shutdown rods: 6 or 12; shutdown-rod absorber radius: 1.30–1.45 cm; shutdown-rod cladding radius: 1.50–1.575 cm; control-drum absorber arc: 120°, 135°, or 150° |
| GCMR | Core rings: 4–8; active height: approximately 127.8–557.3 cm; preferred aspect-ratio families: 1.0, 1.4, and 1.8, with realized core aspect ratios of approximately 0.66–2.39; TRISO packing fraction: 20–40%; target uranium inventory: approximately 259–2,460 kg; reflector thickness: 9.75–35 cm; shutdown-system size: 24, 48, 84, or 120 rods; central shutdown-rod absorber radius: 0.85 or 0.90 cm; surrounding shutdown-rod absorber radius: 0.45, 0.70, or 0.90 cm; control-drum absorber arc: 120° |

Figure 3 presents the FOAK and NOAK LCOE results for the 9.9% LTMR and GCMR designs that satisfied the analysis criteria. The minimum LCOEs identified at each power level are summarized in Table 5.

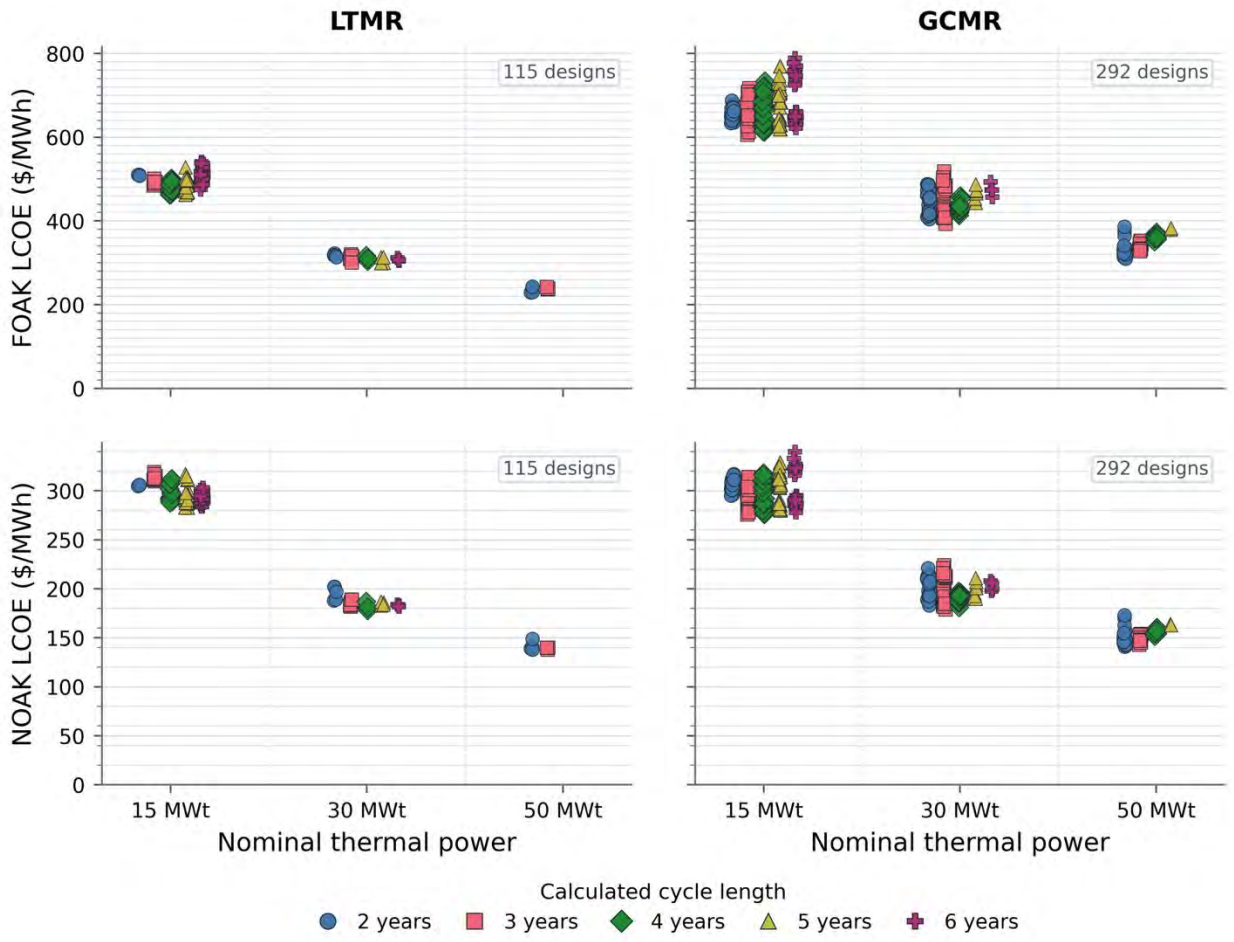



Figure 3. FOAK and NOAK LCOE for constraint-satisfying LTMR and GCMR designs using 9.9% U-235 fuel. Only designs at nominal thermal power levels of 15, 30, and 50 MWt are included. A design is included only when its most limiting shutdown margin is greater than 1,000 pcm and its most limiting temperature coefficient is less than 0 pcm/K. The analysis is limited to calculated cycle-length categories of 2–6 years. The thermal-power axis is categorical; the horizontal separation of cycle-length markers within each power group is used only to improve readability and does not represent differences in thermal power. The labels “115 designs” and “292 designs” report the numbers of LTMR and GCMR design cases, respectively, included in each corresponding FOAK and NOAK panel.

Table 5. Minimum calculated LCOE among the constraint-satisfying 9.9% U-235 designs shown in Figure 3.

| Thermal power | LTMR FOAK | LTMR NOAK | GCMR FOAK | GCMR NOAK |
|---|---|---|---|---|
| 15 MWt | $463/MWh (4 years) | $283/MWh (5 years) | $606/MWh (3 years) | $276/MWh (3 years) |
| 30 MWt | $299/MWh (5 years) | $178/MWh (4 years) | $393/MWh (3 years) | $179/MWh (3 years) |
| 50 MWt | $229/MWh (2 years) | $138/MWh (2 years) | $310/MWh (2 years) | $141/MWh (2 years) |

The minimum LCOE decreases with increasing reactor power, consistent with the scale effect observed for the 4.95% designs. The explanation of this trend is provided in the preceding subsection and is not repeated here.

Increasing the enrichment from 4.95% to 9.9% reduced the minimum LCOE found for both reactor models at every evaluated power level. For the LTMR, the minimum FOAK LCOE decreased by approximately 12.6–14.8%, while the minimum NOAK LCOE decreased by approximately 6.6–12.3%. The corresponding reductions for the GCMR were larger: approximately 30.6–38.0% for FOAK and 23.3–30.9% for NOAK. These comparisons quantify the difference between the lowest-cost designs found in the two explored design spaces. They do not isolate the effect of enrichment for an otherwise identical reactor design because the cost-minimizing configurations and cycle lengths can differ between the two enrichment cases.

The LTMR has the lower minimum FOAK LCOE at all three power levels. The NOAK minima, however, are nearly identical for the two reactor models. Thus, although the FOAK results continue to favor the lowest-cost LTMR designs found in the exploration, the economic distinction between the two technologies becomes small under the modeled NOAK assumptions.

The cycle length associated with the minimum LCOE varies from two to five years and does not consistently correspond to the longest available cycle. This result is consistent with the competing effects of operating lifetime and the additional fuel, core volume, reflector material, and control capability that may be required to obtain longer cycles, as discussed for the 4.95% case.

An HPMR panel is not included because no constraint-satisfying HPMR results were available within the 15–50 MWt and 2–6-year analysis window at 9.9% enrichment. This absence should not be interpreted as demonstrating that a 9.9% HPMR is infeasible. It indicates that a comparable HPMR design and economic dataset was not obtained within the simulation campaigns completed for this analysis.

### 4.1.3 15% U-235

The 15% U-235 case applies the same design-screening and economic-analysis framework to an intermediate HALEU enrichment. The design-space methodology, inclusion criteria, and limitations described in the preceding subsections also apply here and are not repeated. The principal variables and ranges represented in the 15% simulation campaigns are summarized in Table 6.

Table 6. Principal design variables explored in the 15% U-235 simulation campaigns.

| Reactor model | Design variables and explored values or ranges |
|---|---|
| LTMR | Core rings: 8–17; active height: approximately 23.7–147.7 cm; moderator arrangement: fuel-rich, baseline, and moderator-rich; reflector thickness: 20–50 cm; shutdown rods: 6 or 12; shutdown-rod absorber radius: 1.30–1.45 cm; shutdown-rod cladding radius: 1.50–1.575 cm; control-drum absorber arc: 120°, 135°, or 150° |
| GCMR | Core rings: 3–8; active height: approximately 99.0–701.1 cm; preferred aspect-ratio families: 1.0, 1.4, and 1.8, with realized core aspect ratios of approximately 0.64–3.60; TRISO packing fraction: 20–40%; target uranium inventory: approximately 171–1,672 kg; reflector thickness: 9.75–35 cm; shutdown-system size: 24, 36, 48, 84, or 120 rods; central shutdown-rod absorber radius: 0.85–1.00 cm; surrounding shutdown-rod absorber radius: 0.45–1.00 cm; control-drum absorber arc: 120° or 150° |
| HPMR | Core rings: 3–6; active height: approximately 135–568.9 cm; realized core aspect ratio: approximately 0.50–2.18; TRISO packing fraction: 10–40%; fuel-compact meat radius: 1.00, 1.15, or 1.30 cm; fuel-compact outer radius: 1.05, 1.20, or 1.35 cm; lattice pitch: 3.2 or 3.4 cm; assembly configuration: 72 fuel compacts with 19 heat pipes or 78 fuel compacts with 13 heat pipes; reflector thickness: approximately 57.7–87.7 cm; shutdown-rod absorber radius: 3.0–10.0 cm; shutdown-rod cladding radius: 3.2–10.2 cm; control-drum absorber arc: 120° or 150° |

Figure 4 presents the FOAK and NOAK LCOE results for the 15% designs that satisfied the analysis criteria. The minimum LCOEs identified at each available power level are summarized in Table 7.

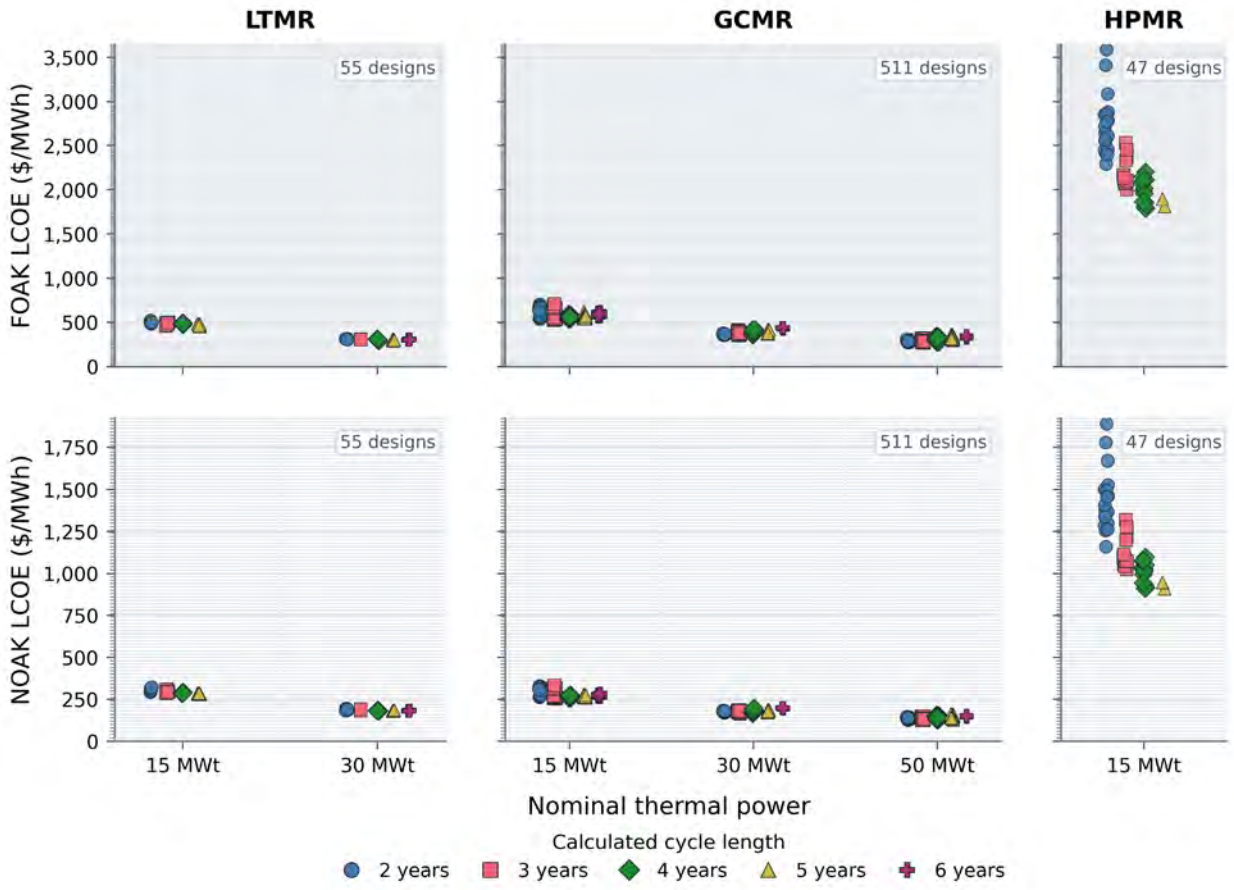



Figure 4. FOAK and NOAK LCOE for constraint-satisfying LTMR, GCMR, and HPMR designs using 15% U-235 fuel. LTMR designs are shown at nominal thermal power levels of 15 and 30 MWt, GCMR designs are shown at 15, 30, and 50 MWt, and HPMR designs are shown at 15 MWt. A design is included only when its most limiting shutdown margin is greater than 1,000 pcm and its most limiting temperature coefficient is less than 0 pcm/K. The analysis is limited to calculated cycle-length categories of 2–6 years. The thermal-power axis is categorical; the horizontal separation of cycle-length markers within each power group is used only to improve readability and does not represent differences in thermal power. The labels “55 designs,” “511 designs,” and “47 designs” report the numbers of LTMR, GCMR, and HPMR design cases, respectively, included in each corresponding FOAK and NOAK panel.

Table 7. Minimum calculated LCOE among the constraint-satisfying 15% U-235 designs shown in Figure 4.

| Thermal power | LTMR FOAK | LTMR NOAK | GCMR FOAK | GCMR NOAK | HPMR FOAK | HPMR NOAK |
|---|---|---|---|---|---|---|
| 15 MWt | $453/MWh (5 years) | $280/MWh (5 years) | $528/MWh (3 years) | $254/MWh (3 years) | $1,788/MWh (4 years) | $910/MWh (5 years) |
| 30 MWt | $290/MWh (4 years) | $180/MWh (4 years) | $354/MWh (3 years) | $165/MWh (3 years) | — | — |
| 50 MWt | — | — | $268/MWh (3 years) | $126/MWh (3 years) | — | — |

The minimum LCOE continues to decrease as thermal power increases for the reactor models with results at multiple power levels. The economic benefit of increasing enrichment from 9.9% to 15% differs between the LTMR and GCMR results. For the LTMR, the minimum FOAK LCOE decreases by 2.2% at 15 MWt and 3.0% at 30 MWt. The minimum NOAK LCOE decreases by 1.1% at 15 MWt but increases by 1.1% at 30 MWt. These small changes indicate that the additional enrichment did not produce a substantial reduction in the lowest LTMR LCOEs found within the explored 15% design space.

The GCMR shows a larger economic response. Relative to the 9.9% results, the minimum GCMR FOAK LCOE decreases by approximately 12.9%, 9.9%, and 13.5% at 15, 30, and 50 MWt, respectively. The corresponding NOAK reductions are approximately 8.0%, 7.8%, and 10.6%. Within the explored GCMR cases, the increase from 9.9% to 15% therefore provided additional flexibility to reduce the fuel and reactor configuration costs associated with satisfying the cycle-length and reactivity constraints.

These percentages compare the minimum values found in separately sampled design spaces. They should not be interpreted as the effect of changing enrichment while holding all other design variables constant.

At 15 and 30 MWt, the LTMR retains the lower minimum FOAK LCOE. The GCMR, however, has the lower minimum NOAK LCOE at both shared power levels: $254/MWh compared with $280/MWh at 15 MWt and $165/MWh compared with $180/MWh at 30 MWt.

No 50 MWt LTMR result is shown because none of the evaluated 15% LTMR cases at that power level simultaneously met the cycle-length and design-constraint criteria.

The 15% dataset is the first enrichment case in this analysis to produce constraint-satisfying HPMR results within the displayed power range. The 47 qualifying HPMR cases are all at 15 MWt and cover calculated cycle-length categories from two to five years. Their minimum LCOEs are $1,788/MWh for FOAK deployment and $910/MWh for NOAK deployment, which are substantially higher than the corresponding LTMR and GCMR minima.

### 4.1.4 19.75% U-235

The 19.75% U-235 case evaluates the highest enrichment considered in this analysis. The same design-screening criteria, economic assumptions, and limitations described in the preceding subsections apply. The LTMR and GCMR cases cover 15, 30, and 50 MWt, whereas the single qualifying HPMR case is at 15 MWt. The principal design variables and ranges represented in the 19.75% simulation campaigns are summarized in Table 8.

Table 8. Principal design variables explored in the 19.75% U-235 simulation campaigns.

| Reactor model | Design variables and explored values or ranges |
|---|---|
| LTMR | Core rings: 8–17; active height: approximately 23.7–147.7 cm; moderator arrangement: fuel-rich, baseline, and moderator-rich; reflector thickness: 20–50 cm; shutdown rods: 6 or 12; shutdown-rod absorber radius: 1.30–1.45 cm; shutdown-rod cladding radius: 1.50–1.575 cm; control-drum absorber arc: 120°, 135°, or 150° |
| GCMR | Core rings: 3–8; active height: approximately 88.5–510.8 cm; preferred aspect-ratio families: 1.0, 1.4, and 1.8, with realized core aspect ratios of approximately 0.57–2.40; TRISO packing fraction: 20%, 30%, or 40%; target uranium inventory: approximately 130–1,233 kg; reflector thickness: 9.75–35 cm; shutdown-system size: 24, 48, 84, or 120 rods; central shutdown-rod absorber radius: 0.85 or 0.90 cm; surrounding shutdown-rod absorber radius: 0.45, 0.70, or 0.90 cm; control-drum absorber arc: 120° |
| HPMR | Core rings: 3, 5, or 6; active height: approximately 116.5–432.1 cm; realized core aspect ratio: approximately 0.38–2.41; TRISO packing fraction: 10–40%; fuel-compact meat radius: 1.00, 1.15, or 1.30 cm; fuel-compact outer radius: 1.05, 1.20, or 1.35 cm; lattice pitch: 3.2 or 3.4 cm; assembly configuration: 72 fuel compacts with 19 heat pipes or 78 fuel compacts with 13 heat pipes; reflector thickness: approximately 49.7–87.7 cm; shutdown-rod absorber radius: 3.0–12.5 cm; shutdown-rod cladding radius: 3.2–12.7 cm; control-drum absorber arc: 120° or 150° |

Figure 5 presents the FOAK and NOAK LCOE results for the 19.75% designs that satisfied the analysis criteria. The minimum LCOEs identified at each available power level are summarized in Table 9.

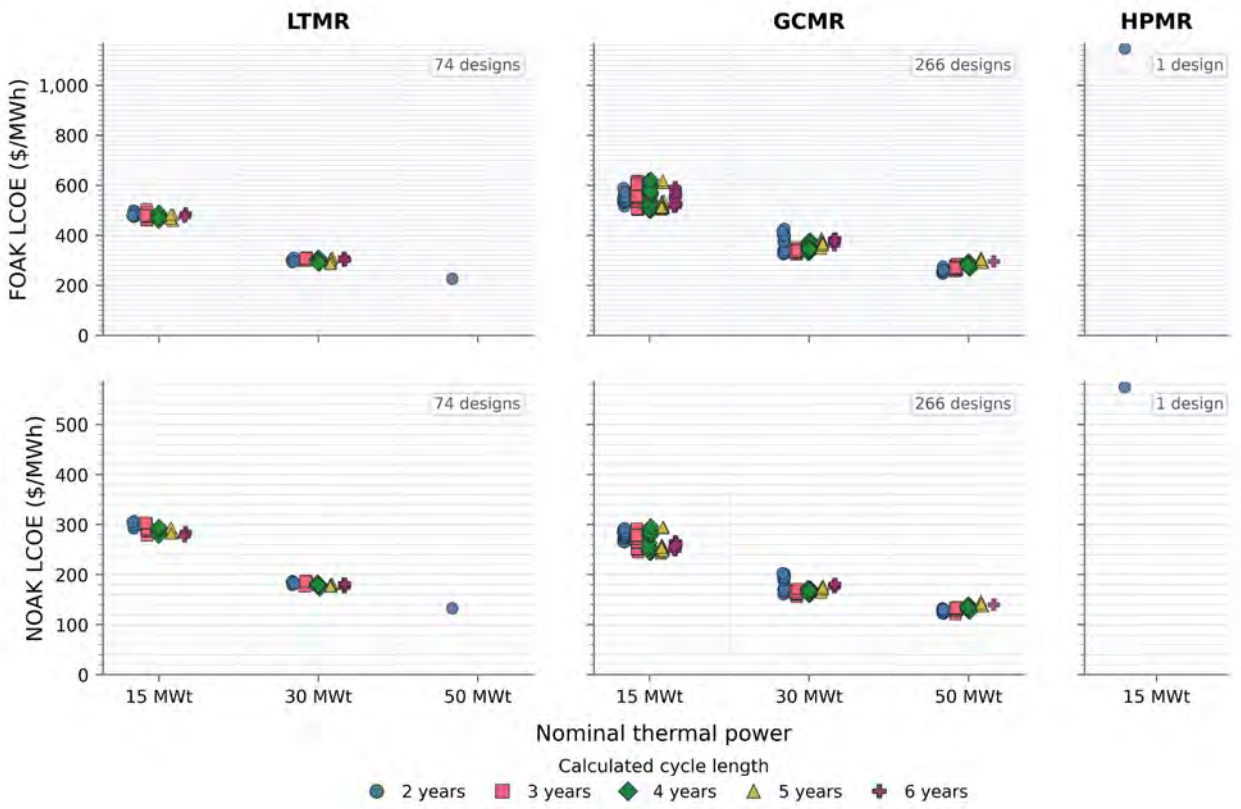



Figure 5. FOAK and NOAK LCOE for constraint-satisfying LTMR, GCMR, and HPMR designs using 19.75% U-235 fuel. LTMR and GCMR designs are shown at nominal thermal power levels of 15, 30, and 50 MWt, whereas the HPMR design is shown at 15 MWt. A design is included only when its most limiting shutdown margin is greater than 1,000 pcm and its most limiting temperature coefficient is less than 0 pcm/K. The analysis is limited to calculated cycle-length categories of 2–6 years. The thermal-power axis is categorical; the horizontal separation of cycle-length markers within each power group is used only to improve readability and does not represent differences in thermal power. The labels “74 designs,” “266 designs,” and “1 design” report the numbers of LTMR, GCMR, and HPMR design cases, respectively, included in each corresponding FOAK and NOAK panel.

Table 9. Minimum calculated LCOE among the constraint-satisfying 19.75% U-235 designs shown in Figure 5.

| Thermal power | LTMR FOAK | LTMR NOAK | GCMR FOAK | GCMR NOAK | HPMR FOAK | HPMR NOAK |
|---|---|---|---|---|---|---|
| 15 MWt | $458/MWh (5 years) | $277/MWh (6 years) | $500/MWh (4 years) | $243/MWh (5 years) | $1,148/MWh (2 years) | $574/MWh (2 years) |
| 30 MWt | $286/MWh (5 years) | $173/MWh (4 years) | $324/MWh (3 years) | $156/MWh (3 years) | — | — |
| 50 MWt | $226/MWh (2 years) | $133/MWh (2 years) | $247/MWh (2 years) | $121/MWh (3 years) | — | — |

The minimum LCOE decreases with increasing thermal power for both the LTMR and GCMR. This trend is consistent with the lower-enrichment results and the scale effect discussed previously.

Increasing enrichment from 15% to 19.75% produces only small changes in the minimum LTMR LCOEs. At 15 MWt, the minimum FOAK LCOE increases from $453/MWh to $458/MWh, while the minimum NOAK LCOE decreases from $280/MWh to $277/MWh. At 30 MWt, the minimum FOAK and NOAK LCOEs decrease by approximately 1.4% and 3.9%, respectively. A qualifying 50 MWt LTMR is identified at 19.75%, but only one such design is present in the filtered dataset. These results do not show a substantial economic benefit from increasing LTMR enrichment above 15% within the design spaces explored.

The GCMR exhibits a clearer, although still moderate, reduction in minimum LCOE. Relative to the 15% results, the minimum GCMR FOAK LCOE decreases by approximately 5.3%, 8.5%, and 7.8% at 15, 30, and 50 MWt, respectively. The corresponding NOAK reductions are approximately 4.3%, 5.5%, and 4.0%. These reductions are smaller than those observed when increasing enrichment from 9.9% to 15%. Within the explored cases, the results are therefore consistent with a diminishing economic benefit from further enrichment as the assay approaches 19.75%.

The LTMR has the lower minimum FOAK LCOE at all three power levels, although the FOAK difference between the LTMR and GCMR decreases as power increases. In contrast, the GCMR has the lower minimum NOAK LCOE at every shared power level. The differences are $34/MWh at 15 MWt, $17/MWh at 30 MWt, and $12/MWh at 50 MWt. Under the modeled NOAK assumptions, the economic advantage therefore shifts toward the lowest-cost GCMR designs found at 19.75% enrichment.

The 19.75% HPMR results require particular caution because only one design satisfies all inclusion criteria. This case is a 15 MWt design with a calculated two-year cycle and LCOEs of $1,148/MWh for FOAK deployment and $574/MWh for NOAK deployment. These values are

approximately 36% lower than the corresponding minimum HPMR values found at 15% enrichment.

The small number of qualifying HPMR cases is primarily associated with the shutdown-margin requirement. Among the 340 evaluated 19.75% HPMR cases at 15 MWt that had non-extrapolated calculated cycle lengths of 2–6 years and complete economic results, 339 satisfied the negative temperature-coefficient requirement, but only one had a shutdown margin greater than 1,000 pcm. Higher enrichment increases the available excess reactivity and can support smaller cores or longer operating cycles, but it also increases the control-system capability required to maintain an adequate shutdown margin. For the 19.75% HPMR cases evaluated here, shutdown margin is therefore the binding design constraint.

### 4.1.5 Summary

Table 10 consolidates the principal economic results from the enrichment analysis. Each entry reports the minimum calculated FOAK and NOAK LCOE identified among the constraint-satisfying designs at the corresponding enrichment and power level.

Table 10. Minimum calculated FOAK/NOAK LCOE by reactor model, thermal power, and uranium enrichment. Values are reported as FOAK/NOAK in $/MWh.

| Reactor model | Thermal power | 4.95% U-235 | 9.9% U-235 | 15% U-235 | 19.75% U-235 |
|---|---|---|---|---|---|
| LTMR | 15 MWt | 530 / 303 | 463 / 283 | 453 / 280 | 458 / 277 |
| LTMR | 30 MWt | 351 / 203 | 299 / 178 | 290 / 180 | 286 / 173 |
| LTMR | 50 MWt | 263 / 149 | 229 / 138 | — | 226 / 133 |
| GCMR | 15 MWt | 873 / 360 | 606 / 276 | 528 / 254 | 500 / 243 |
| GCMR | 30 MWt | 609 / 248 | 393 / 179 | 354 / 165 | 324 / 156 |
| GCMR | 50 MWt | 500 / 204 | 310 / 141 | 268 / 126 | 247 / 121 |
| HPMR | 15 MWt | — | — | 1,788 / 910 | 1,148 / 574 |

The principal takeaways are:

- Restricting fuel enrichment to 4.95% U-235 did not eliminate feasible LTMR or GCMR designs, but it imposed an economic penalty. Relative to the minimum 19.75% results, the penalty ranged from $37 to $72/MWh for LTMR FOAK cases and from $253 to $373/MWh for GCMR FOAK cases.
- The LTMR captured most of its observed enrichment-related cost reduction by 9.9% U-235. The GCMR continued to benefit from increasing enrichment to 15% and 19.75%, although the incremental reduction became smaller at the higher enrichments.

- The HPMR was more strongly constrained by enrichment and shutdown-margin requirements. Qualifying HPMR results were obtained only at 15% and 19.75% U-235, and their calculated LCOEs remained substantially higher than those of the LTMR and GCMR within the explored design spaces.
- Minimum LCOE generally decreased with increasing reactor power. The results also show that the preferred reactor model can depend on deployment maturity: the LTMR generally produced the lower FOAK minimum, whereas the GCMR produced the lower NOAK minimum at the higher enrichments.
- These values are the lowest LCOEs identified through design-space exploration rather than formal optimization. Comparisons between enrichment levels therefore quantify the differences between the best designs found in each sampled design space, not the isolated effect of changing enrichment in an otherwise identical reactor.

## 4.2 Transportability Requirements

Transportability is frequently identified as an important characteristic of microreactors because it can reduce on-site construction and allow factory-fabricated systems to serve locations that are difficult or expensive to supply with conventional fuels. However, transportability is not a single requirement that applies equally to every market. A reactor delivered once to a permanent site faces a different requirement from a reactor that must be removed after operation or delivered by military aircraft. This analysis therefore evaluates two market-linked transportation requirements: conventional standard-road delivery of a fresh reactor and a permitted heavy-haul return of an irradiated reactor. These scenarios are evaluated separately rather than classifying reactor designs simply as transportable or non-transportable.

Table 11 defines the reactor shipment evaluated and the pass/fail condition for each scenario. Numerical transportation limits and detailed modeling assumptions are provided in the corresponding subsections.

Table 11. Transportability scenarios and design-filtering criteria evaluated in this study.

| Scenario | Representative application | Reactor shipment evaluated | Design passes when |
|---|---|---|---|
| **Standard-road stationary remote deployment** | Road-accessible remote community, military installation, or industrial facility | Initial delivery of the fresh, unirradiated reactor module | The fresh reactor module satisfies the applicable standard-road mass and dimensional limits |
| **Temporary mine deployment with permitted heavy-haul vendor take-back** | Mine or other industrial site with a finite operating life and road access suitable for a permitted heavy-haul shipment | Initial standard-road delivery of the fresh reactor module and permitted heavy-haul return of the intact irradiated module after 60 months of cooling and addition of transportation shielding. | The fresh module satisfies the standard-road criteria, and the shielded irradiated return package weighs no more than 140,000 lb, remains within the specified width, loaded-height, and length limits, and meets 10 mrem/h at 2 m from the outer lateral plane of the transport vehicle |

The selected scenarios are grounded in deployment models discussed by potential users, reactor developers, and government programs. Remote communities, mines, and defense installations have been identified as potential markets for microreactors, particularly where electricity generation depends on expensive or vulnerable fuel deliveries (NEI 2019). Transportation studies have identified conventional highway, heavy-haul highway, rail, barge, and military-air shipment as potentially relevant modes and have emphasized that the applicable requirements change after reactor operation (Maheras 2020). More recent PNNL work estimates that a microreactor prepared for highway transportation could have a package mass of approximately 50–70 tons and a gross vehicle weight of approximately 70–100 tons. Such shipments would likely use heavy-haul vehicles and require state-specific permits, escorts, and route evaluations (Maheras 2025).

The standard-road stationary remote deployment scenario represents a reactor delivered by truck to a road-accessible site and operated there throughout its planned operating campaign. Only the initial shipment is treated as a market-imposed design constraint. This does not imply that the reactor would never require decommissioning or removal; rather, routine return of the complete irradiated module is not required for the reactor to serve this market.

The temporary mine deployment with permitted heavy-haul vendor take-back scenario adds the requirement that the reactor be removed after operation. The fresh reactor module must first satisfy the standard-road criteria applied in the preceding scenario. Following operation and 60 months of cooling, external transportation shielding is added to the intact fueled reactor module. The shielded return package may be transported using a specialized multi-axle vehicle under an overweight permit and therefore is not subject to the 80,000-lb gross-vehicle limit or the 48,000-lb standard-flatbed cargo limit. Instead, this study applies a representative maximum shielded-package mass of 140,000 lb while retaining the standard width, loaded-height, and length

envelope. The radiation calculation applies the regulatory limit of 10 mrem/h at 2 m from the outer lateral plane of the transport vehicle, consistent with 49 CFR 173.441(b)(3) (DOT 2026). This deployment model remains consistent with market analysis concluding that a microreactor serving a remote mine should be prefabricated, pre-fueled, and removable at the end of the mine's operating life (Shropshire 2021).

For both scenarios, transportability is evaluated at the reactor-module level. Balance-of-plant systems may be divided among separate shipments and do not determine whether the reactor design passes the transportability filter. The reactor module is assumed to be transported horizontally. For the temporary-mine scenario, the return package consists of the intact irradiated reactor module and the calculated external transportation shielding. Removal and separate transportation of the fuel or core are not assumed. The transport filters are applied only after the designs have satisfied the shutdown-margin, temperature-coefficient, and fuel-lifetime requirements established for the analysis. A design exceeding the heavy-haul screening criteria is not classified as universally non-transportable; rather, it is identified as requiring a different transportation strategy, such as a larger superload configuration, rail or barge shipment, or separate transportation of a removable core or fuel package.

For each scenario, the results identify the number of qualifying designs, the transportation condition controlling their eligibility, and the minimum FOAK and NOAK LCOEs among the qualifying designs. The economic consequence of the market requirement is measured by comparing the minimum LCOE after applying the transportation filter with the corresponding minimum obtained without that filter.

### 4.2.1 Standard-Road Stationary Remote Deployment

This scenario represents a microreactor delivered by conventional road transportation to a remote but road-accessible location, where it remains installed for an extended operating period. Relevant applications include remote communities, mining operations, and enduring military installations. NEI distinguishes these stationary applications from mobile reactors intended to be installed and removed on shorter timescales (NEI 2019).

The objective of this scenario is to determine whether a fresh, unirradiated reactor module can be transported horizontally on a conventional flatbed tractor-semitrailer without requiring an oversize or overweight permit. This is not an ISO-container scenario. The reactor-module dimensions are compared directly with the usable flatbed and legal-road envelope. The scenario also does not evaluate removal or transportation of the reactor after irradiation.

The transported reactor module includes the fuel, moderator, reflectors, control drums, reactor vessel, applicable guard and passive-cooling vessels, and the heat pipes represented in the current reactor models. Balance-of-plant equipment is assumed to be transported separately.

The screening criteria were selected from federal commercial-vehicle requirements and standard flatbed-trailer characteristics. Federal regulations limit gross vehicle weight on the Interstate System to 80,000 lb and commercial-vehicle width on the National Network to approximately 2.59 m, or 102 in. Federal regulations do not establish a nationwide vehicle-height limit, but

FHWA reports that most state limits range from 4.11 to 4.27 m, or 13.5 to 14 ft. FHWA also identifies 14.63 m, or 48 ft, as the minimum semitrailer length that states must allow on the National Network. Standard commercial flatbeds are commonly 48–53 ft long, 8.5 ft wide, have an approximately 60-in deck height, and carry approximately 48,000 lb of cargo (FHWA 2015, Ryan Transportation 2026).

Based on these sources, a reactor design was classified as suitable for standard-road transportation only if it satisfied *all* of the following criteria:

- **Module mass:** no more than 48,000 lb. This is consistent with the reported cargo capacity of a standard flatbed and results in a gross vehicle weight of 80,000 lb when combined with a 32,000-lb tractor-and-trailer allowance.
- **Module width:** no more than 2.59 m, corresponding to the 102-in federal commercial-vehicle width limit and the width of a standard flatbed.
- **Loaded height:** no more than 4.11 m. Using a standard flatbed deck height of approximately 1.52 m, or 60 in, limits the module's vertical dimension to 2.59 m. The 4.11-m value corresponds to the lower end of the state vehicle-height range reported by FHWA and therefore provides a conservative screening value for transportation across multiple states.
- **Module length:** no more than 14.63 m, corresponding to a 48-ft flatbed. Although longer trailers are available, the 48-ft value represents the lower end of the standard flatbed range and the minimum semitrailer length that states must allow on the National Network.

All four criteria were applied simultaneously. Failure of any criterion disqualified the design. These criteria provide a consistent screening basis, but they do not replace a route-specific transportation evaluation. Federal axle-weight limits, the Federal Bridge Formula, turning clearance, load securement, center of gravity, local bridge capacities, and state-specific route requirements were not evaluated. Therefore, a passing result indicates compatibility with the defined standard-road transportation envelope, not final carrier or permitting approval.

Before applying the transportation criteria, the analysis retained only designs having a shutdown margin greater than 1,000 pcm and a negative temperature coefficient. Designs using 4.95%, 9.9%, 15%, and 19.75% U-235 were considered together. Table 12 summarizes the transportation-screening and economic results.

Table 12. Standard-road screening results and minimum LCOE before and after applying the transportation criteria.

| Reactor | Reactor power (MWt) | Eligible designs | Road-qualified designs | Pass rate (%) | Weight failures | Width/loaded-height failures | Minimum FOAK LCOE ($/MWh), before → after | Minimum NOAK LCOE ($/MWh), before → after |
|---|---|---|---|---|---|---|---|---|
| LTMR | 2 | 148 | 148 | 100 | 0 | 0 | 2,227 → 2,227 | 1,391 → 1,391 |
| LTMR | 15 | 163 | 163 | 100 | 0 | 0 | 453 → 453 | 277 → 277 |
| LTMR | 30 | 106 | 105 | 99 | 1 | 0 | 286 → 286 | 173 → 173 |
| LTMR | 50 | 33 | 24 | 73 | 9 | 0 | 226 → 226 | 133 → 133 |
| GCMR | 2 | 204 | 120 | 59 | 84 | 62 | 2,373 → 2,373 | 1,249 → 1,249 |
| GCMR | 15 | 629 | 157 | 25 | 468 | 375 | 500 → 500 | 243 → 243 |
| GCMR | 30 | 374 | 35 | 9 | 339 | 297 | 324 → 324 | 156 → 156 |
| GCMR | 50 | 385 | 9 | 2 | 376 | 366 | 247 → 247 | 121 → 123 |
| HPMR | 2 | 54 | 0 | 0 | 54 | 54 | 3,122 → — | 1,613 → — |
| HPMR | 15 | 48 | 0 | 0 | 48 | 48 | 1,148 → — | 574 → — |

Of the 2,144 eligible designs, 761 satisfy all standard-road criteria. Weight is the most widespread reason for exclusion. Of the 1,383 disqualified designs, 1,379 exceed the 48,000-lb module-mass limit. Dimensional limits are nevertheless also important: 1,202 disqualified designs exceed both the width and loaded-height limits. These failures frequently overlap. In particular, 1,198 designs fail the weight, width, and loaded-height criteria simultaneously. Only four designs fail the dimensional criteria without also failing the weight criterion. Therefore, most excluded designs are too heavy, but many of the heavier GCMR and HPMR designs are also too large in diameter for standard-road transportation.

The LTMR is the least affected reactor model. Every evaluated 2- and 15-MWt LTMR design qualifies for standard-road transportation. Only one 30-MWt design and nine 50-MWt designs are excluded, all because of weight. No LTMR design exceeds the width, loaded height, or length criteria. The minimum FOAK and NOAK LCOEs are consequently unchanged at every LTMR power level.

Transportability is substantially more restrictive for the GCMR. The qualification rate decreases from 59% at 2 MWt to 25% at 15 MWt, 9% at 30 MWt, and 2% at 50 MWt. Nearly all disqualified GCMR designs exceed the weight limit, while most also exceed the width and loaded-height limits. Nevertheless, the minimum FOAK LCOE remains unchanged at every power level because the lowest-cost FOAK design in each group already satisfies the transportation criteria.

The exclusion of GCMR designs is related to enrichment, but enrichment is not itself a transportation criterion. The road screen evaluates only mass and dimensions. None of the 381

GCMR designs using 4.95% U-235 qualifies. In comparison, 34 of 334 GCMR designs using 9.9% U-235, 140 of 568 designs using 15% U-235, and 147 of 309 designs using 19.75% U-235 qualify. Lower enrichment generally requires additional fuel inventory or a larger core to provide the specified power and operating lifetime. These changes can indirectly increase module mass and diameter. However, the relationship depends on reactor architecture and on the design space explored and should not be interpreted as a universal enrichment threshold.

The LTMR results demonstrate that conventional LEU is not inherently incompatible with standard-road transportation. Of the 91 LTMR designs using 4.95% U-235, 81 qualify. This includes all 4.95% designs at 2 and 15 MWt, 16 of 17 designs at 30 MWt, and 16 of 25 designs at 50 MWt. All evaluated LTMR designs using 9.9%, 15%, or 19.75% U-235 also qualify. Thus, low enrichment alone does not explain the overall number of excluded designs. Lower enrichment is particularly consequential for the GCMR, whereas the LTMR remains comparatively compact across the evaluated enrichment range.

No evaluated HPMR satisfies the standard-road criteria, including the 2-MWt cases. Every HPMR design exceeds the weight, width, and loaded-height criteria simultaneously. The minimum calculated HPMR module mass is approximately 176,000 lb at 2 MWt and approximately 605,000 lb at 15 MWt, both substantially above the 48,000-lb cargo limit. Higher enrichment does not resolve this result. This result applies to the current HPMR model and explored design space and should not be interpreted as evidence that all heat-pipe reactor concepts are unsuitable for road transportation. It indicates that an HPMR meeting the defined standard-road envelope was not identified in the present design exploration.

The economic effect of the transportation constraint is therefore different from its effect on design availability. The filter removes a large fraction of the GCMR design space and all evaluated HPMR designs, but it has almost no effect on the minimum LCOE of the surviving LTMR and GCMR options. This occurs because the lowest-cost designs are generally among the smaller and lighter configurations. Standard-road transportability is therefore a binding feasibility constraint for many individual designs even when its calculated penalty on the minimum available LCOE is small.

### 4.2.2 Temporary Mine Deployment with Permitted Heavy-Haul Vendor Take-Back

This scenario represents a microreactor deployed at a mine or comparable industrial site with a finite operating life. The reactor is initially delivered as a fresh module, operated at the site, allowed to cool after shutdown, and then returned intact to the vendor or another servicing facility. This deployment model is relevant to remote mining because the energy system may need to be removed when mining operations end. Shropshire et al. (2021).

This scenario is more restrictive than the standard-road stationary deployment evaluated in Sec. 4.2.1 because it considers two separate transportation movements:

- **Fresh delivery:** The unirradiated reactor module must satisfy all standard-road mass and dimensional criteria defined in Section 4.2.1.

- **Irradiated return:** The intact reactor module must be transported after operation and a 60-month cooldown period. External transportation shielding is added, and the resulting module-plus-shield package must satisfy the heavy-haul return criteria.

Returning a complete irradiated microreactor to a factory after a period of onsite cooling is a deployment model discussed in the transportation literature. Maheras et al. (2025) distinguish this model from deployments in which used fuel or the complete reactor remains in onsite storage. However, the return movement is substantially more challenging than the initial delivery because the irradiated fuel produces decay heat and radiation and because the required shielding increases both package mass and dimensions.

The return shipment is treated as a permitted overweight shipment that remains within the standard width, height, and length envelope. In other words, the scenario allows a heavier specialized vehicle and route-specific overweight permits, but it does not allow the reactor package to become an oversize load. The following criteria were applied:

- **Return-package mass:** no more than 140,000 lb, including the reactor module and added lead shielding.
- **Package width:** no more than 2.59 m.
- **Loaded height:** no more than 4.11 m. With the assumed 1.52-m trailer-deck height, the package height cannot exceed 2.59 m.
- **Package length:** no more than 14.63 m.
- **Radiation dose rate:** no more than 10 mrem/h at 2 m from the outer lateral plane of the vehicle.
- **Cooldown period:** 60 months following reactor shutdown.
- **Shipment configuration:** one intact reactor module transported horizontally; splitting the reactor into multiple return packages is not considered.

The 140,000-lb value is a screening criterion rather than a federal legal limit. Maheras et al. (2025) estimate that a microreactor prepared for highway shipment could weigh approximately 50–70 tons without additional transportation shielding and note that such shipments would require heavy-haul equipment and state-specific permits. The present analysis uses the upper end of that range—70 short tons, or 140,000 lb—as the maximum combined mass of the reactor and added shield.

The 10-mrem/h dose criterion is taken from the exclusive-use transportation limits in U.S. Department of Transportation regulations. For a flatbed vehicle, 49 CFR 173.441(b)(3) limits the radiation level to 10 mrem/h at 2 m from the vertical planes projected from the vehicle's outer lateral edges. The dose point was therefore located relative to the assumed 2.59-m vehicle width rather than 2 m from the shield surface.

The required shielding was estimated using the MOUSE irradiated-transport screening model. For each design, the model estimates decay heat using the reactor power, operating lifetime and a 60-month cooldown period. The shield is represented as a closed cylindrical shell surrounding the complete reactor module. This calculation is intended for comparative design screening and is not a transportation-package design or certification analysis.

A design passes this scenario only when it satisfies all criteria for both movements. Before applying these transportation filters, the analysis retained only designs with a shutdown margin greater than 1,000 pcm, a limiting temperature coefficient below 0 pcm/K, and an interpolated, non-extrapolated fuel lifetime between two and six years. Table 13 summarizes the resulting design availability and minimum LCOEs.

Table 13. Screening results and minimum LCOE for temporary mine deployment with permitted heavy-haul vendor take-back.

| Reactor | Reactor power (MWt) | Eligible designs | Fresh-delivery pass | Complete take-back pass | Pass rate (%) | Return package-mass failures | Return width/loaded-height failures | Minimum FOAK LCOE, before → after ($/MWh) | Minimum NOAK LCOE, before → after ($/MWh) |
|---|---|---|---|---|---|---|---|---|---|
| LTMR | 2 | 148 | 148 | 142 | 96 | 6 | 0 | 2,227 → 2,227 | 1,391 → 1,391 |
| LTMR | 15 | 163 | 163 | 70 | 43 | 93 | 9 | 453 → 453 | 277 → 280 |
| LTMR | 30 | 106 | 105 | 19 | 18 | 87 | 2 | 286 → 288 | 173 → 178 |
| LTMR | 50 | 33 | 24 | 0 | 0 | 33 | 12 | 226 → — | 133 → — |
| GCMR | 2 | 204 | 120 | 89 | 44 | 115 | 90 | 2,373 → 2,373 | 1,249 → 1,249 |
| GCMR | 15 | 629 | 157 | 0 | 0 | 629 | 615 | 500 → — | 243 → — |
| GCMR | 30 | 374 | 35 | 0 | 0 | 374 | 374 | 324 → — | 156 → — |
| GCMR | 50 | 385 | 9 | 0 | 0 | 385 | 385 | 247 → — | 121 → — |
| HPMR | 2 | 54 | 0 | 0 | 0 | 54 | 54 | 3,122 → — | 1,613 → — |
| HPMR | 15 | 48 | 0 | 0 | 0 | 48 | 48 | 1,148 → — | 574 → — |

Of the 2,144 eligible designs, 761 satisfy the fresh-delivery criteria, but only 320 satisfy both the fresh-delivery and irradiated-return requirements. The overall qualification rate is therefore 14.9%. Every design that passes the irradiated-return filter also passes the fresh-delivery filter.

The 140,000-lb return-package limit is the decisive criterion. A total of 1,824 designs exceed this limit, which equals the number of designs that fail the complete scenario. Of these designs, 1,589 also exceed the width and loaded-height limits, while 235 exceed the mass limit without exceeding the dimensional limits.

The LTMR provides the largest number of qualifying designs. Nearly all 2-MWt LTMR designs pass, but the qualification rate decreases to 43% at 15 MWt and 18% at 30 MWt. The required lead shielding increases with reactor power: the calculated thickness ranges from approximately 13.9–15.9 cm at 2 MWt, 17.6–19.7 cm at 15 MWt, 19.1–20.9 cm at 30 MWt, and 20.1–21.7 cm at 50 MWt. Although these differences in thickness appear moderate, the shield surrounds the

complete cylindrical module. Consequently, small increases in thickness and module dimensions can produce large increases in shield volume and mass.

No 50-MWt LTMR design passes the complete scenario. The lightest calculated shielded return package in this group is approximately 162,000 lb, already about 22,000 lb above the screening limit. Therefore, the take-back requirement eliminates the LTMR power class having the lowest unrestricted LCOE.

Within the power levels for which qualifying LTMR designs remain, the direct design-selection penalties are relatively small. At 15 MWt, the minimum FOAK LCOE remains $453/MWh, while the minimum NOAK LCOE increases from $277/MWh to $280/MWh. At 30 MWt, the minimum FOAK LCOE increases from $286/MWh to $288/MWh, and the minimum NOAK LCOE increases from $173/MWh to $178/MWh.

The more important economic consequence is the loss of the 50-MWt option. The minimum unrestricted 50-MWt LTMR LCOEs are $226/MWh for FOAK deployment and $133/MWh for NOAK deployment. Among the designs that pass the take-back scenario, the lowest corresponding values occur at 30 MWt and are $288/MWh and $178/MWh. These values are approximately 27% and 34% higher, respectively, than the unrestricted 50-MWt values.

This comparison illustrates the economic value lost when the return requirement excludes the larger reactor, but it is not a capacity-matched comparison. A 30-MWt reactor does not provide the same output as a 50-MWt reactor.

The GCMR is more strongly constrained. Eighty-nine of the 204 eligible 2-MWt GCMR designs pass the complete scenario, and the minimum FOAK and NOAK LCOEs remain unchanged at $2,373/MWh and $1,249/MWh. However, no GCMR design at 15, 30, or 50 MWt passes. Even the lightest return package is approximately 164,000 lb at 15 MWt, 201,000 lb at 30 MWt, and 228,000 lb at 50 MWt. Therefore, vendor take-back under the defined road-transport envelope limits the evaluated GCMR options to 2 MWt.

Enrichment affects these results indirectly through its influence on core size and fuel inventory. At 2 MWt, all 33 evaluated 4.95%-enriched LTMR designs pass, demonstrating that conventional LEU is compatible with this take-back scenario at sufficiently low power. Two 4.95%-enriched LTMR designs also qualify at 15 MWt, but none qualifies at 30 or 50 MWt. For the GCMR, no 4.95%-enriched case qualifies; the 2-MWt qualifying set consists of one 9.9%-enriched design, 45 designs at 15%, and 43 designs at 19.75%. Higher enrichment generally supports a more compact core, but enrichment is not itself a transportation criterion.

No HPMR design passes the scenario. As discussed in Section 4.2.1, the evaluated HPMR modules already exceed the standard-road fresh-delivery limits.

Overall, the vendor take-back requirement has a larger economic and design effect than the fresh-delivery requirement alone. It produces only modest within-power LCOE increases where qualifying designs remain, but it removes the 50-MWt LTMR, all GCMRs above 2 MWt, and all

evaluated HPMRs. Its principal economic consequence is therefore the loss of larger, lower-LCOE reactor options rather than a large cost increase among designs at the same power level.

### 4.2.3 Summary

The transportation requirements affect the availability of reactor designs more strongly than the minimum LCOE among designs at the same power level. Their effect also depends substantially on whether the market requires only initial delivery of a fresh reactor or removal of the intact reactor after operation. The principal conclusions are:

- **Mass is the controlling transportation constraint.** For standard-road delivery, 1,379 of the 1,383 disqualified designs exceed the 48,000-lb module-mass limit. For vendor take-back, all 1,824 designs that fail the complete scenario exceed the 140,000-lb return-package limit. Width and loaded height are also important, particularly for GCMR and HPMR designs, but they generally fail together with mass rather than independently.
- **Initial delivery alone leaves both LTMR and GCMR options available.** The LTMR is consistently compatible with the standard-road envelope across the evaluated power range, whereas the number of qualifying GCMR designs decreases sharply with increasing power. Nevertheless, low-LCOE GCMR designs remain available at each evaluated power level. The preferred reactor can therefore depend on deployment maturity.
- **Vendor take-back substantially narrows the reactor options.** The requirement to return the intact irradiated reactor after 60 months of cooling reduces the qualifying population from 761 fresh-delivery designs to 320 complete take-back designs. It limits the evaluated GCMR options to 2 MWt and eliminates the 50-MWt LTMR option. Consequently, the LTMR becomes the only evaluated reactor model capable of satisfying the take-back requirement at 15 and 30 MWt.
- **The main economic penalty is the loss of larger, lower-LCOE reactors rather than a large within-power cost increase.** For qualifying LTMR designs, the maximum observed within-power increase is \$2/MWh for FOAK LCOE and \$5/MWh for NOAK LCOE. However, excluding the 50-MWt LTMR shifts the lowest available take-back option to 30 MWt. Its minimum FOAK and NOAK LCOEs of \$288/MWh and \$178/MWh are 27% and 34% higher, respectively, than the unrestricted 50-MWt values of \$226/MWh and \$133/MWh. This comparison illustrates the lost economy of scale but is not capacity matched.
- **Enrichment affects transportability indirectly and does not establish a universal eligibility threshold.** Conventional-LEU LTMR designs qualify for both transportation scenarios, particularly at lower power. In contrast, no 4.95%-enriched GCMR qualifies for standard-road delivery. These differences reflect the interaction of enrichment with core size, fuel inventory, and reactor architecture.

## 4.3 Long Operating-Cycle Requirement

In this analysis, operating-cycle length means the period during which a reactor core can operate at its nominal power before refueling or core replacement. A longer operating cycle reduces how

frequently fresh fuel, specialized personnel, fuel-handling equipment, and replacement components must be transported to the site. It can also reduce planned refueling outages.

Long operating cycles are particularly valuable for:

- **Remote and Arctic communities**, where seasonal access, severe weather, and limited transportation infrastructure can make fuel delivery and maintenance difficult.
- **Remote mines and industrial sites**, where an extended refueling outage could interrupt production and where specialized nuclear personnel may not be permanently available.
- **Defense and other mission-critical installations**, where reducing dependence on external fuel deliveries can improve energy security and mission readiness.
- **Sites with limited local infrastructure**, where constructing and maintaining facilities for frequent on-site refueling may be impractical.

Shropshire, Black, and Araújo (2021, Section 6.1) identified remote mines, military installations, and isolated communities as potential applications. Their analysis specifically found that operating for at least three years without refueling could benefit mission readiness at remote military installations.

A long operating cycle is nevertheless not universally preferable. Achieving it may require additional fissile material, a larger core, greater reflector thickness, or other design changes that increase capital and fuel costs. For sites with reliable transportation access and established maintenance infrastructure, accepting more frequent refueling may therefore produce a lower LCOE. The purpose of this section is to quantify this tradeoff: how much does the minimum achievable LCOE increase when the market requires a longer operating cycle?

The analysis used the combined LTMR, GCMR, and HPMR design datasets developed for the enrichment studies. Designs using 4.95%, 9.9%, 15%, and 19.75% U-235 were considered together because this section isolates the operating-cycle requirement rather than the separate constraint imposed by enrichment availability. Only designs satisfying the two principal design constraints (shutdown margin and temperature coefficient) were included.

For each reactor model, nominal thermal power, and FOAK or NOAK cost basis, the procedure was:

1. Identify the minimum LCOE among designs with a calculated operating cycle of at least two years. This value is the baseline minimum LCOE.
2. Progressively require minimum operating cycles of three, four, five, and six years.
3. Recalculate the minimum LCOE among the designs remaining at each requirement.
4. Calculate the long-cycle penalty.

Thus, the penalty is measured relative to the least-cost design having an operating cycle of at least two years for the same reactor model, power level, and FOAK or NOAK basis. Figure 6 presents the calculated LCOE penalties associated with progressively increasing the minimum operating-cycle requirement from two to six years. The vertical axis reports the increase in minimum LCOE relative to the corresponding two-year baseline, while the horizontal axis

reports the minimum required cycle length. The baseline table included in the figure provides the FOAK and NOAK LCOEs to which these penalties are added. Each curve therefore shows how the least-cost available design changes as the cycle-length requirement becomes more restrictive.

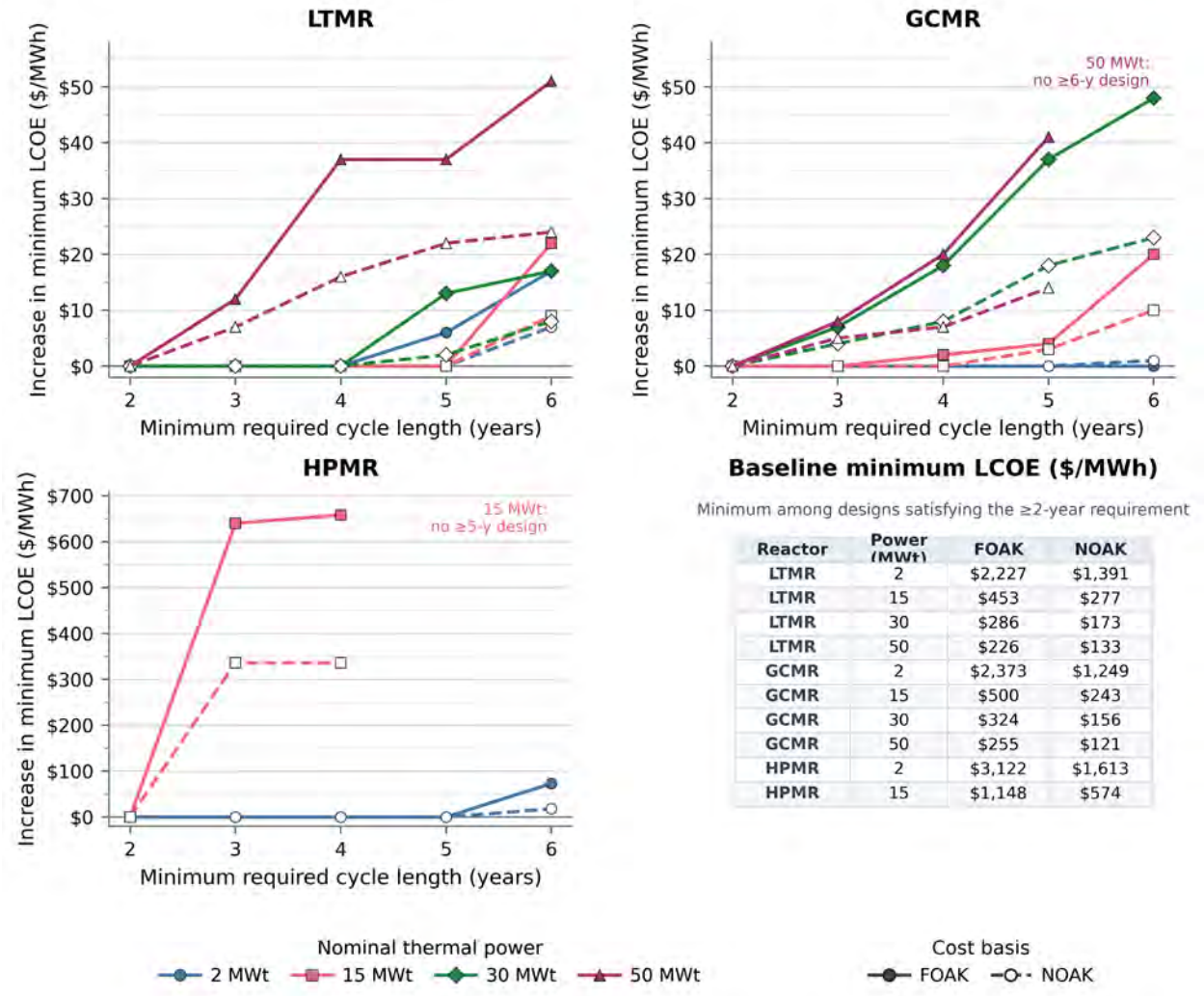



Figure 6. Increase in the minimum FOAK and NOAK LCOE resulting from progressively longer minimum operating-cycle requirements for LTMR, GCMR, and HPMR designs. The penalty is calculated relative to the minimum LCOE among designs with a calculated operating cycle of at least two years for the same reactor model, nominal thermal power, and cost basis. Colors distinguish nominal thermal-power levels; solid lines with filled markers represent FOAK costs, and dashed lines with open markers represent NOAK costs. The accompanying table reports the baseline LCOE to which each penalty is added.

The results show that imposing a longer operating cycle does not produce a uniform cost penalty. The magnitude of the penalty depends on the reactor model, power level, cost basis, and availability of qualifying long-cycle designs.

- **LTMR:** Minimum operating-cycle requirements of three or four years generally produce little or no penalty. At a six-year requirement, the FOAK penalty ranges from $17/MWh at 2 MWt to $51/MWh at 50 MWt. The corresponding NOAK penalties range from $7/MWh to $24/MWh. The largest LTMR penalty occurs at 50 MWt, where increasing the minimum requirement from two to three years already adds approximately $12/MWh to the FOAK LCOE, and a six-year requirement adds approximately $51/MWh.
- **GCMR:** The 2-MWt GCMR cases accommodate the longer-cycle requirement with essentially no increase in minimum LCOE through six years. The penalty becomes more pronounced at higher powers. At a six-year requirement, the minimum FOAK LCOE increases by approximately $20/MWh at 15 MWt and $48/MWh at 30 MWt; the corresponding NOAK penalties are approximately $10/MWh and $23/MWh. At 50 MWt, a five-year requirement adds approximately $41/MWh for FOAK and $14/MWh for NOAK.
- **HPMR:** The 2-MWt HPMR cases show no calculated penalty through a five-year requirement, followed by penalties of approximately $73/MWh for FOAK and $18/MWh for NOAK at six years. The 15-MWt HPMR cases show a much stronger tradeoff. Increasing the minimum cycle from two to three years raises the minimum LCOE by approximately $640/MWh for FOAK and $336/MWh for NOAK.

Overall, the results demonstrate that the economic consequence of a long-cycle requirement must be evaluated for the specific reactor and power level. For several LTMR and GCMR cases, operating cycles of three or four years can be required with little or no increase in the minimum calculated LCOE. Requirements approaching five or six years can produce a measurable penalty, eliminate otherwise attractive designs, or, particularly for the 15-MWt HPMR, leave no qualifying design in the currently explored space.

The calculated penalties represent only the direct design and cost consequences captured by MOUSE. They do not assign an economic value to avoided refueling outages, fewer fuel shipments, reduced dependence on seasonal transportation, improved mission readiness, or greater resilience against fuel-supply interruptions. A remote or mission-critical customer may therefore rationally accept a higher LCOE for a longer operating cycle when these operational benefits exceed the calculated LCOE penalty.

## 4.4 Power Requirement

Required reactor power varies substantially among microreactor markets. Small rural communities, isolated critical loads, and disaster-response applications may require relatively little power, whereas mines, regional communities, industrial facilities, and military installations may require tens of megawatts. Shropshire (2021) report representative electrical-demand ranges of 0.5–10 MWe for small rural communities, 10–25 MWe for rural hub communities, 10–40 MWe for remote mining operations, and 7–40 MWe for military installations. Their market analysis also identifies systems below 1 MWe for some distributed-energy applications and systems up to approximately 20 MWe for mines and microgrids (Shropshire 2021).

This section therefore evaluates the power-scale cost consequence by comparing the LCOE ranges and minimum LCOEs obtained at the modeled power levels.

The analysis considered designs using 4.95%, 9.9%, 15%, and 19.75% U-235. Designs were retained when their shutdown margin was greater than 1,000 pcm, their limiting temperature coefficient was below 0 pcm/K, and their operating-cycle category was between two and six years.

Figure 7 presents electrical power on the lower horizontal axis and the corresponding modeled thermal power on the upper axis. Both axes are categorical; their spacing distinguishes the simulated power cases and does not represent continuous numerical spacing.

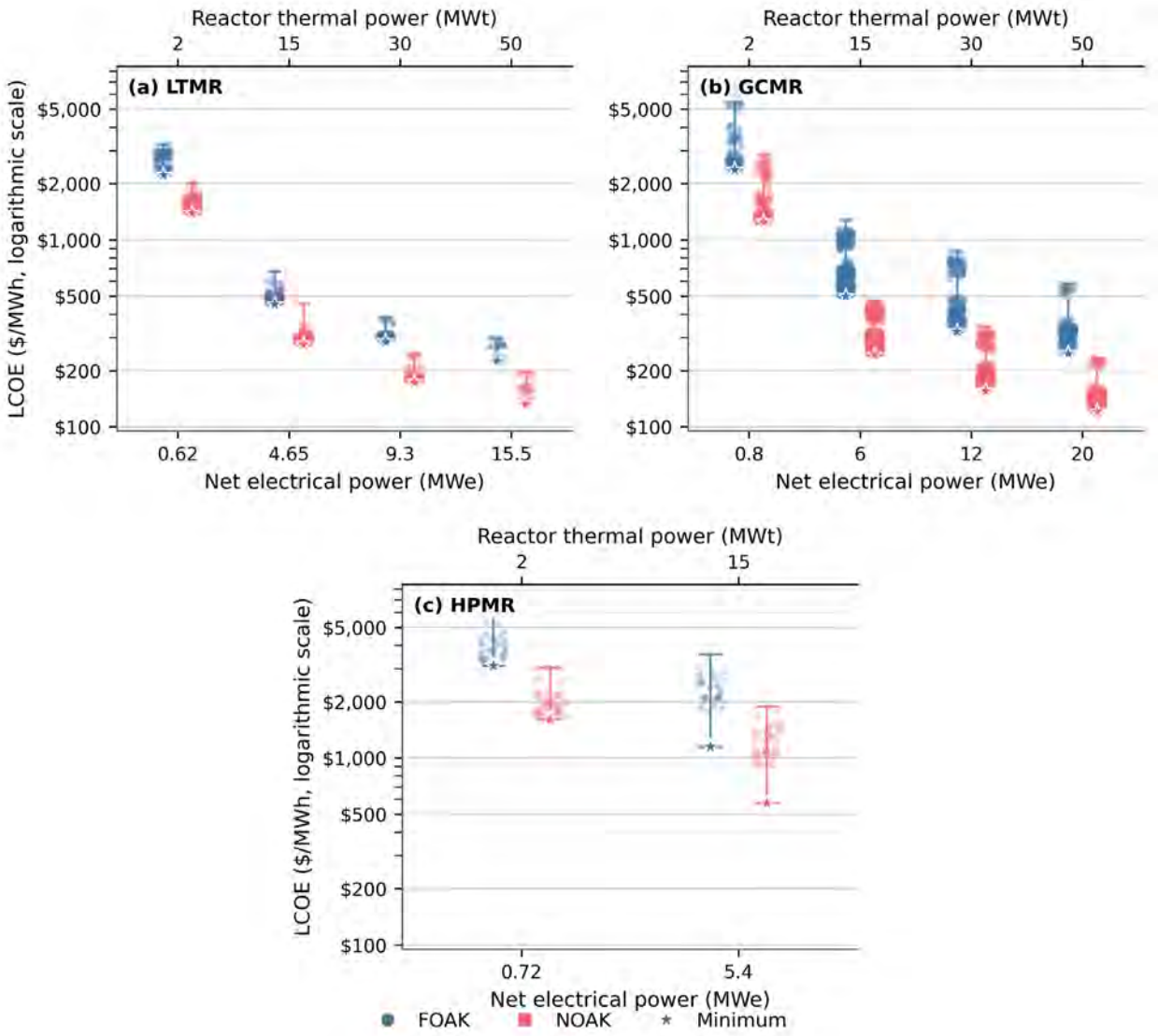



Figure 7. FOAK and NOAK LCOE ranges for constraint-satisfying LTMR, GCMR, and HPMR designs at the modeled reactor -power levels. Each transparent point represents one design, the vertical line reports the complete sampled minimum-to-maximum range, and the star identifies the minimum LCOE. The power axis is categorical. The logarithmic LCOE axis is used to display the large difference between the 2-MWt cases and the higher-power cases without obscuring the variation at 15, 30, and 50 MWt.

Table 14 provides the numerical LCOE ranges shown in Figure 7. Power is reported as thermal power followed by the corresponding net electrical power in brackets.

Table 14. Calculated LCOE ranges at the evaluated reactor power levels.

| Reactor | Power, MWt [MWe] | # Designs | FOAK LCOE range ($/MWh) | NOAK LCOE range ($/MWh) |
|---|---|---|---|---|
| LTMR | 2 [0.62] | 148 | 2,227–3,258 | 1,391–2,013 |
| LTMR | 15 [4.65] | 163 | 453–678 | 277–456 |

| | | | | |
|---|---|---|---|---|
| LTMR | 30 [9.30] | 106 | 286–385 | 173–245 |
| LTMR | 50 [15.50] | 33 | 226–300 | 133–198 |
| GCMR | 2 [0.80] | 204 | 2,373–7,004 | 1,249–2,844 |
| GCMR | 15 [6.00] | 629 | 500–1,278 | 243–473 |
| GCMR | 30 [12.00] | 374 | 324–873 | 156–346 |
| GCMR | 50 [20.00] | 385 | 247–584 | 121–235 |
| HPMR | 2 [0.72] | 54 | 3,122–6,043 | 1,613–3,052 |
| HPMR | 15 [5.40] | 48 | 1,148–3,587 | 574–1,889 |

As shown in Figure 7 and Table 14, LCOE decreases substantially as reactor power increases. Many reactor, site, instrumentation and control, staffing, and other project costs do not increase in direct proportion to output. Greater output therefore distributes these costs over more electricity generation. The reduction is especially pronounced between the 2- and 15-MWt cases.

For the LTMR, increasing output from 0.62 MWe to 4.65 MWe reduces the minimum FOAK LCOE from $2,227/MWh to $453/MWh and the minimum NOAK LCOE from $1,391/MWh to $277/MWh. The minimum values decline further to $226/MWh for FOAK and $133/MWh for NOAK at 15.50 MWe. Relative to the largest evaluated LTMR, requiring the 0.62-MWe size therefore corresponds to an increase of approximately $2,001/MWh in the minimum FOAK LCOE and $1,258/MWh in the minimum NOAK LCOE.

The GCMR exhibits a similar scale effect. Its minimum FOAK LCOE decreases from $2,373/MWh at 0.80 MWe to $500/MWh at 6.00 MWe and $247/MWh at 20.00 MWe. The corresponding minimum NOAK values decrease from $1,249/MWh to $243/MWh and $121/MWh. The small GCMR cases also exhibit a comparatively wide cost range, indicating that design choices have a particularly large economic effect when the reactor output is low.

The available HPMR dataset contains qualifying cases at 0.72 and 5.40 MWe. Between these two levels, the minimum FOAK LCOE decreases from $3,122/MWh to $1,148/MWh, while the minimum NOAK LCOE decreases from $1,613/MWh to $574/MWh. Qualifying HPMR results were not available at the 30- and 50-MWt categories.

The results demonstrate that a low-power requirement can impose a substantial LCOE penalty even when technically acceptable designs are available. However, the results do not imply that the largest reactor is preferable for every market. The benefit of a lower LCOE at higher output can be realized only when the market can use that output at the assumed operating conditions.

## 4.5 Capital-Constrained Applications

A capital-constrained application is one in which the project owner cannot exceed a specified initial investment, even if a more expensive reactor would produce electricity at a lower LCOE.

This condition may be relevant to remote communities, municipal utilities, private industrial facilities, and other customers with limited access to financing. NEI identifies capital cost and reactor size as major drivers of microreactor LCOE and notes that financing costs depend on the type of owner and the availability of loan guarantees (NEI 2019).

This analysis uses total capital investment (TCI) as the measure of initial investment. In MOUSE, TCI includes the overnight capital cost and capitalized financial costs.

The analysis includes the 2,144 designs having a shutdown margin greater than 1,000 pcm, a limiting temperature coefficient below 0 pcm/K, and a fuel-lifetime category between two and six years. Designs using 4.95%, 9.9%, 15%, and 19.75% U-235 were considered together. Designs were grouped into $50 million FOAK TCI intervals, beginning at $100 million and extending through $500 million. Table 15 reports the power and enrichment ranges available for each reactor model within each interval, together with the minimum FOAK and NOAK LCOEs. Tax credits are excluded.

Table 15. Reactor options and minimum LCOE within each FOAK total-capital-investment range.

| FOAK TCI range ($ million) | LTMR: power, MWt (enrichment, % U-235) | GCMR: power, MWt (enrichment, % U-235) | HPMR: power, MWt (enrichment, % U-235) | LTMR minimum LCOE: FOAK (NOAK), $/MWh | GCMR minimum LCOE: FOAK (NOAK), $/MWh | HPMR minimum LCOE: FOAK (NOAK), $/MWh |
|---|---|---|---|---|---|---|
| 100–150 | 2 (4.95–19.75) | 2 (9.9–19.75) | 2 (19.75) | 2,227 (1,391) | 2,373 (1,249) | 3,122 (1,613) |
| 150–200 | 15–30 (4.95–19.75) | 2–15 (4.95–19.75) | 2 (15–19.75) | 286 (177) | 500 (243) | 3,789 (1,788) |
| 200–250 | 15–50 (4.95–19.75) | 2–30 (4.95–19.75) | 15 (19.75) | 226 (133) | 324 (156) | 1,148 (574) |

| | | | | | | |
|---|---|---|---|---|---|---|
| 250–300 | 30–50<br>(4.95–9.9) | 15–50<br>(4.95–19.75) | — | 237<br>(138) | 247<br>(121) | — |
| 300–350 | 50<br>(4.95) | 15–50<br>(4.95–19.75) | 15<br>(15) | 265<br>(149) | 271<br>(127) | 2,452<br>(1,286) |
| 350–400 | — | 30–50<br>(4.95–15) | 15<br>(15) | — | 316<br>(140) | 1,788<br>(910) |
| 400–450 | — | 30–50<br>(4.95) | 15<br>(15) | — | 517<br>(208) | 1,896<br>(947) |
| 450–500 | — | 50<br>(4.95) | — | — | 555<br>(220) | — |

The $100–150 million interval contains only 2-MWt designs. Although these designs require the least initial investment, their minimum LCOEs remain above $2,200/MWh for FOAK LTMR and GCMR designs and above $1,200/MWh for their NOAK equivalents. The lowest-capital designs therefore do not provide the lowest cost of electricity because their fixed costs are distributed over relatively little electricity generation.

Increasing the available FOAK capital to $150–250 million provides access to higher-power designs and substantially lower LCOE. Within these intervals, the LTMR has the lowest minimum FOAK and NOAK LCOEs. In the $200–250 million intervals, its minimum LCOE reaches $226/MWh for FOAK deployment and $133/MWh for NOAK deployment. The same interval contains one qualifying 15-MWt HPMR, but its minimum LCOEs remain considerably higher at $1,148/MWh and $574/MWh.

The GCMR becomes most competitive in the $250–300 million interval. Its minimum FOAK LCOE is $247/MWh, compared with $237/MWh for the LTMR, while its minimum NOAK LCOE is lower at $121/MWh, compared with $138/MWh for the LTMR. Higher capital investment does not consistently produce lower LCOE. Above $300 million, the minimum LCOEs generally increase because these intervals contain more capital-intensive designs without a proportional increase in electricity generation.

The results demonstrate that minimizing capital investment and minimizing LCOE are different objectives. A severe capital constraint limits the available market primarily to low-power reactors with high LCOE. Moderate increases in available capital provide access to higher-power LTMR and GCMR designs with substantially better economics. Within the explored design space, the LTMR generally provides the lowest LCOE below $250 million of FOAK TCI, while the GCMR becomes competitive between approximately $250 million and $350 million, particularly on a NOAK basis. The preferred reactor nevertheless depends on both the available capital and the required power; a higher-power design should not be selected solely because it produces a lower LCOE if the market cannot use its output.

# 5 Conclusions

This report used MOUSE to determine how market requirements change the set of available LTMR, GCMR, and HPMR designs and the minimum LCOE achievable within that set. The

analysis did not assume that one reactor model is optimal for every market. Instead, candidate designs were first screened using shutdown-margin and temperature-coefficient requirements and were then filtered according to fuel availability, transportation constraints, operating-cycle requirements, required power, and available capital. The results demonstrate that the lowest-cost reactor depends on the customer's constraints and on whether the project is evaluated as a FOAK or NOAK deployment.

The central conclusion is that market requirements can affect economics in two different ways. Some requirements increase the LCOE of the lowest-cost design within a given reactor and power category. Other requirements have little effect on within-category LCOE but eliminate entire reactor models or power classes. The latter effect is particularly important for transportability and capital availability because excluding a larger reactor can remove the economy-of-scale benefit responsible for its lower LCOE.

Table 16 summarizes the answers to the principal market questions evaluated quantitatively in this report. The reported selections are the lowest-LCOE designs identified within the explored MOUSE design space and should not be interpreted as universally optimal commercial reactor designs.

Table 16. Reactor selections and economic implications of the market requirements evaluated in this report.

| Market condition or application | Reactor selection within the explored design space | Calculated LCOE result | Principal conclusion |
|---|---|---|---|
| **HALEU unavailable; 4.95% U-235 required** | LTMR provides the lowest FOAK and NOAK LCOE at 15, 30, and 50 MWt. GCMR designs remain feasible but are more expensive. No qualifying HPMR was identified. | LTMR FOAK/NOAK LCOE: \$530/\$303 per MWh at 15 MWt; \$351/\$203 per MWh at 30 MWt; and \$263/\$149 per MWh at 50 MWt. | Avoiding HALEU does not eliminate LTMR or GCMR deployment, but it imposes an economic penalty. The LTMR is the strongest option when conventional LEU compatibility is required. |
| **HALEU available** | LTMR provides the lowest FOAK minimum, while GCMR provides the lowest NOAK minimum at the shared power levels. HPMR remains substantially more expensive and has few qualifying designs. | At 15, 30, and 50 MWt, the lowest FOAK LCOEs are \$453, \$286, and \$226/MWh, respectively, using LTMR designs. The lowest NOAK values are \$243, \$156, and \$121/MWh, respectively, using GCMR designs. | The LTMR captures most of its enrichment-related benefit by approximately 9.9–15% U-235. The GCMR continues to benefit from higher enrichment, although the incremental benefit decreases as enrichment approaches 19.75%. |

| | | | |
|---|---|---|---|
| **Permanent road-accessible remote community, mine, military installation, or industrial site requiring only fresh-reactor delivery** | Both LTMR and GCMR remain available. LTMR has substantially higher qualification rates and provides the lowest FOAK LCOE. A smaller subset of GCMRs qualifies and provides the lowest NOAK LCOE. No evaluated HPMR qualifies. | Lowest road-qualified FOAK/NOAK outcomes are $2,227/$1,249 per MWh at 2 MWt; $453/$243 per MWh at 15 MWt; $286/$156 per MWh at 30 MWt; and $226/$123 per MWh at 50 MWt. The FOAK values correspond to LTMR and the NOAK values to GCMR. | Standard-road delivery removes many GCMR designs and all HPMR designs but has little effect on the minimum LCOE because low-cost LTMR and GCMR configurations remain available. |
| **Temporary mine or industrial deployment requiring intact irradiated-reactor take-back** | At 2 MWt, both LTMR and GCMR options remain. At 15 and 30 MWt, only LTMR designs qualify. No 50-MWt design and no HPMR design qualify. | At 2 MWt, the lowest FOAK result is $2,227/MWh for LTMR, while the lowest NOAK result is $1,249/MWh for GCMR. Qualifying 15-MWt LTMR designs have minimum values of $453/$280 per MWh, and qualifying 30-MWt LTMR designs have minimum values of $288/$178 per MWh. | Vendor take-back favors LTMR for applications requiring more than 2 MWt. Its principal penalty is the loss of larger reactors rather than a large within-power increase in LCOE. |
| **Remote, Arctic, mining, or defense application requiring a longer operating cycle** | LTMR and GCMR generally accommodate three- or four-year minimum cycles with small penalties. HPMR is less favorable, particularly at 15 MWt. | At a six-year requirement, LTMR penalties range from $17–$51/MWh for FOAK and $7–$24/MWh for NOAK. GCMR penalties at six years reach approximately $20/$10 per MWh at 15 MWt and $48/$23 per MWh at 30 MWt. A three-year requirement increases the 15-MWt HPMR LCOE by approximately $640/$336 per MWh. | A three- or four-year cycle can often be obtained without substantially changing the preferred LTMR or GCMR. Requirements approaching five or six years require a reactor- and power-specific assessment and can eliminate otherwise attractive designs. |
| **Small remote load represented by the 2-MWt category** | LTMR provides the lowest FOAK LCOE, while GCMR provides the lowest NOAK LCOE. HPMR is more expensive and does not satisfy the evaluated | Minimum FOAK LCOE is $2,227/MWh for LTMR. Minimum NOAK LCOE is $1,249/MWh for GCMR. | The small required output imposes a large cost penalty because fixed reactor, site, staffing, and balance-of-plant costs are distributed over |

| | | | |
|---|---|---|---|
| | road-transport requirements. | | relatively little electricity generation. |
| **Larger mine, military, community, or industrial load represented by 15–50 MWt** | LTMR provides the lowest FOAK LCOE at each modeled power level; GCMR provides the lowest NOAK LCOE. | At 15, 30, and 50 MWt, the lowest FOAK values are $453, $286, and $226/MWh for LTMR. The lowest NOAK values are $243, $156, and $121/MWh for GCMR. | Increasing power produces the largest reduction in LCOE observed in the study. The economic benefit is relevant only when the market can use the additional output. |
| **Severely capital-constrained project with $100–150 million in FOAK TCI** | Only 2-MWt LTMR, GCMR, and HPMR designs are available. LTMR has the lowest FOAK LCOE, while GCMR has the lowest corresponding NOAK LCOE. | Minimum FOAK and NOAK outcomes are $2,227/MWh for LTMR and $1,249/MWh for GCMR, respectively. | Minimizing initial investment forces the customer toward low-power designs with high LCOE. Low capital investment and low electricity cost are not the same objective. |
| **Project with approximately $150–250 million in FOAK TCI** | LTMR is the preferred reactor on both FOAK and NOAK bases within the evaluated designs. | Minimum LTMR LCOE is $286/$177 per MWh in the $150–200 million interval and $226/$133 per MWh in the $200–250 million intervals. | Moderate additional capital provides access to higher-power LTMR designs and produces a substantial reduction in LCOE relative to the $100–150 million intervals. |
| **Project with approximately $250–300 million in FOAK TCI** | LTMR retains a small FOAK advantage, while GCMR provides the lowest NOAK LCOE. | Minimum FOAK LCOE is $237/MWh for LTMR. Minimum NOAK LCOE is $121/MWh for GCMR. | This capital range provides the most competitive GCMR NOAK result. Capital investment above this range does not consistently reduce LCOE. |

The enrichment results show that the LTMR is the most robust option when fuel availability is restricted. Constraint-satisfying LTMR designs were identified using conventional 4.95% U-235 fuel at 15, 30, and 50 MWt, and 81 of the 91 evaluated 4.95% LTMR designs also satisfy the standard-road transportation criteria. In contrast, no 4.95% GCMR satisfies the standard-road criteria, although road-qualified GCMR designs become available at higher enrichment.

Fuel form is an important contributor to the differences among the reactor models. Both the GCMR and HPMR use TRISO fuel in the current MOUSE models. The TRISO particles, graphite matrix, and associated structural materials reduce the uranium density of the fuel region and can require a larger core and greater material inventory to achieve a specified power and operating lifetime. Together with concept-specific geometry, reflectors, coolant systems, and

heat-transport components, these characteristics contribute to the larger GCMR and HPMR modules identified in the explored design space and to their more limited compatibility with standard-road transportation.

TRISO fabrication also represents a comparatively large cost contribution in the current MOUSE models, particularly under FOAK assumptions, when production volumes are limited and manufacturing and supply-chain learning have not yet been realized. This contributes to the LTMR providing the lowest FOAK LCOE at most evaluated power levels. Under NOAK assumptions, the modeled effects of standardized production, higher manufacturing throughput, and learning reduce this disadvantage. Consequently, the GCMR becomes economically competitive and frequently provides the lowest NOAK LCOE when HALEU is available, and transportation constraints do not eliminate the design.

Transportation requirements illustrate why reactor selection cannot be based on LCOE alone. The standard-road filter removes 1,383 of the 2,144 technically eligible designs, including all evaluated HPMR designs and higher-power GCMR designs. A market requiring irradiated-module take-back is much more restrictive. It eliminates all 50-MWt designs, all GCMR designs at 15 MWt or greater, and all HPMR designs. The principal penalty is the loss of lower-cost reactor and power options.

Operating-cycle requirements produce a more direct cost tradeoff. Requiring a longer cycle can reduce the frequency of refueling, fuel deliveries, and site access, which may be valuable for Arctic communities, temporary mines, and defense installations. However, longer cycles can require additional fuel, a larger core, or changes to the reflector and control systems. The results show that three- and four-year cycles are often available with little economic penalty, whereas five- and six-year requirements can increase LCOE or remove otherwise attractive designs. Because the analysis does not assign an economic value to avoided refueling operations, the reported LCOE penalties should be compared with the market-specific cost and risk of performing an additional refueling campaign.

Power and capital requirements must also be considered together. The lowest LCOEs occur at the higher evaluated power levels because several reactor, site, staffing, instrumentation and control, and balance-of-plant costs do not scale proportionally with energy production. However, selecting a larger reactor requires greater total capital and is beneficial only when the market can use or sell the additional output. Conversely, the lowest-capital designs are limited primarily to 2 MWt and have substantially higher LCOEs. A capital-constrained market may therefore select a small reactor because it is financially accessible, not because it minimizes the cost of electricity.

Taken together, the results support the following market-oriented reactor-selection conclusions:

- Under the modeled FOAK assumptions, the LTMR is the strongest candidate among the evaluated concepts for markets without assured HALEU access, road-transport-constrained applications, and temporary applications requiring take-back at moderate power. It provides the lowest FOAK LCOE at most evaluated power levels and retains feasible conventional-LEU configurations.

- GCMR is more attractive for mature-fleet, stationary applications with access to HALEU. Its NOAK LCOE is lower than the LTMR minimum at the evaluated HALEU power levels, but its larger and heavier TRISO-fueled configurations make transportation constraints more consequential.
- Very small markets face a substantial LCOE penalty regardless of reactor type. Their potential value is therefore more likely to depend on replacing expensive incumbent generation, improving resilience, or avoiding difficult fuel logistics than on competing with grid-scale wholesale electricity prices.
- No single reactor design is optimal for every market. The preferred configuration changes with fuel availability, deployment maturity, transportation requirements, operating lifetime, required power, and available capital.

These conclusions are subject to the limitations of the analysis. The simulations constitute design-space exploration rather than formal optimization, and lower-cost configurations may exist outside the sampled ranges. The economic calculations exclude tax credits and do not monetize resilience, avoided fuel deliveries, emissions reductions, or avoided refueling risk. The transportation analysis is a screening calculation rather than a route-specific licensing or logistics assessment.

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# APPENDIX A: MOUSE Reactor Models and Principal Cost Assumptions

The MOUSE tool connects reactor-physics calculations, simplified engineering models, balance-of-plant sizing, and bottom-up cost estimation. For a specified reactor configuration, MOUSE uses OpenMC to calculate quantities such as reactivity, fuel lifetime, temperature coefficients, shutdown margin, material inventories, and reactor dimensions. These results are then used to size major systems and estimate capital, fuel-cycle, operation and maintenance, replacement, decommissioning, and financing costs. The principal economic outputs include FOAK and NOAK total capital investment LCOE (Hanna et al. 2025).

MOUSE includes three pre-conceptual reactor models representing different microreactor technology classes. The three reactor models are depicted in Figure 8, Figure 9 and Figure 10. The models are intended for comparative design and economic analysis and do not represent final, licensed, or commercially available reactor configurations.

The liquid-metal thermal microreactor (LTMR) model used in this report contains annular uranium dioxide fuel pins, separate zirconium-hydride moderator pins, and NaK coolant. Each fuel pin includes a central zirconium displacer, an annular $UO_2$ fuel region, gaps, and stainless-steel cladding. The fuel and moderator pins are arranged in a hexagonal lattice surrounded by graphite radial and axial reflectors. Reactivity control is provided by enriched-boron-carbide absorber drums located in the radial reflector, while a separate system of six or twelve enriched-boron-carbide shutdown rods is incorporated into selected lattice positions.

The **g**as-cooled microreactor (GCMR) model uses explicitly represented TRISO particles containing uranium oxycarbide fuel kernels surrounded by buffer-carbon, pyrolytic-carbon, and silicon-carbide layers. The particles are dispersed at a specified packing fraction within cylindrical graphite fuel compacts. The compacts, helium coolant channels, and zirconium-hydride moderator-booster rods are arranged within hexagonal graphite assemblies, which are surrounded by graphite radial and axial reflectors. Reactivity control is provided by enriched-boron-carbide control drums in the radial reflector. The shutdown system includes rods distributed within the central assembly and six surrounding shutdown assemblies.

The heat-pipe microreactor (HPMR) model uses homogenized TRISO fuel compacts based on $UO_2$ fuel kernels embedded in a graphite matrix. The fuel compacts and heat pipes are arranged within hexagonal graphite monolith assemblies, with helium-filled gaps represented around the fuel compacts and heat pipes. Heat removal is provided by the heat pipes rather than by a pumped primary coolant loop. The evaluated configurations included two sixfold-symmetric assembly layouts: one containing 72 fuel compacts and 19 heat pipes and another containing 78 fuel compacts and 13 heat pipes. The core is surrounded by graphite radial and axial reflectors and includes rotating enriched-boron-carbide control drums and a central enriched-boron-carbide shutdown rod.

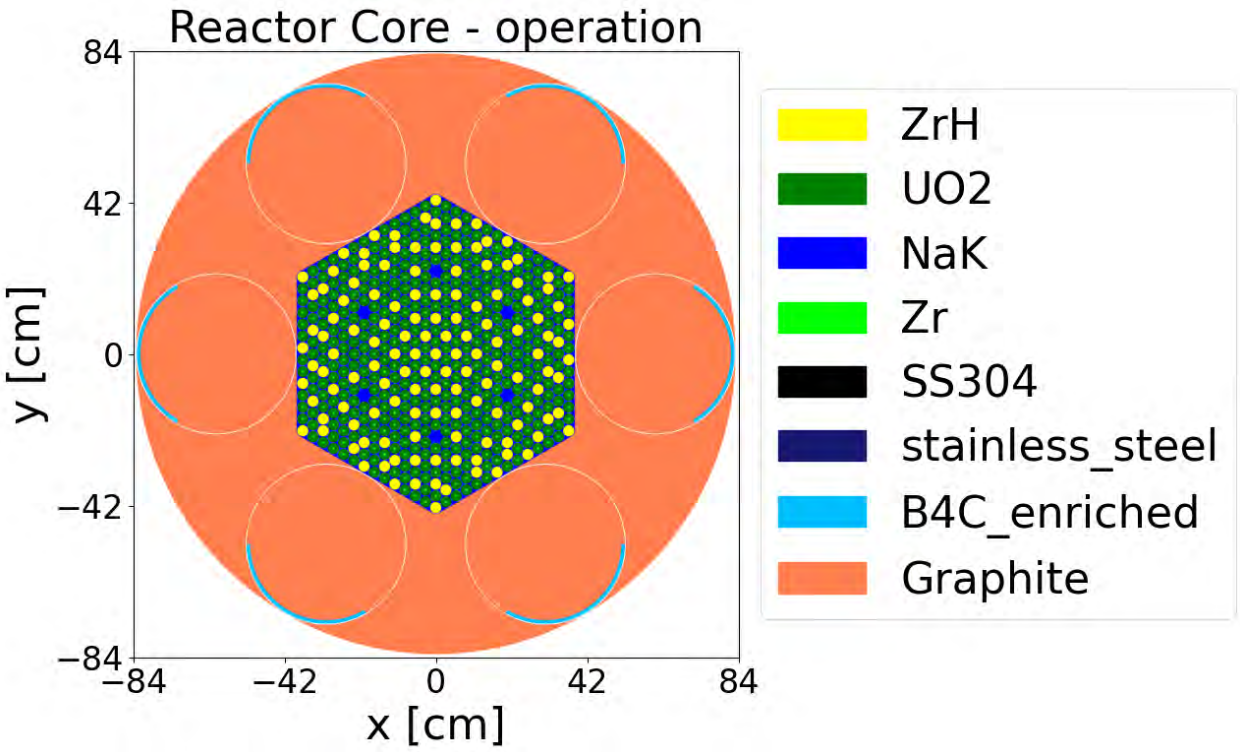



Figure 8. LTMR core OpenMC model. The reactor core (hexagonal assembly surrounded by control drums and the graphite reflector.

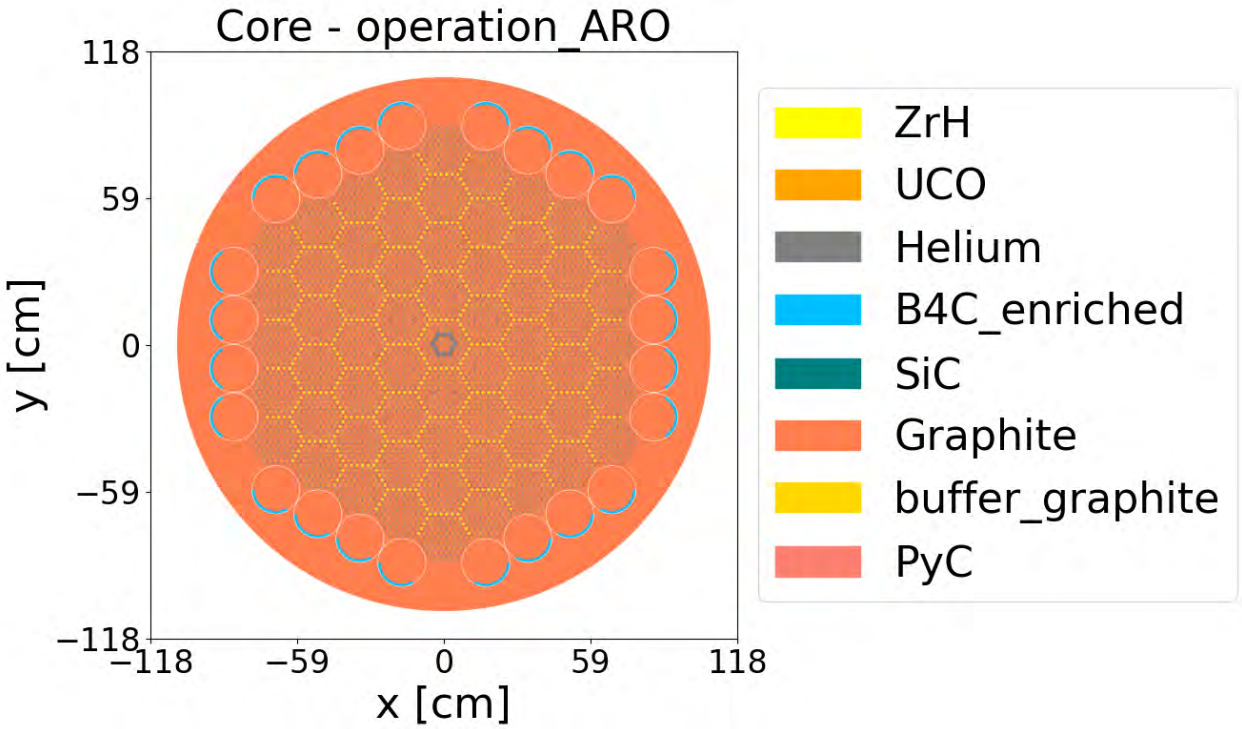



Figure 9. The TRISO-fueled GCMR hexagonal core, which is surrounded by control drums and the graphite reflector.

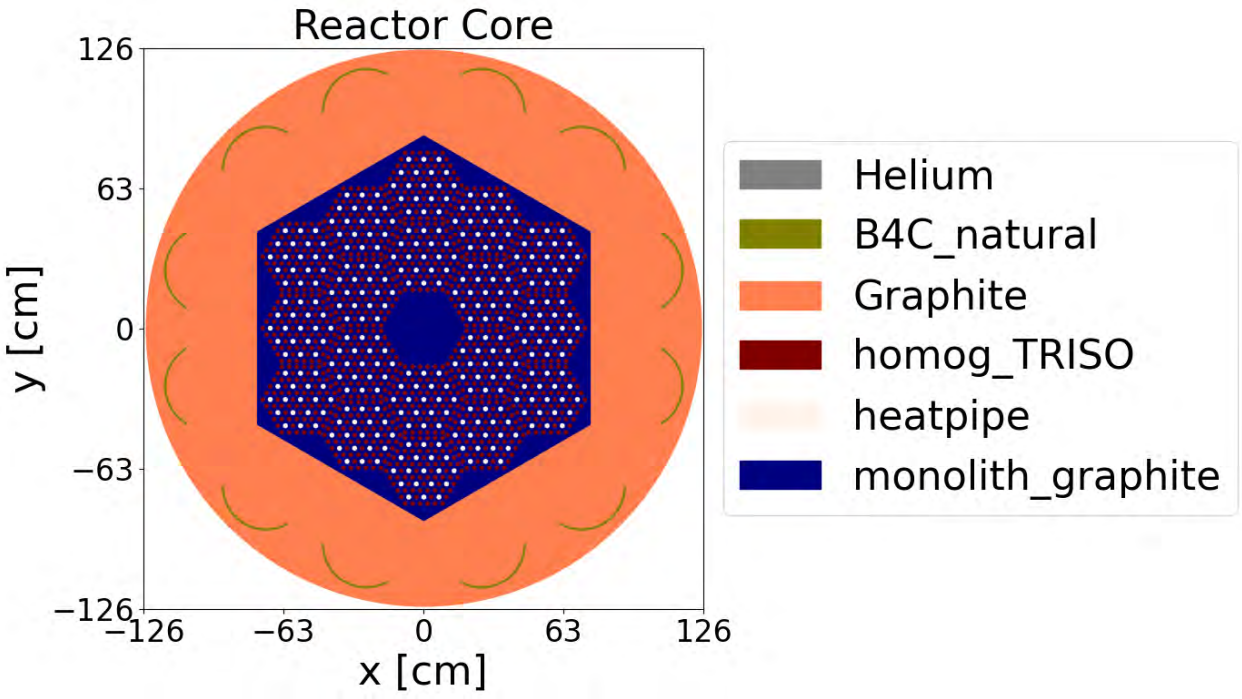



Figure 10. The HPMR reactor core: the homogenized TRISO fuel and the heat pipes are surrounded by monolith graphite. The hexagonal reactor core is surrounded by drums and the reflector.

The following resources provide access to the current code, application, documentation, and cost data:

- **MOUSE GitHub repository:** https://github.com/IdahoLabResearch/MOUSE
- **MOUSE web application:** https://mouse-microreactors.streamlit.app/
- **MOUSE cost database:** https://github.com/IdahoLabResearch/MOUSE/blob/main/cost/Cost_Database.xlsx

The GitHub repository contains the source code and example input files. The MOUSE cost database workbook is the principal source for the account-level cost values, escalation bases, learning assumptions, cost references, and supporting notes used by the model.

Fuel cost depends on the uranium inventory, enrichment, fuel form, fabrication assumptions, and replacement frequency. TRISO fabrication is a particularly important cost contributor for the GCMR and HPMR. Under the modeled assumptions, TRISO fuel contributes to the relatively high FOAK costs of these two reactor models. Its relative economic effect becomes smaller in the NOAK cases as learning is applied to eligible fuel-fabrication and manufacturing accounts.

Component-replacement assumptions also affect calculated LCOE because MOUSE evaluates costs over the complete levelization period. A component replaced every fuel cycle can contribute substantially more to lifetime cost than a component retained for several cycles or for a specified number of years. The principal economic, operational, and replacement assumptions used in this report are summarized in Table A-1. The values in the table are input assumptions for comparative analysis. They should not be interpreted as validated component lifetimes, maintenance requirements, or vendor commitments.

Table 17. Principal economic and operating assumptions used in the MOUSE calculations for this report.

| Assumption | Value or treatment used in this report |
|---|---|
| Cost basis | Costs escalated to 2025 dollars |
| Levelization period | 60 years |
| Discount rate | 7% annual weighted average cost of capital |
| Construction financing | 7% interest rate; 12-month construction period; debt-to-equity ratio of 1:1 |
| Thermal efficiency | LTMR: 31%; GCMR: 40%; HPMR: 36% |
| Refueling downtime | 7-day refueling period followed by a 2-day startup period |
| Emergency-shutdown downtime | 0.2 shutdowns per year and a 14-day startup period following each shutdown |
| Capacity factor | Calculated separately for each design from its fuel lifetime and modeled downtime |
| Replacement schedule | Outer vessel structure every 20 years; inner vessel structure, reflector, and reactor control devices every 10 years; moderator and moderator-booster component every fuel cycle |

FOAK and NOAK costs are calculated by applying account-specific learning assumptions to eligible costs. Different components and activities do not necessarily have the same learning rate, and some costs may receive little or no learning. The NOAK results correspond to the modeled cost of unit 100.

The cost estimates were also developed with incomplete engineering, procurement, construction, and vendor information. Uncertainty is particularly high for novel or FOAK components, including TRISO fuel fabrication, heat pipes, specialized vessels, shielding systems, and factory-manufacturing infrastructure. The estimates do not constitute vendor quotations or project-specific cost estimates and should not be used as the basis for investment, procurement, or financing decisions.

# APPENDIX B: Shielding Treatment

MOUSE uses separate calculations for shielding installed at the reactor site and shielding added to transport an irradiated reactor module. These shields serve different purposes and are not interchangeable. The out-of-vessel site shield remains at the deployment location, whereas the transportation shield is added only when an irradiated module must be removed.

The site-shielding calculation begins with the beginning-of-life neutron leakage spectrum calculated by OpenMC. MOUSE condenses the leakage into 11 energy groups and transports it through a simplified one-dimensional cylindrical representation of the in-vessel shield, steel vessels, and intervening gaps. In the representative input models used for this report, the LTMR includes a 10.16-cm natural-boron-carbide in-vessel shield, while the GCMR and HPMR do not include a separate in-vessel shielding layer.

Outside the reactor vessels, MOUSE represents a removable water-extended-polyester shield surrounding a below-grade reactor pit. An effective density factor of 0.5 is applied to represent partial filling of the shield region. The required shield thickness varies among designs because reactor power, core dimensions, and calculated neutron leakage are design dependent.

The model estimates activation of the surrounding ordinary concrete over a 60-year irradiation period. After reactor shutdown, the reactor and removable shield are assumed to be removed, the activated concrete is allowed to decay for 90 days, and the photon dose rate is calculated 30 cm above the pit opening. The external shield thickness is varied to meet a screening dose criterion of 0.5 mrem/h at this location. The geometry is intentionally simplified. The calculated thicknesses are therefore intended for cost estimation rather than licensing or final radiation-protection design.

Transportation shielding is evaluated for the vendor take-back scenario in Section 4.2.2. The calculation assumes that the intact reactor module is transported after a 60-month cooldown period. Decay heat is estimated from reactor thermal power, operating lifetime, and cooldown time. Fifty percent of the calculated decay heat is assigned to gamma energy. Energy-dependent lead attenuation coefficients are used to calculate the shield thickness needed to meet a dose rate of 10 mrem/h at 2 m from the outer lateral plane of the transport vehicle. This criterion corresponds to the exclusive-use vehicle limit applied in the transportation analysis. The lead is

represented as a closed cylindrical shell surrounding the complete reactor module. Lead is added radially and at both ends; consequently, the shield increases package mass, width, height, and length.

The transportation model does not credit attenuation from the fuel, reflectors, reactor vessel, internal structures, or retained reactor shielding. It is therefore an early design-screening calculation, not a transportation-package design or licensing analysis. The calculated shield affects eligibility through package mass and dimensions.