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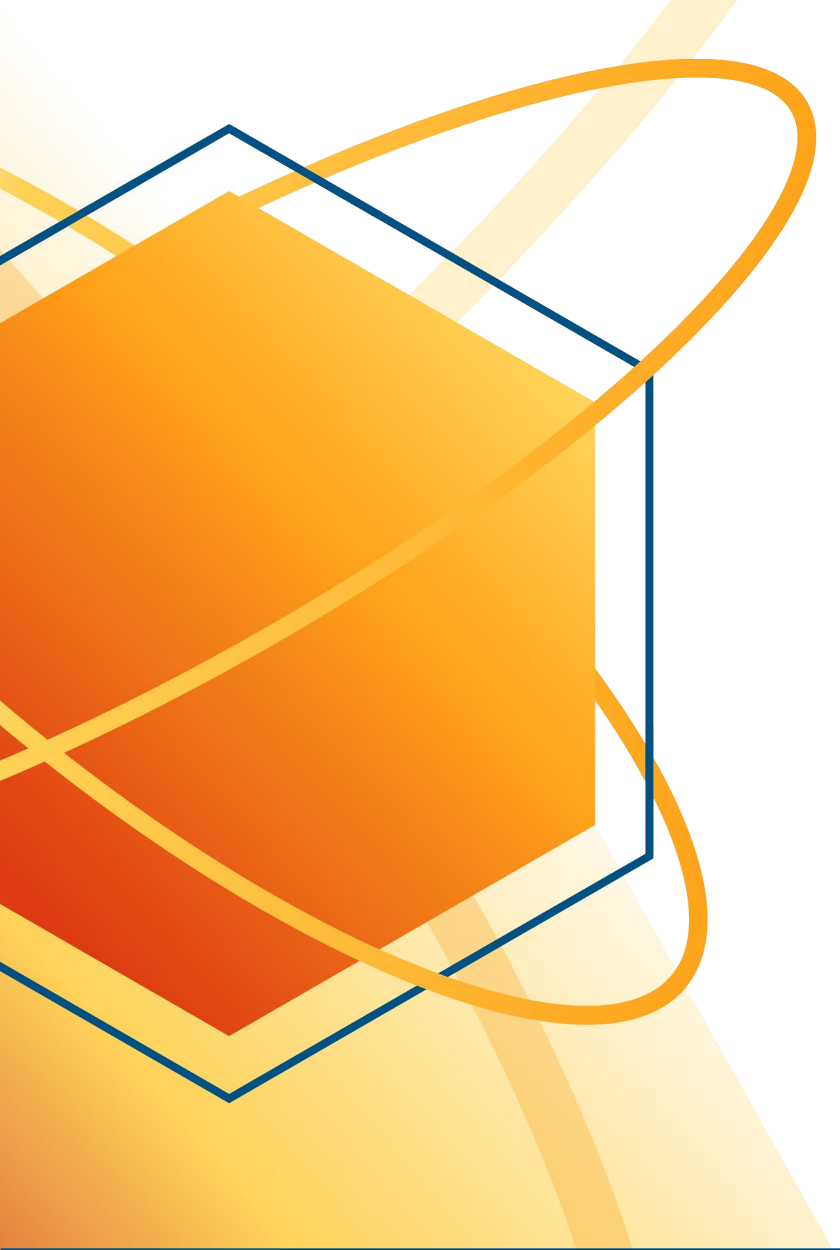

Microreactor Economics

2026 Microreactor Annual Review

March 2026

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Background

- **Motivation**
  - There is growing interest in microreactors.
  - There is need for a detailed bottom-up assessment of microreactor costs to evaluate their competitiveness for several markets.
  - Mostly, reactor designs have been guided by physics and engineering first, with economics assessed later.
    - That approach is risky because design choices affect component mass, fuel lifetime, …, and ultimately capital cost and LCOE.
    - This motivates a workflow that tightly couples design calculations with bottom-up cost estimation, so concepts are economic by design.
- **Opportunity**
  - Microreactor Applications Research, Validation, and Evaluation (MARVEL) cost data is the only microreactor cost dataset available for detailed design, the primary coolant system, and fuel fabrication.
  - Even though MARVEL is not built to be cost-competitive, its costs can still serve as a starting point for developing a microreactor cost model.

(Abou-Jaoude, 2021)

MRP Microreactor Program

FY25 Summary and FY26 Plan

- **FY25 Summary (accomplished)**
  - Developed MOUSE (Microreactor Optimization Using Simulation and Economics), a cost-estimation tool that combines OpenMC core simulations, balance-of-plant modeling, and project cost data to produce bottom-up CAPEX and LCOE estimates; demonstrated through case-study examples how it supports design decisions and deployment strategy tradeoffs.
- **FY26 Plan**
  - Published the first public cost estimate for INL's MARVEL microreactor (90% design complete), delivering a reusable cost database for technoeconomic analysis and design trade studies (paper under NT Journal review).
  - Improving MOUSE Tool (new features)
  - MOUSE Web-Based App.
  - Nuclear Microreactor Transportability Optimization.
  - Tailoring Reactor Design by Incorporating User-Specified Market Constraints.

MRP Microreactor Program

FY25 Summary

Bridging Microreactor Design and Economics: The Microreactor Optimization Using Simulation And Economics (MOUSE) Tool

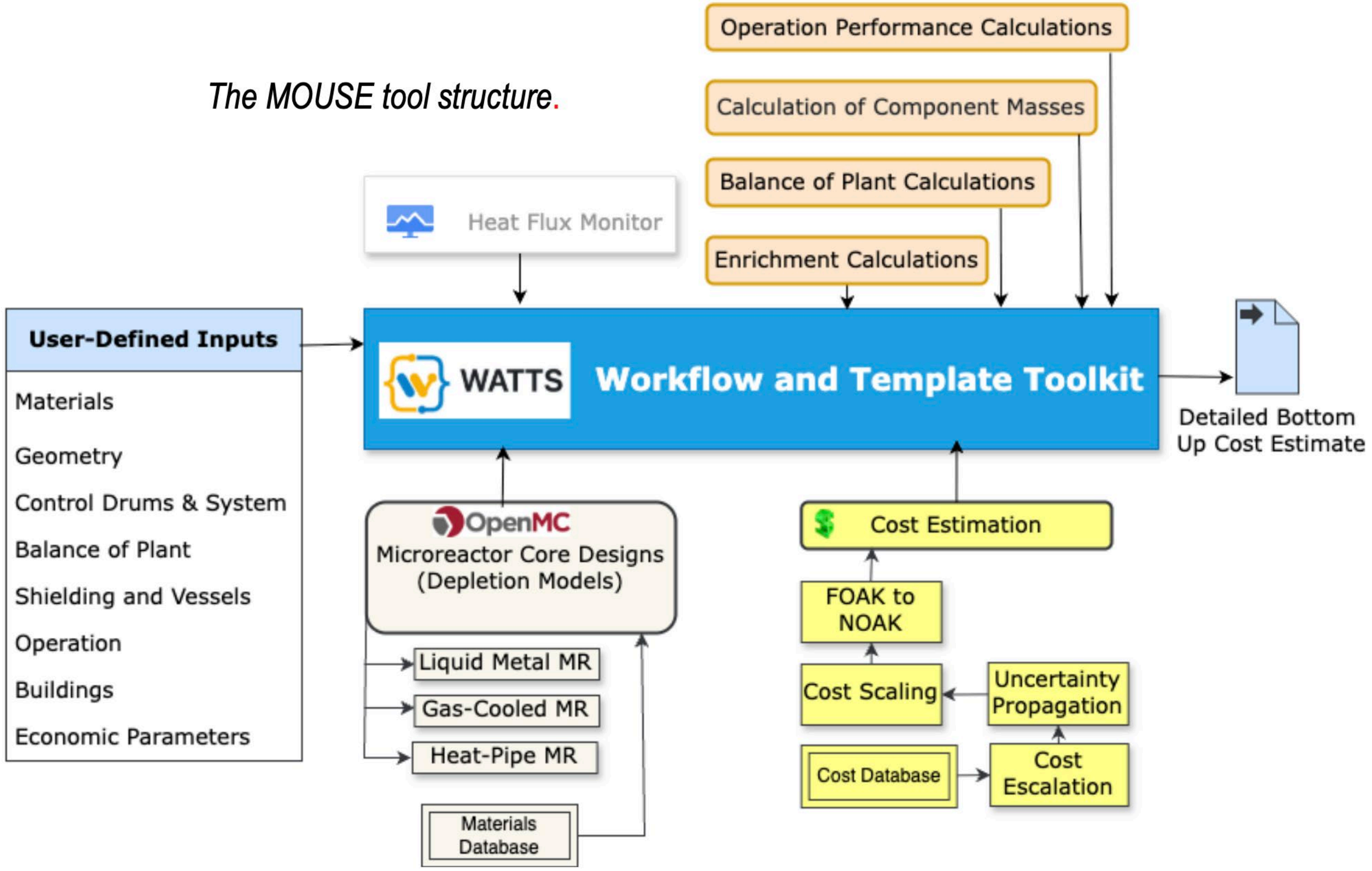
MRP Microreactor Program

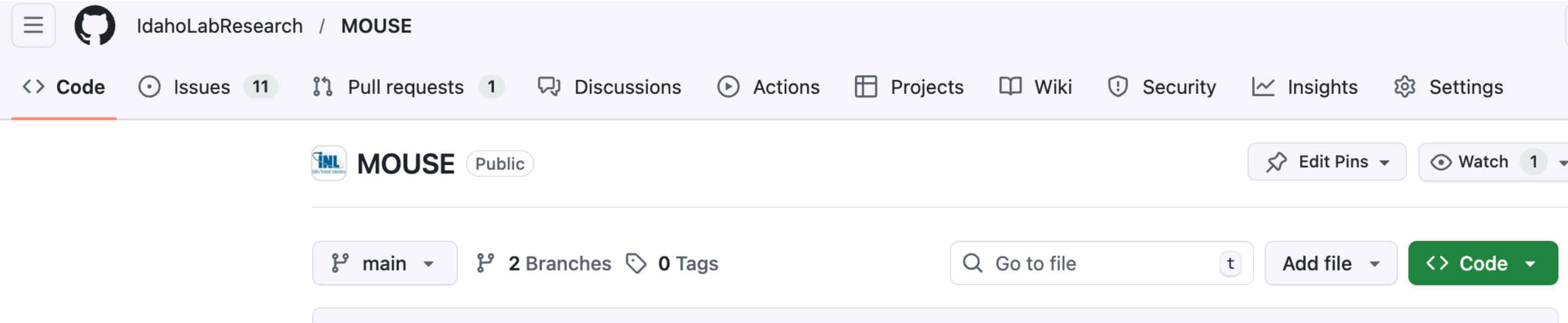
MOUSE Tool (Structure)

- MOUSE is a Python-based tool that is located on a GitHub repo.
- This diagram provides a high-level description of MOUSE.
- The software components are explained in the following slides.
- The user can change many inputs (design inputs and economic inputs).

https://github.com/IdahoLabResearch/MOUSE

The MOUSE tool structure.





MOUSE Tool (Structure): User-Defined Inputs

Vessels
Vessel Radius
Vessel Thickness
Vessel Lower Plenum Height
Vessel Upper Plenum Height
Vessel Upper Gas Gap
Vessel Bottom Depth
Vessel Material
Gap Between Vessel And Guard Vessel
Guard Vessel Thickness
Guard Vessel Material
Gap Between Guard Vessel And Cooling Vessel
Cooling Vessel Thickness
Cooling Vessel Material
Gap Between Cooling Vessel And Intake Vessel
Intake Vessel Material
Intake Vessel Thickness

Economic Parameters
Interest Rate
Escalation Year
Construction Duration
Debt to Equity Ratio

Overall System
Reactor Power (MWt)
Thermal Efficiency (%)
Heat Flux Criteria
Reactor Burnup Steps

Balance of Plant
Coolant Inlet and Outlet Temperatures
Thermal Efficiency (%)
Compressor Pressure Ratio
Pump Efficiency

Operation
Operation Mode (autonomous or not)
Number of Operators
Plant Lifetime
Refueling Period
Number of Emergency Shutdowns Per Year
Startup Duration after Refueling
Startup Duration after Emergency Shutdown
Number of Reactors Monitored Per Operator
Number of Security Staff Per Shift

Materials
Fuel
Enrichment
Coolant
Reflector
Matrix Material
Moderator
Moderator Booster
Control Drum Absorber
Control Drum Reflector
Fuel Pin Materials

Buildings
Dimensions of Reactor Building
Dimensions of Turbine Building
Dimensions of Control Building
Dimensions of Refueling Building
Dimensions of Spent Fuel Building
Dimensions of Emergency Building
Dimensions of Storage Building
Dimensions of Radioactive Waste Building

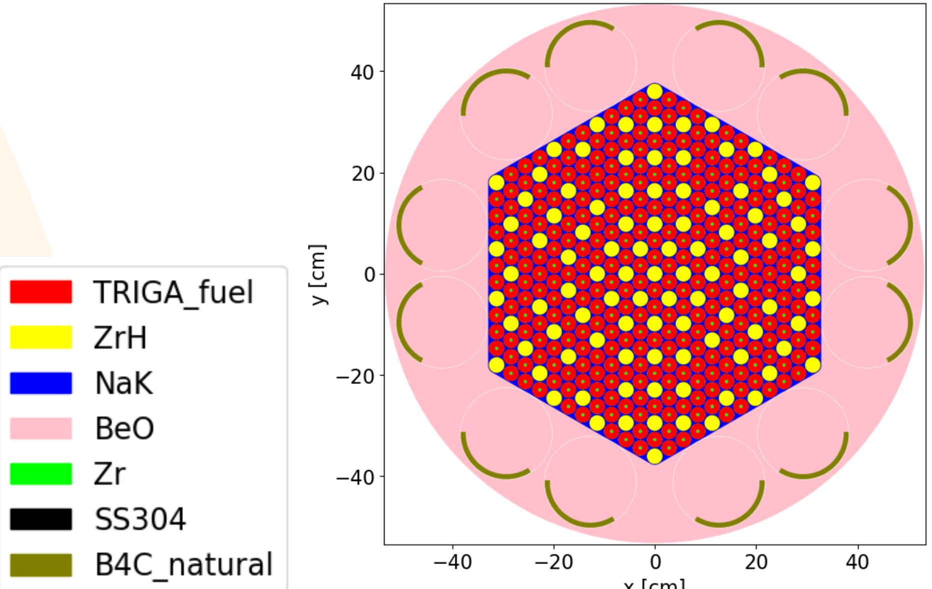
Geometry
Fuel Pin Radii
TRISO Packing Fraction
Coolant Channel Radius
Moderator Booster Radius
Lattice Pitch
Number of Rings per Assembly
Number of Assemblies per Core
Core Active Height
Reflector Thickness
Control Drum Radius
Control Drum Height
Control Drum Absorber Layer Thickness

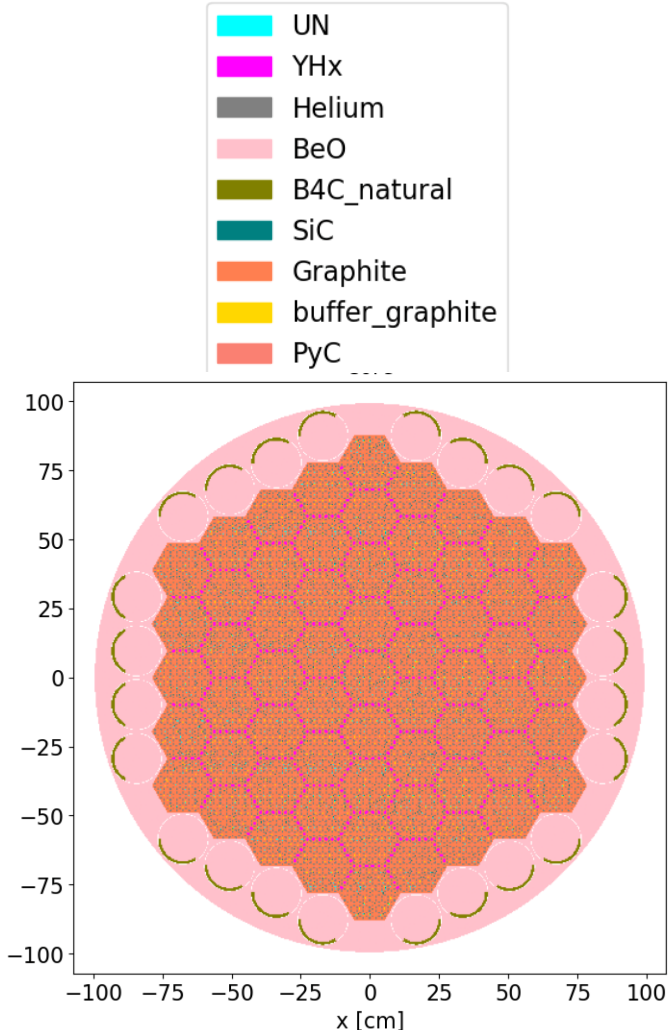
Shielding
In Vessel Shield Thickness
In Vessel Shield Inner Radius
In Vessel Shield Material
Out Of Vessel Shield Thickness
Out Of Vessel Shield Material

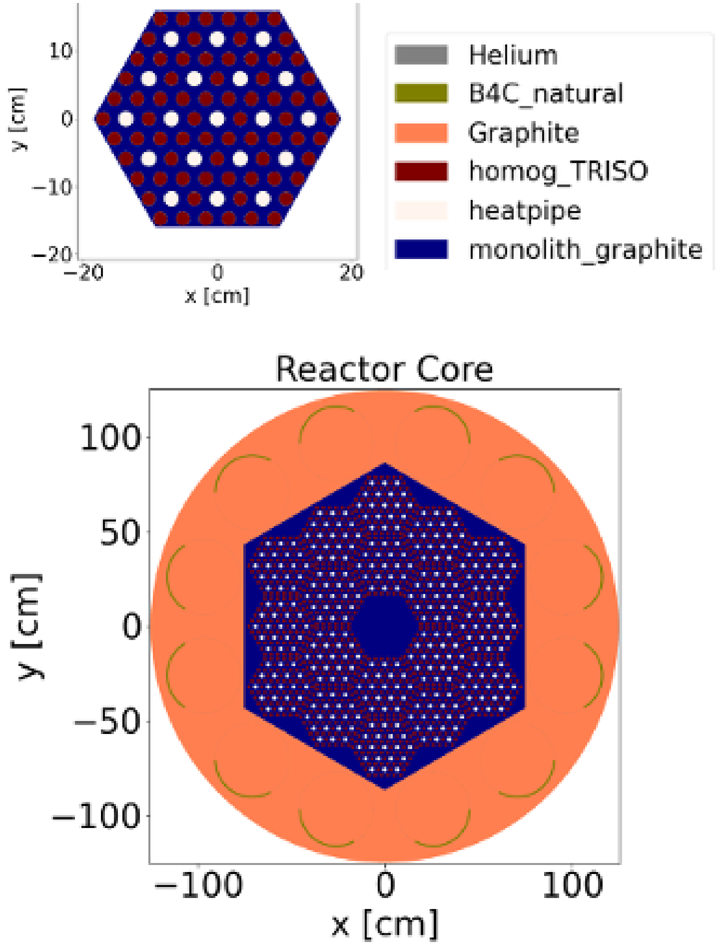
MRP Microreactor Program

MOUSE Tool (Structure)

- Three reactor designs are included so far:
  1. Liquid-metal thermal microreactor (LTMR)
  2. Gas-cooled microreactor (GCMR)
  3. Heat pipe microreactor (HPMR).







MOUSE Tool (Applications)
How much do FOAK Microreactors cost ?

- **LCOE of the Liquid metal reactor is significantly lower** than the other 2 designs that depend on the expensive TRISO fuel.
  - Also, the low fuel density of the TRISO particles leads to the need for more fuel and an increase in reactor size, which also increase the cost.
- **Heat pipe reactor has the highest LCOE** which can be explained by the low power (7 MW$_t$), and low power density, the high cost of the TRISO fuel.
- **Several accounts are insensitive to reactor design** such as pre-construction costs, training costs, and operations and maintenance (O&M) staff.

Account	**20-MWt Liquid Metal**	**15-MWt Gas-Cooled**	**7-MWt Heat-pipe**
Total Capital Investment	$153 M (±$21 M)	$161 M (±$16 M)	$136 M (±$11 M)
Total Capital Investment per kW	$25K (±$4K)	$27K (±$3K)	$54K (±$4K)
Annualized Cost	$7 M (±$0.4 M)	$10 M (±$0.5 M)	$12 M (±$0.8 M)
Annualized Cost per MWh$_e$	$130 (±$8)	$190 (±$10)	$540 (±$38)
Levelized Cost of Electricity ($/MWh$_e$)	$330 (±$33)	$410 (±$29)	$980 (±$59)
Levelized Cost of Heat ($/MWh$_t$)	$87 (±$7)	$141 (±$7)	$315 (±$16)

MOUSE Tool (Applications)
How much do NOAK Microreactors cost ?

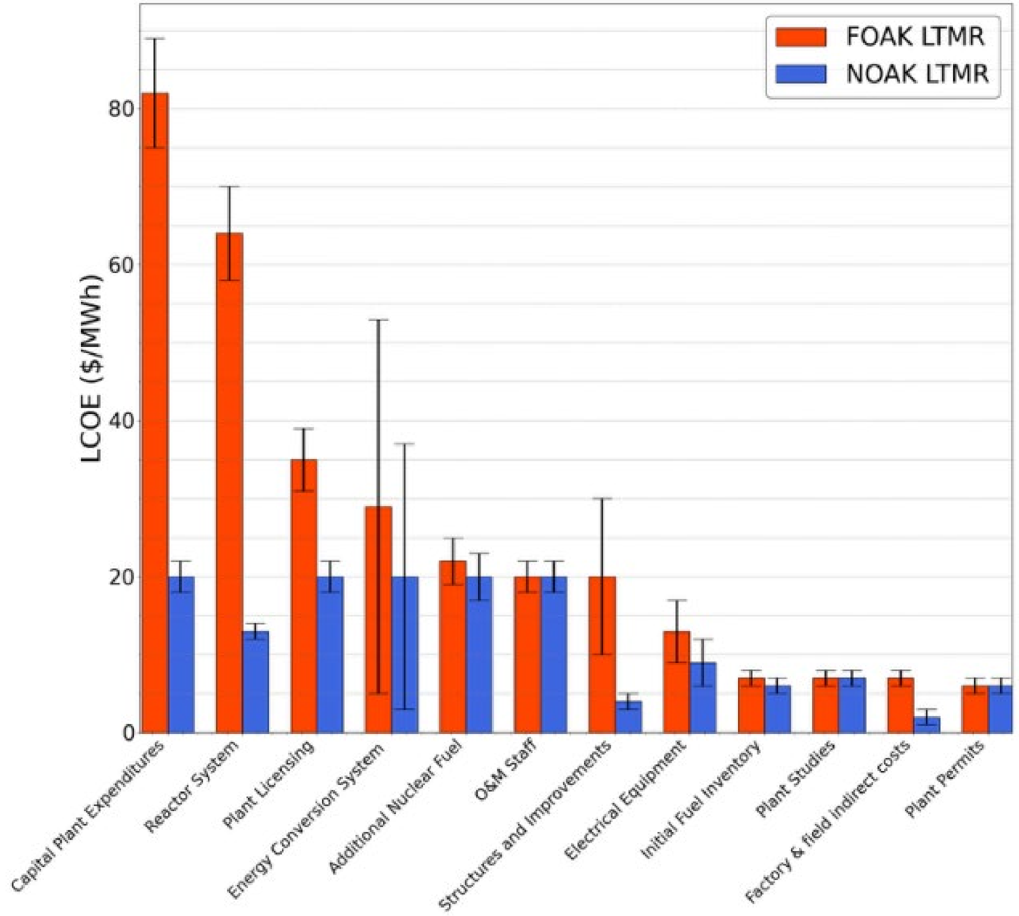
- The cost reduction in each NOAK cost item is estimated.
  - Mass production and factory fabrication leads to a significant cost reduction,
  - The costs of onsite activities are not expected to be reduced as much as factory activities
  - Some cost items have slight or no cost reduction (e.g., site studies, staff training).

- The cost differences between the three reactor types are more significant for the FOAK stage compared to the NOAK stage. For example, the LCOE for the FOAK LTMR is 25% cheaper compared to the GCMR, but it is only 6% cheaper when comparing the NOAK cost.

Account	20-MWt Liquid Metal	15-MWt Gas-Cooled	7-MWt Heat-pipe
Total Capital Investment	\$73 M (±\$14 M)	\$72 M (±\$10 M)	\$63 M (±\$6 M)
Total Capital Investment per kW	\$12K (±\$2K)	\$12K (±\$2K)	\$25K (±\$3K)
Annualized Cost	\$3 M (±\$0.3 M)	\$4 M (±\$0.3 M)	\$5 M (±\$0.5 M)
Annualized Cost per MWh_e	\$60 (±\$5)	\$70 (±\$5)	\$250 (±\$23)
Levelized Cost of Electricity (\$/MWh_e)	\$160 (±\$21)	\$170 (±\$15)	\$450 (±\$36)
Levelized Cost of Heat (\$/MWh_t)	\$42 (±\$4)	\$59 (±\$4)	\$145 (±\$10)

MOUSE Tool (Applications)
Nuclear Costs in Perspective

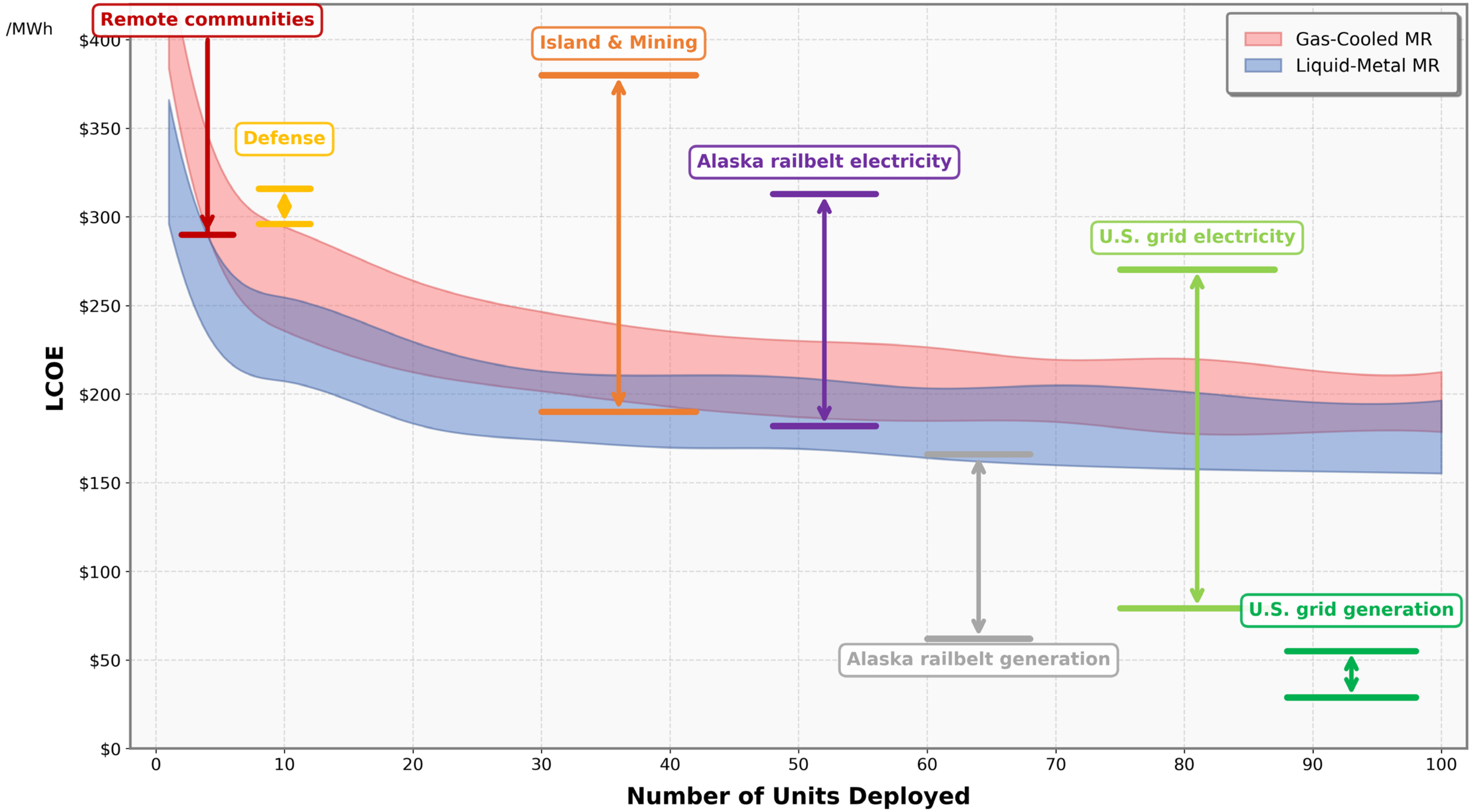
- **Cost drivers for liquid metal microreactor**
  - Capital plant expenditure (the annualized cost of replacing the reactor vessel, the reflector, the drums, etc.),
  - Reactor system,
  - Plant licensing,
  - Energy conversion system,
  - Fuel (annualized + initial inventory)
- Similar cost drivers were found for the GCMR and HPMR, except that the contribution of the fuel is higher (TRISO fuel).
- **NOAK cost drivers** are dominated by expenses with limited learning-curve benefits, including Capital plant expenditure, licensing, energy conversion systems, fuel, and O&M staffing



MOUSE Tool (Applications)

Nuclear Costs in Perspective: more units ….more market penetration

- U.S. Grid Generation: Regional average wholesale price; excludes transmission, distribution, and customer charges.
- U.S. Grid Electricity: State-level average retail electricity price, all sectors; excludes Alaska and Hawaii.
- Alaska Railbelt Generation: Wholesale generation cost; excludes transmission, distribution, and customer charges.
- Alaska Railbelt Electricity: Retail price including generation, transmission, distribution, and adjustments.
- Island & Mining: All-in diesel- or liquefied natural gas-based electricity cost, including fuel delivery.
- Defense: Remote base electricity cost plus a premium for reliability and security.
- Remote Communities: Off-road community diesel generation cost.



MOUSE Tool (Applications)

Design Choices: Increasing the TRISO particles packing fraction?

- For the TRISO-fueled microreactor, it may be desirable to increase the packing fraction of the TRISO particles to increase the cycle length.
- Packing with conventional manufacturing up to ~0.4-0.44
- Figure 1: increasing the packing fraction increases the fuel lifetime by more than 40%.
- Figures 2 and 3: The annual cost does not change much while the TCI increases slightly due to the opposing effects of the cost decrease related to the longer fuel lifetime and the cost increase related to the need for more fuel.
- Figure 4: Increasing the packing fraction slightly increases the LCOE.

Figure 1: Fuel Lifetime

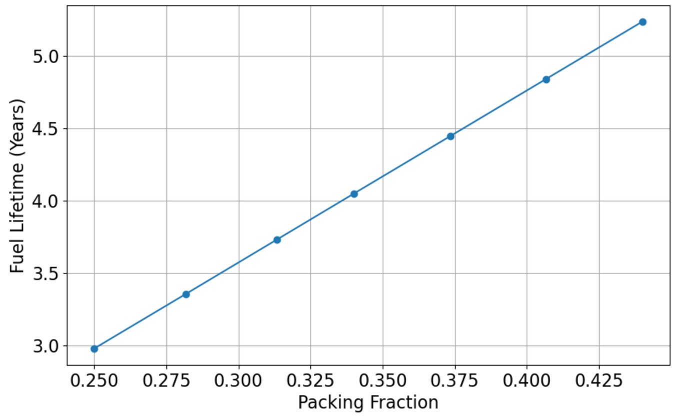


Figure 2: Annual Cost

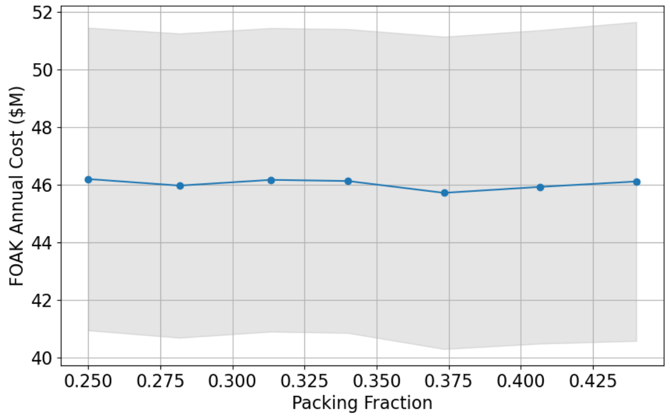


Figure 3: Total Capital Investment (TCI)

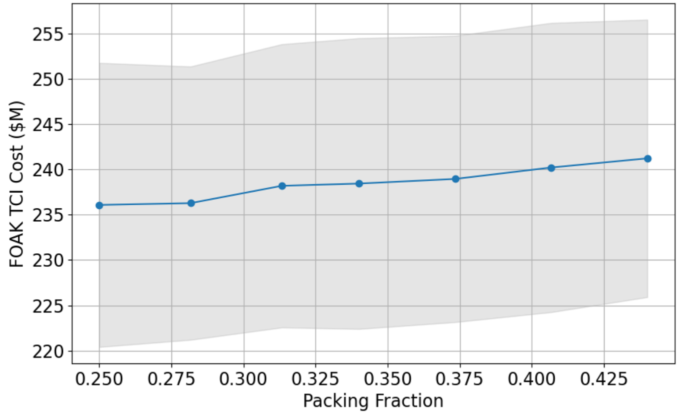
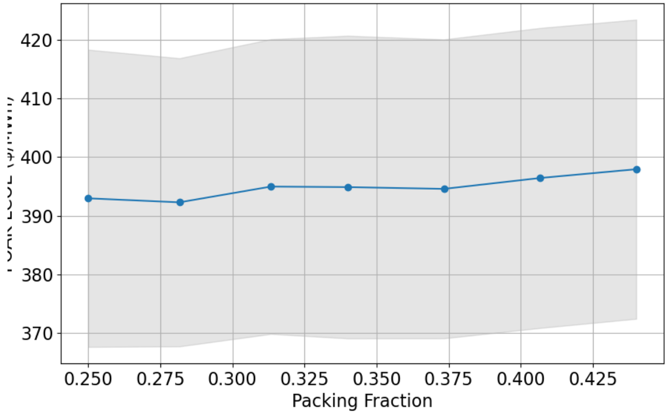


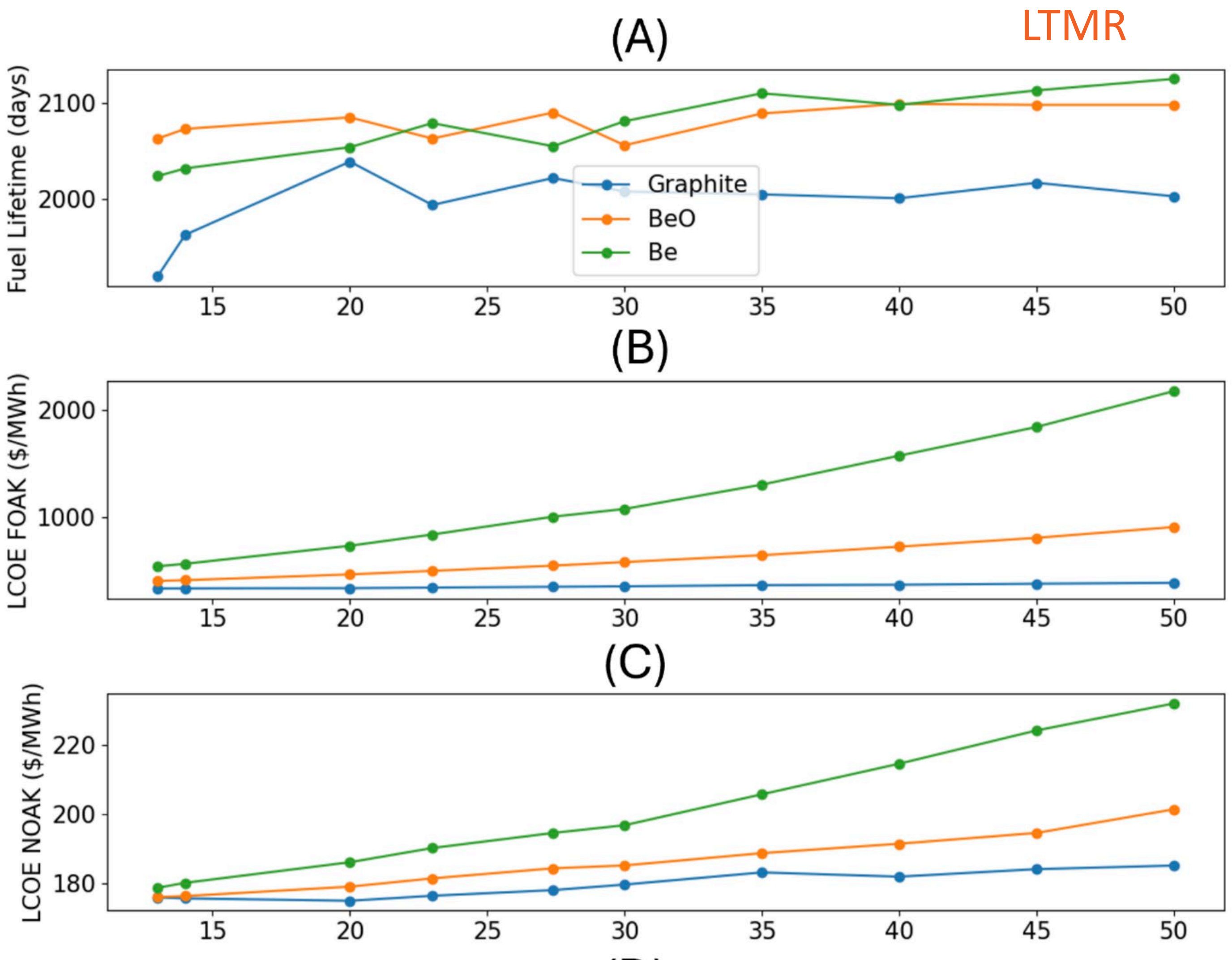
Figure 4: LCOE



MOUSE Tool (Applications)

Design Choices: Be or BeO or Graphite Reflector

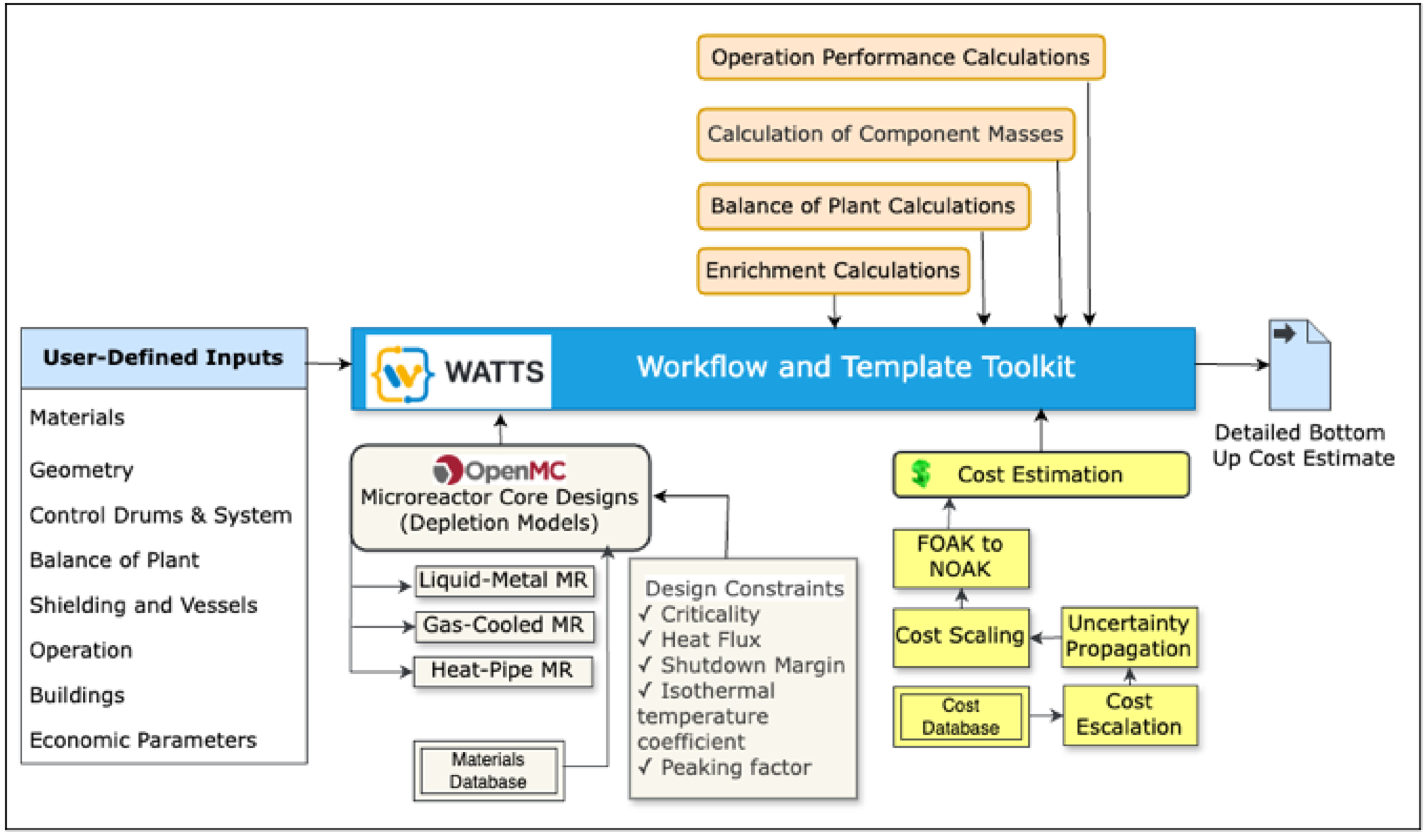
- The tradeoff is complex and non-intuitive:
  - Beryllium's higher slowing-down power yields both a smaller core (lower capital cost) and a longer fuel lifetime (lower annual cost).
  - Yet graphite has a lower unit cost.
- The winning choice is not obvious without a coupled design-economics tool.
  - Graphite is the better economic choice overall.
  - Lower unit cost outweighs the combined capital and fuel-cycle benefits of beryllium.
- Quantified impact of reflector selection: NOAK LCOE: up to $60/MWh (Gas-Cooled) and $40/MWh (Liquid Metal)
- Exception — transportability: Beryllium is preferred when core size and weight are constrained by transport mode.



FY26 Plan

FY26: Improving MOUSE Tool (new features)

- Realistic design constraints are implemented: estimating key neutronics parameters—peaking factor, shutdown margin, and temperature reactivity feedback coefficient—ensuring results reflect physically achievable designs.
- Government subsidies (ITC/PTC) are now incorporated into the economic analysis, enabling more accurate cost projections under current U.S. energy policy incentives.
- Parametric study capability has been added to MOUSE, covering design parameters as well as unit and fixed costs (particularly valuable given the scarcity of cost data for several materials).



FY26

- **MOUSE User Experience**
  - MOUSE is a Python-based tool. It may not suit all users. Therefore, a web-based app is being developed.
  - More user friendly but less flexible
- **Nuclear Microreactor Transportability Optimization**
  - Calculating the minimum cost of a transportable microreactor for air, truck, or rail shipping, ensuring optimal cost-efficiency and transport ease within weight and dimension limits.
- **Tailoring Reactor Design by Incorporating User-Specified Market Constraints**
  - Aligning design costs with market constraints (e.g., HALEU availability, refueling frequency, requirements of US military bases vs. remote Arctic villages) and assessing design and cost implications to select the optimal reactor design for each market.
- **Collaboration with other projects**
  - NNSA: Costs associated with the security of microreactors.
  - LDRD: Economics-Driven Optimization of Advanced Manufacturing for Fission Battery Mass Production.

MRP Microreactor Program

Summary & Publications

- **FY25**: Developed MOUSE (Microreactor Optimization Using Simulation and Economics), a cost-estimation tool that combines OpenMC core simulations, simplified balance-of-plant modeling, and project cost data to produce bottom-up LCOE estimate; demonstrated through case-study examples how it supports design decisions.
- **FY26**:
  - Enhancing MOUSE to improve design fidelity and economic accuracy. A web-based interface is under development to broaden accessibility
  - Transportability optimization module that minimizes cost
  - Market-driven design tailoring

- **Publications:**
  - B. Hanna et al., “Technoeconomic Evaluation of Microreactor Using Detailed Bottom-up Estimate”, Idaho National Laboratory, INL/RPT-24-80433, (2024), https://www.osti.gov/biblio/2447366/
  - Mohammad Al Dawood, Khaldoon Ali, Abou Jaoude, Abdalla, Bolisetti, Chandu, Hanna, Botros N, Gonzaga de Oliveira, Rodrigo Gonzalez, Lindley, Ben, and Garcia , Sam. Open-Source Microreactor Design Models for Technoeconomic Assessments. United States: N. p., 2026. Web. doi:10.1016/j.nucengdes.2025.114210.
  - Hanna, Botros, et al. A Bottom-Up Cost Estimation Tool for Nuclear Microreactors. No. INL/RPT-25-87273-Rev000. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2025
  - B. Hanna, S. Strain, V. F. Schwartz, and A. Abou-Jaoude, "Cost Breakdown and Evolution of the MARVEL Microreactor Project," *Nuclear Technology*, under review.
  - B. Hanna et al., "Bridging Microreactor Design and Economics: The Microreactor Optimization Using Simulation And Economics (MOUSE) Tool," *Transactions of the American Nuclear Society*, ANS Annual Meeting, 2026