Technoeconomic Evaluation of Microreactor Using Detailed Bottom-up Estimate

INL/RPT-24-80433
Revision 0

U.S. Department of Energy—
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AUGUST 2024

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ABSTRACT

Microreactors are a novel class of nuclear reactors that are expected to be factory produced, transportable, and self-regulating. They are expected to be several orders of magnitude smaller in size than traditional reactors (with power outputs in the 1–20 MW_e range typically). They are primarily envisaged to target niche, remote markets that are difficult to access and where energy costs are high. There has been a scarcity of technoeconomic assessment for these types of reactors due to the scarcity of designs without proprietary restraints (e.g., those that include balance of plants and building layouts) and cost estimates. The primary objective of this report was to develop a transparent, detailed, bottom-up cost estimate for a microreactor. While there is a high degree of uncertainty associated with the projected costs, this work provides a foundation that can built upon and improved to better model the economics of microreactors. The Microreactor Applications Research, Validation, and EvaLuation (MARVEL) microreactor was selected for this analysis. This Department of Energy–sponsored demonstration was chosen because (1) its final design was recently completed and (2) a detailed class-3 cost-and-schedule estimation was conducted for it. This provided a strong technical basis for further analysis. The tabulated MARVEL cost estimates are expected to prove useful to various stakeholders separately as well. Because the MARVEL design was never intended to be economically competitive, it was necessary to modify its design specifications toward something more representative of a commercial design. In this work, the economics-by-design approach was followed and backed by high-levle reactor physics, thermal hydraulic, shielding, and other considerations. Throughout the process, design choices were carefully grounded in economic considerations. This led to a new reference design referred to as the Liquid-Metal Thermal Reactor (LMTR), which has a thermal power output of 20 MW_{th}. Next, the cost estimates for MARVEL were projected to the larger LMTR-20 variant. All missing costs from the MARVEL estimate (e.g., fuel enrichment, civil works) were also estimated using assumptions detailed in the text. This led to a new reference technoeconomic model for a commercial microreactor design, with an estimated overnight cost of ~$14,600/kWe (excluding initial fuel load). Building on this, several technoeconomic assessments were conducted. By directly linking the physics model to the cost projections, parametric studies of design options could be rapidly screened. Further, using a previously published study on the mass production of microreactors, the Nth-of-a-kind (NOAK) cost for the LMTR-20 could be projected. It was estimated that an NOAK microreactor could reach overnight costs of around ~$6,000/kWe and levelized costs of electricity in the ~$120/MWh range. At these levels, microreactors could be approaching electricity retail prices. At these cost ranges, this could potentially enable microreactors to be directly embedded with end-users at a broader scale. However, co-location bypassing the grid would require several additional considerations (including siting, grid/nuclear regulatory, staffing, security, etc.)

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ACRONYMS

ASME	American Society of Mechanical Engineers
CD	Control Drum
CIA	central insurance absorber
DOE	Department of Energy
GN-COA	General Nuclear Code of Account
HALEU	high-assay low-enriched uranium
HX	Heat Exchanger
I&C	instrumentation and control
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
LCOE	levelized cost of energy
LMTR	Liquid-Metal Thermal Reactor
MARVEL	Microreactor Applications Research, Validation, and EvaLuation
NOAK	Nth-of-a-kind
OCC	overnight construction cost
O&M	operations and maintenance
PCHE	printed circuit heat exchanger
PCS	primary coolant system
PM/CM	Project Management/ Construction Management
RVACS	Reactor Vessel Auxiliary Cooling System
SAR	Safety Analysis Report
SFR	Sodium-Cooled Fast Reactor
SHLD	reactor shielding system
SS	stainless steel
SWU	separative work unit
TCI	total capital investment
TREAT	Transient Reactor Test
TREX-C	TREAT microReactor Experiment Cell
TRIGA	Training, Research, Isotopes, General Atomics
WEP	Water-Extended Polyester

Technoeconomic Evaluation of Microreactor Using Detailed Bottom-up Estimate

1. INTRODUCTION

Microreactors offer the potential for a radically new form of nuclear technology that can be factory produced, transportable, and self-regulating. These MW-scale nuclear reactors are expected to be easier to contract and deploy than their larger counterparts. The Department of Energy (DOE) Microreactor Program is actively sponsoring research and development activities to help mature the technology and facilitate its deployment. To better focus research and development efforts, it is important to have a better understanding of the main cost drivers and commercial weak points for microreactors. The main purpose of this report is to develop detailed bottom-up cost estimates for a microreactor from first principles that are rooted in high-level reactor analyses. Stakeholders could then leverage these (1) as reference costs to investigate the economic viability of microreactors, (2) to provide a starting point for more robust and detailed technoeconomic cost estimation, (3) to help guide vendors to make design/technology choices that may reduce costs, (4) to help prioritize DOE and other governmental support activities that will help drive down costs for microreactors, and (5) to project the broad economic viability and potential market size for microreactors in the future.

1.1. Microreactor Economics

While it is widely recognized that microreactors will be attractive candidates for remote applications (Shropshire and Geoffrey 2021), it is unclear if they will be able to compete beyond niche markets. Buongiorno et al (2021) evaluated conditions under which microreactors may be more broadly attractive. While the broader deployment of microreactors might benefit from economies of mass production, micro reactors are expected to suffer from a lack of economies of scale that benefit GW-scale reactors. Detailed bottom-up estimates are therefore needed to provide a clearer picture of the potential for microreactors to compete at larger scale.

Several studies have attempted to quantify the likely cost ranges for microreactors. The Nuclear Energy Institute (2019) surveyed vendors and compiled likely cost ranges for the technology. Some studies attempted to leverage top-down economies-of-scale curves to project microreactor costs by normalizing larger plant costs to their power output (Froese, Kunz, and Ramana 2020 and Lovering 2023). Idaho National Laboratory (INL) developed a bottom-up estimate for a heat-pipe microreactor and attempted to project the cost to a commercial variant (Abou-Jaoude et al. 2021). A case study for remote markets in Canada also referenced cost estimates obtained from third parties (Moore et al. 2021). More recently, a study led by the Massachusetts Institute of Technology (MIT) developed a detailed cost estimate for UO_2-fueled microreactors (Shirvan et al. 2023).

While all these articles in the literature attempt to quantify microreactor costs, significant uncertainty remains regarding projected cost estimates—especially relative to larger design variants. There is therefore a need for DOE-led “best estimate” efforts to provide justifiable cost projections for microreactors as a whole. This is the primary scope of this report.

1.2. Study Overview and Objectives

Determining the economic viability of microreactors for a given application necessarily hinges on their associated capital and operational expenses. Providing a justifiable range for these expenses hinges on detailed bottom-up evaluations—the purpose of this report. The end results should not be interpreted as professional cost estimates (sometimes referred to as class 1–5 estimates (AACE 2020)), but rather “best estimates” based on available data. The lack of complete microreactor designs on which to develop a cost estimate complicates this estimating process. Hence the first step for the scope of this work was to develop an open microreactor design rooted in physical constraints.

To do so, an "economics-by-design" approach was followed (Abou-Jaoude et al. 2021 and Forsberg, Foss, and Abou-Jaoude 2022). The methodology is illustrated in Figure 1. This approach consists of ensuring all design or technology choices are market/economics informed. The main end goal is to assess whether microreactors can be more broadly competitive beyond niche markets. Hence, realistic projections of future capabilities (beyond those of the types of reactors already licensed) are acceptable. However, to ensure that design choices are grounded in reality, several technical assessments must be conducted. These high-level analyses and calculations are not intended to definitively answer the technical viability of the proposed concept, but rather to illuminate limiting constraints that may drive economic considerations. This is, in some sense, intentional as per the economics-by-design philosophy. Rather than spending time and resources doing detailed design analysis, it is important to first explore the design space at a high level to identify promising economic solutions and then go back to the engineering analysis to finalize the optimal options that were identified. This report, however, only provides a first-pass estimate by identifying promising configurations for microreactors. Conducting detailed engineering design is well outside the scope and budget of this project.

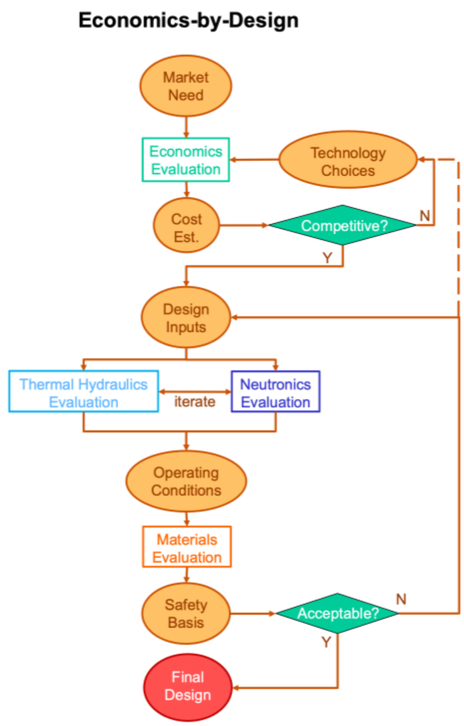

Figure 1. Illustration of the economics-by-design methodology (Abou-Jaoude et al. 2021).

As a starting point, the Microreactor Applications Research, Validation, and EvaLuation (MARVEL) reactor demonstration was leveraged (Gerstner and Arafat 2023). The reason for choosing MARVEL is twofold: (1) 90% of the MARVEL concept's design was recently completed (Gerstner and Arafat 2023), and (2) a detailed class-3 cost estimate for the MARVEL demonstration has been executed. The first reason ensures that no important design items were missed in the analysis, ensuring the design will provide a strong basis for reactor specifications/constraints. The second item provides a robust basis for the economic projection of microreactor costs.

However, since the MARVEL reactor is not intended to be cost competitive (it was designed primarily for ease of deployment at an existing INL facility), it is a poor use case in and of itself for determining microreactor viability beyond niche remote markets. Hence, the design was modified in this study, using the economics-by-design philosophy, to project the cost range of a more attractive alternative.

The next section provides additional background on the MARVEL reactor, along with a detailed overview of the latest cost estimate generated for the demonstration. These costs were mapped onto a standardized structure to facilitate cross comparison with other reactor types. Section 3 dives into the technical analysis and basis for the alternative design configuration, including a simplified reactor physics calculation, the technical basis for the balance of plant, shielding calculations, and material and thermal-hydraulic considerations. These design specifications and correlations are then leveraged in Section 4 to develop a technoeconomic model to evaluate cost trade-offs for the proposed alternative design. This framework is finally used in Section 5 to discuss promising pathways for the economic competitiveness of microreactor concepts.

2. MARVEL COST DATA

The MARVEL reactor was used as starting point for this analysis. The reactor's final design was 90% complete as of September 2023 (Gerstner and Arafat 2023), and a detailed class-3 cost estimate (Finch 2024) was conducted based on that design. This cost estimate grounds the analysis conducted here regarding detailed cost data obtained from suppliers, hourly labor requirements, inspection needs, etc., all of which are crucial for a suitable projection of costs. While the MARVEL design is not intended to be economical, it can provide a useful foundation for evaluating alternate design configurations. This section will provide some background information on the MARVEL design along with an overview of the currently projected cost breakdown for the project.

2.1. Overview of MARVEL Reactor

MARVEL is a reactor demonstration project that is planned to be installed and operated at INL's Transient Reactor Test (TREAT) Facility. It is an 85-kWt reactor inspired by previous designs and existing technology. MARVEL fuel elements are identical to the standard TRIGA (Training, Research, Isotopes, General Atomics) uranium zirconium hydride (UZrH) fuel elements, except that each element contains five (versus three) fuel meats, making them 10 in. longer than the standard element. The MARVEL core design holds 36 fuel rods containing 30 wt% uranium, enriched to 19.75% ^{235}U. The project currently intends to use four Stirling engines to generate around 20 kWe total. The reactor has a design life of 2 effective full-power years and will operate intermittently within a 2-calendar-year period.

The MARVEL core is cooled by 120 kg of naturally circulating sodium potassium (NaK) liquid metal. This primary coolant system (PCS) consists of a four-loop hydraulic system transporting heat from the core to the intermediate heat exchangers (IHXs) where the heat is then transferred to a secondary liquid: GaInSn (or Galinstan) which is a liquid metal alloy of gallium, indium, and tin. The cooled NaK then flows downward through four downcomer pipes where it mixes in the lower plenum. From the lower plenum, the NaK rises again through the active core due to buoyancy forces created by the fuel heating the NaK, completing the primary circuit. The NaK coolant leaves the core region in the temperature range of 500–550°C. The PCS is the high-temperature, low-pressure boundary that houses the core internals, reactor primary coolant, and argon-gas headspace. In addition, the PCS passively maintains decay-heat removal capability. The boundary is a metal weldment made from 316H stainless steel for high-temperature reactors, designed per the American Society of Mechanical Engineers (ASME) Section III Division 5.

Inside the core barrel, Beryllium metal serves as a reflecting material. Toward the core periphery, the outer reflector is composed of beryllium oxide (BeO) plates within four control drums (CDs) and stationary BeO plates between the CDs. The MARVEL active reactivity control/shutdown system consists of the four CDs located outside the core barrel and one central insurance absorber (CIA) in the center of the core. One-third of the CDs' BeO surface is covered by a boron carbide (B_4C) plate that absorbs more neutrons when rotated toward the fuel. The CIA can be inserted vertically down the central pin location in the core to insert negative reactivity. Controls are connected to the CD and CIA motor drives to position them as needed. Passive actuation functions are built into the design for loss of power and inadvertent energizations of the motors. Instrumentation to ensure reliable plant control and early recognition of abnormal conditions is also provided.

Most MARVEL components will be fabricated off-site and installed in the TREAT Facility's north storage pit. MARVEL will not be permanently affixed, and at the end of its useful life it will be defueled and removed. The current plan is to dispose of the equipment and materials as waste or to disposition it for long-term interim storage as used nuclear fuel.

A cross-sectional view of the MARVEL reactor is shown in Figure 2, and Table 1 lists key specifications for the MARVEL design. These provide the physical basis for the normalization of cost estimations that are conducted in later sections. Additional information on the reactor can be found in the MARVEL preliminary documented safety analysis.

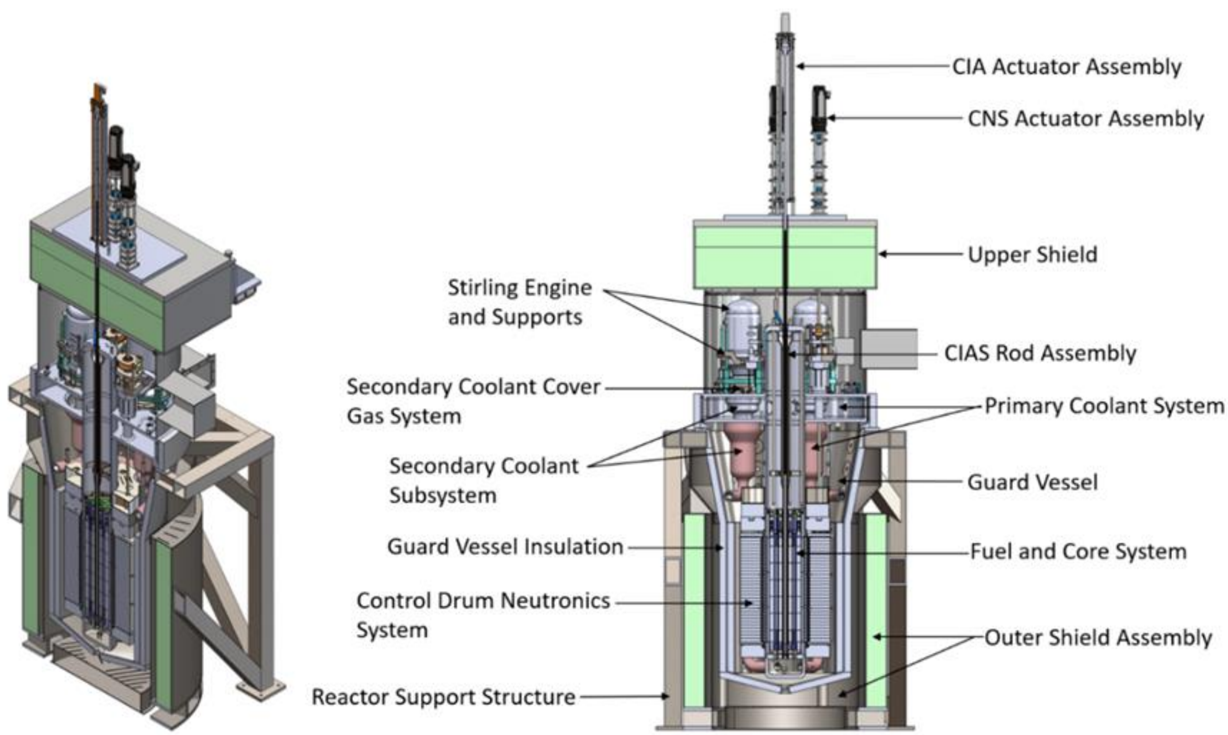

Figure 2. MARVEL microreactor cutaway view. Taken from (Gerstner and Arafat 2023). CIA stands for the central insurance absorber

Table 1. A list of the MARVEL design specifications that have been used in this work (taken from the MARVEL design report in (Gerstner 2024))

Variable	Value	Units	Description
Overall System			
Thermal power	100	kWth	—
Core outer radius	5.5	inches	—
Reflector outer radius	16.5	inches	—
Fuel			
Fuel mass	145.3	kg	UZrH
U Weight fraction	30	wt%	U/UZrH
U enrichment	19.75	wt%	High-assay low-enriched uranium (HALEU)
Pins	36	#	—
Reflector			
Outer reflector material	BeO	—	99% theoretical density
Elements	124	#	Quarter plates
Reflector plate thickness	1	inches	—
Reflector plate volume	818.4	cm^3/plate	—
Mass of BeO reflector	318	Kg	
Insert volume	570	cm^3/plate	—
Mass of Be-metal reflector	0.019	MT	—
Control Elements			
Control drums	4	#	—
Shutdown rods	1	#	—
Control drum elements	124	#	Discs
Drum disc thickness	1	inches	—
Drum reflector volume	880.8	cm^3/plate	BeO 99%
Mass of drum reflector	309	Kg	—
Drum poison volume	49.2	cm^3/plate	B_4C
Mass of drum poison	14	Kg	—
Mass of rod poison	14	Kg	B_4C
Instruments and Controls			
Control cabinet	5		—
Instrument cabinet	2		—
Nuclear input/output (IO)	9		—
Non-nuclear IO	213		—
Stirling engine IO	48	—	—
TOTAL	277		
Shielding in Vessel			
Stainless Steel cans	54.2	Kg	Stainless Steel cans of the boron carbide shielding material (SS316H)
Gamma shield material	56.3	Kg	Gamma shield material inside the guard vessel (of Tungsten)
Neutron shield material in the guard vessel	39.7	Kg	made of natural B4C powder and is located above the core (a donut around the core barrel)—
Boron Carbine shielding	95.3	Kg	made of natural B4C (called base shield) below the core
Radial (lead)	2571.9	Kg	lead
Radial (WEP)	925.3	Kg	made of Water Extended Polyster (WEP)
Shielding in Pit			
Mass of the pit neutron shielding	8.3	MT	Approximated 6-in.-thick covering whole pit and made of Water-extruded poly (WEP)

Variable	Value	Units	Description
Heat Transfer			
Mass of coolant	156	Kg	—
Number of loops	4	#	—
Mass of PCSs	0.86	MT	SS316H
Subassembly Structure Masses			
Reactor support frame	1.11	MT	—
Guard vessel	1.587	MT	—

2.2. Mapping Nonrecurring MARVEL Costs

The cost information compiled from the MARVEL reactor demonstration project is used as a starting point for estimating the microreactor cost. In this section, the MARVEL costs are mapped to the General Nuclear Code of Account (GN-COA), which is a structure for organizing the cost of nuclear reactors so the costs of several reactors can be compared. The MARVEL project costs were taken from the following sources.

The first source is the most recent class-3 cost estimate sheet from the MARVEL team (February 2024 version), which has more than 2,000 items. The costs of each account (as described in the MARVEL cost estimate) are mapped to the GN-COA and broken down into labor, material, equipment costs (see Table 2). The total cost, is the sum of the material, labor, equipment costs plus a price markup (accounting for the difference between the selling price of a good or service and its estimated cost). The escalation of the total cost is mapped to account 61, titled "Escalation." The MARVEL's project management reserve cost (budget withheld for management control purposes for future considerations to handle execution risks) was not considered.

To account for the cost discrepancy in labor costs for government national labs and industry, it is assumed that labor hours in the private sector are 40% lower. This reduction in labor cost propagates to the total cost. The adjusted labor cost and total cost are calculated and estimated in Table 2. After adjustment, the total labor cost is reduced to $63.3M from $72.7M. All the cost items from the recent class-3 cost estimate sheet were mapped to the GN-COA except for those that are not considered part of the total cost of commercial microreactors, such as:

- The MARVEL leadership, which refers to the executive leadership that interfaces with industry/academia. Activities under the MARVEL leadership include the DOE programmatic communications and programmatic planning.
- The Battelle Energy Alliance (BEA) cost adders[a] that are specific to BEA.

[a] Cost adders represent additional factors or activities that will increase the cost of the work. Private companies may have cost adders too that need to be considered in the total project cost estimate.

Table 2. A list of MARVEL costs that are mapped from the MARVEL class-3 cost estimate (February 2024) to the GN-COA. The cost is broken into labor, material, and equipment costs. The labor cost and total cost are adjusted to account for the labor cost discrepancy between industry and the government. The highlighted (in yellow) accounts are nonrecurring costs.

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
10	**Capitalized Preconstruction Costs**								
15	**Plant Studies**	MARVEL Readiness	TREAT Safety Analysis Report (SAR) Addendum	2,285,720	161,001	-	4,262,137	1,371,432	3,347,849
			Management Self-assessment (MSA)—Implementation of SAR	68,290	-	-	68,290	40,974	40,974
			Management Self-assessment (MSA)—Fuel Receipt	68,290	-	-	68,290	40,974	40,974
			MSA—Fuel Loading and Startup	50,518	-	-	50,518	30,311	30,311
			Contractor Readiness Assessment (CRA) for Fuel Receipt	68,290	-	-	68,290	40,974	40,974
			CRA for Fuel Loading	50,518	-	-	50,518	30,311	30,311
			CRA for Reactor Startup	50,518	-	-	50,518	30,311	30,311
			DOE Readiness Assessment (RA) for Reactor Startup and Fuel Loading	50,518	-	-	50,518	30,311	30,311
20	**Capitalized Direct Costs**								
21	**Structures and Improvements**								
212	Reactor Island Civil Structures	MARVEL Construction and Assembly	MARVEL TREX Coordination and Mods	-	-	-	500,000	-	500,000
			Stage Material and Components (Construction)	64,203	6,360	42,667	177,770	38,522	152,089
		MARVEL Construction and Assembly (Install Upper Reactor Components)	Assemble/Place Fire Barrier	82,484	15,900	5,333	103,717	49,490	70,723
22	**Reactor Systems**								
221	Reactor Components								
221.11	Reactor Support	Reactor Structure Fabrication	Machining Support Frame Weldment	46,426	-	-	60,354	46,426	60,354
		MARVEL Construction and Assembly (Assembly of Reactor Internals)	Lift and Lower Air Plenum into Position	24,076	3,180	4,000	49,072	14,446	39,442
			Lift and Lower Reactor Support Frame into Position	16,051	1,060	2,667	31,050	9,631	24,630
			Install Upper Support Plate Hardware	18,893	10,600	2,000	49,444	11,336	41,887
			Lower Support Plate Hardware	17,885	10,600	1,333	46,815	10,731	39,661
			Install Lower Straps	17,885	3,180	2,667	37,259	10,731	30,105
		MARVEL Construction and Assembly	Preps—Place in Support Frame and Level	19,719	3,180	2,667	40,139	11,831	32,251
			Secondary Support Structure (SSS) Frame in Pit	70,719	5,300	5,333	127,724	42,431	99,436

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
		(Install Guard Vessel)							
		MARVEL Construction and Assembly (Install Upper Reactor Components)	Upper Plenum	103,105	15,900	6,667	125,672	61,863	84,430
			Lock Core in Place with Top Grid Plate	97,536	10,600	2,667	110,803	58,522	71,789
			Place Pit Lid (Connect/Disconnect Neutron Detectors)	97,536	3,180	10,667	111,383	58,522	72,369
			Connect Ducting from Upper Confinement to TREAT Stack	86,247	15,900	6,400	108,547	51,748	74,048
			Route Cabling and Secure Top Hat	97,536	10,600	2,667	110,803	58,522	71,789
221.12	Outer Vessel Structure	Guard Vessel Fabrication (Subcontract)		-	-	-	418,500	-	418,500
		MARVEL Construction and Assembly (Install Guard Vessel)	Lift and Lower Reactor Internal Assembly into Guard Vessel	19,719	3,180	2,667	40,139	11,831	32,251
			Wrap Guard Vessel in Insulation	29,776	31,800	4,000	102,955	17,866	91,045
			Place Reactor Assembly in TREAT Pit	29,776	2,120	8,000	62,637	17,866	50,727
			Connect PCS and Guard Vessel System (GVS)	19,851	8,480	1,333	46,573	11,911	38,633
			Weld Guard Vessel to PCS Distribution Block	24,649	3,180	2,667	47,879	14,789	38,019
221.13	Inner Vessel Structure	Reactor Structure Fabrication (Combined Materials for All Parts and Assemblies)	Hex Head Cap Screw 1/4-20 UNC x 1 1/8" long ASME SA 449 Type 1 CS	-	78	-	88	-	88
			Hex Head Cap Screw, 1/2-13 UNC x 1" long, ASME SA 307 Grade A	-	31	-	35	-	35
			Pipe, 3" Sch 40, SA 106 Grade B, Carbon Steel	-	810	-	907	-	907
			Plate, 1" thick, ASME SA 516 Grade 70	-	3,020	-	3,382	-	3,382
			Plate, 1.25" thick, ASME SA 516 Grade 70	-	9,662	-	10,822	-	10,822
			Plate, 1/4" thick, ASME SA 516 Grade 70	-	15,399	-	17,247	-	17,247
			Plate, 3/4" thick, ASME SA 516 Grade 70	-	1,610	-	1,804	-	1,804
			Tig Weld Wire, ER70S-6N	-	52	-	58	-	58
			Mig Weld Wire, ER70S-6N	-	239	-	267	-	267
			Reactor Seal Anti-Seize	-	81	-	90	-	90
			Spit Lock Washer, 1/2" Zinc, ASTM F436 Type 1	-	26	-	30	-	30
			Sherwin Williams Enamel Silicone, Alkyd Copolymer Semigloss Paint (1 Gallon)	-	822	-	920	-	920
			Sherwin Williams Primer (1 Gallon)	-	223	-	249	-	249
			Helical Products Company Vibration Isolator	-	1,908	-	2,137	-	2,137
			Plate, 2" thick, ASME SA 240, 316H SST	-	61,723	-	69,130	-	69,130

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	Account Title	High-Level Account	Item Description	Labor	Material	Equipment	Total (with Markup)	Adjusted Labor	Adjusted Total (with Markup)
			Plate, 5/8" thick, ASME SA 240, 316H SST	-	19,454	-	21,788	-	21,788
			Precision Alloy Services Centerless Ground Bar, .625" Dia, Nitronic 60	-	595	-	667	-	667
			Sheet, 18 Ga., ASTM A240, 316/316L SST	-	772	-	865	-	865
			Split-Lock Washer, M6, 316 SST	-	38	-	43	-	43
			Socket Head Cap Screw, M6, 316 SST	-	2,186	-	2,448	-	2,448
			Socket Head Cap Screw, M8-1.25 x 25mm Long, Nitronic 60	-	547	-	613	-	613
			Split-Lock Washer, M8, 316 SST	-	60	-	68	-	68
			Crating Materials	-	3,710	-	4,155	-	4,155
			Packaging Materials	-	159	-	178	-	178
			Frontier Technology Corporation Water-Extended Polyester Pour (Includes both Material and Labor)	-	34,170	-	38,270	-	38,270
			Lead Pour (Includes both material and labor)	-	35,460	-	39,715	-	39,715
			Material for Forming Dies for Labyrinth Inner Seal, (drawing 1014762)	-	3,180	-	3,562	-	3,562
			Flat Washer, 9/16", 316 SST	-	14	-	16	-	16
			Hex Head Screw, 1 1/4-5 x 3" long, Carbon Steel	-	133	-	149	-	149
			Hex Nut, 9/16-18 UNC-2B, 316 SST	-	37	-	41	-	41
			Socket Head Cap Screw, 9/16-18 UNF-2 x 2" Long, Nitronic 60	-	2,910	-	3,260	-	3,260
			Socket Head Cap Screw, 9/16-18 UNF-2A x 2.5" long, Nitronic 60	-	2,917	-	3,267	-	3,267
			Hamilton Caster Wheel	-	1,477	-	1,654	-	1,654
			Plate, 1" thick x 48" x 96", 316 SST	-	6,048	-	6,774	-	6,774
			Plate, 1.5" thick, 316 SST	-	25,169	-	28,189	-	28,189
			Plate, 1/2" thick, 316 SST	-	5,181	-	5,803	-	5,803
			Reset Button, 1/2-13, 5/8" wide x 3/4" long	-	24	-	26	-	26
			Round Bar 1.125" Dia, 316 SST	-	573	-	642	-	642
			Round Bar, 1/2" Dia, 316 SST	-	115	-	128	-	128
			Round Bar, 2.13" Dia, 316 SST	-	2,293	-	2,568	-	2,568
			Seamless Round Tube, 1.25" OD x .125" wall, 316 SST	-	686	-	769	-	769

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
			Seamless Round Tube, 1.5" OD x .125" wall, 316 SST	-	692	-	775	-	775
			Seamless Round Tube, 2.5" OD x .125" wall, 316 SST	-	974	-	1,091	-	1,091
			Split-Lock Washer, 916", Nitronic 60	-	1,944	-	2,177	-	2,177
		MARVEL Construction and Assembly (Install Guard Vessel)	Perform Reactor Internals Checks and Verifications	28,800	3,180	1,333	52,301	17,280	40,781
221.21	Reactivity control system	MARVEL Construction and Assembly (Assembly of Reactor Internals)	Install Heater Bands, Cover Gas Bellows and Control Drum Seals	17,885	3,180	2,667	37,259	10,731	30,105
			Reactivity Control System Fabrication	242,392	320,000	-	1,391,560	145,435	1,294,603
			Install Control Drums	17,885	5,300	2,667	40,587	10,731	33,433
		MARVEL Construction & Assembly (Install Upper Reactor Components)	Grey Rod, Control Drum, and Central Insurance Absorber (CIA) Actuator - Temporary Installation	121,920	21,200	6,667	149,787	73,152	101,019
			CIA Housing Welded - Temporary Installation	121,920	3,180	6,667	206,874	73,152	158,106
221.31	Reflector	MARVEL Construction & Assembly (Assembly of Reactor Internals)	Attach Reflector Preload Plates	18,893	1,590	4,000	38,438	11,336	30,881
			Raise Upper Reflector Support Plates	16,051	3,180	2,667	34,379	9,631	27,959
			Install Lower Reflector Support Plates	17,885	3,180	2,667	37,259	10,731	30,105
			Install Thermocouples (TCs) for Reflectors	35,770	8,480	2,667	73,659	21,462	59,351
			Install Fixed BeO Reflectors	17,885	3,180	2,667	37,259	10,731	30,105
		MARVEL Engineering Support/Purchase of Long Lead Procurement	Beryllium Purchase Long Lead Items	-	-	-	850,000	-	850,000
		MARVEL Construction and Assembly (Assembly of Reactor Internals)	Bring Upper Reflector Support Plates into Position	16,051	5,300	2,667	37,707	9,631	31,287
221.32	Shield	Reactor Structure Fabrication	Fabricate Outer Shield Assembly Strap	254	-	-	330	254	330
			Perform Pre-Lead Pour Fit-Up Trial on Outer Shield Assembly	13,539	-	-	17,601	13,539	17,601
			Fabricate Base Neutron Shield	3,300	-	-	4,290	3,300	4,290
		MARVEL Construction & Assembly (Assembly of Reactor Internals)	Install Axial Neutron Shields	17,885	3,180	2,667	37,259	10,731	30,105
			Lift and Lower Reactor Radial Shield into Position	16,051	3,180	5,333	38,566	9,631	32,146
			Install Axial Gamma Shield Blocks	17,885	3,180	2,667	37,259	10,731	30,105

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	Account Title	High-Level Account	Item Description	Labor	Material	Equipment	Total (with Markup)	Adjusted Labor	Adjusted Total (with Markup)
		Reactor Structure Fabrication	Machine Parts for Outer Shield Assembly	13,570	-	-	17,640	13,570	17,640
			Fabricate Outer Shield-A Weldment	55,807	-	-	72,549	55,807	72,549
			Fabricate Outer Shield-B Weldment	36,767	-	-	47,798	36,767	47,798
			Fabricate Outer Shield Lid	5,077	-	-	6,600	5,077	6,600
			Fabricate Outer Shield Middle Weldment	8,716	-	-	11,331	8,716	11,331
			Fabricate Base Neutron Shield Lid	169	-	-	220	169	220
			Machining Upper Shield Assembly	48,515	-	-	63,070	48,515	63,070
		MARVEL Construction and Assembly (Install Upper Reactor Components)	Assemble Gamma Shielding	97,536	5,300	5,333	108,169	58,522	69,155
222	Main Heat Transport System								
222.2	Reactor Heat Transfer Piping System	PCS Structure Fabrication		1,417,882	435,445	-	2,431,871	1,417,882	2,431,871
		MARVEL Construction & Assembly (Assembly of Reactor Internals)	Lower PCS onto Temporary Support Frame	16,051	3,180	2,667	34,379	9,631	27,959
			Install TCs for Piping	35,770	84,800	2,667	193,482	21,462	179,174
222.5	Initial Heat Transfer Fluid Inventory	MARVEL Fabrication	Misc. Material Procurements (Gallium and other Materials)	-	-	-	1,000,000	-	1,000,000
226	Other Reactor Plant Equipment	Reactor Structure Fabrication	Spent Cost Through Jan FY-24	-	-	-	15,381	-	15,381
227	Reactor Instrumentation and Control (I&C)	MARVEL Construction and Assembly (Assembly of Reactor Internals)	Install Core Barrel and Plenum Thermocouples	17,885	10,600	2,667	48,908	10,731	41,754
		MARVEL Construction and Assembly (Install Guard Vessel)	Pull MI Cables through Guard Vessel Wall	16,395	10,600	1,333	44,476	9,837	37,918
			Install Connectors to MI Cable	46,881	6,360	5,333	91,961	28,129	73,209
		Reactor Structure Fabrication	Fabricate Neutron Detector Tube	1,439	-	-	17,374	1,439	17,374
		I&C Fabrication		726,348	-	-	1,476,348	435,809	1,185,809
		MARVEL Construction and Assembly (Install Guard Vessel)	Install CEs (Leak Detectors) for Guard Vessel	19,851	15,900	1,333	58,222	11,911	50,282
		I&C Construction		405,335	-	-	405,335	243,201	243,201

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
228	Reactor Plant Miscellaneous Items	Reactor Structure Fabrication	Fabricate Segment Block	2,369	-	-	3,080	2,369	3,080
23	**Energy Conversion System**								
232.1	Electricity Generation Systems	Reactor Structure Fabrication	Fabricate Stirling Support Structure	101,573	-	-	132,044	101,573	132,044
24	**Electrical Equipment**								
246	Power and Control Cables and Wiring	MARVEL Construction and Assembly (Install Upper Reactor Components)	Connect Reactor Components to Patch Panels	17,580	5,300	2,000	39,062	10,548	32,030
25	**Initial Fuel Inventory**								
254	First Core Fuel	Fuel Production and Procurement	Fuel Production and Support	199,075	-	-	9,324,075	119,445	9,324,075
30	**Capitalized Indirect Services Cost**								
31	**Factory and Field Indirect Costs**								
317	Field Shops	Reactor Structure Fabrication	Paint Assembly	10,154	-	-	13,201	10,154	13,201
			Perform Trial Assembly (Lead and Water-Extended Polyester Fill, Prepaint	13,539	-	-	17,601	13,539	17,601
		Operations	Final Reactor Assembly	231,496	109,180	21,333	986,394	138,898	893,796
33	**Startup Costs**								
331.3	Initial Fuel Loading Operations	Reactor Startup and Testing	Transfer Fuel, Load, and Calibrate	-	-	-	215,000	-	215,000
331.5	Test Runs	Reactor Startup and Testing	Reactor Startup - 0 Power without NaK	157,281	-	-	201,281	94,369	138,369
332	Demonstration Test Run	Operations	Zero Power Physics, Reassembly, and Functionality Testing	897,821	-	-	1,997,821	538,693	1,638,693
			Operations - 0 Power without NaK	471,842	-	-	603,842	283,105	415,105
34	**Shipping and Transportation Cost**								
341	Fuel Shipping and Transportation	Fuel Production and Procurement	TNBGC Cask Licensing Renewal	2,360	-	-	98,685	1,416	97,741
			High-assay low-enriched uranium (HALEU) Shipment from Y12 (National Security Complex in Oak Ridge National Laboratory)	-	-	-	99,000	-	99,000
			Scrap Shipment to Y12	-	-	-	300,000	-	300,000
			FY-25 Fuel Transportation to TREAT, Receipt and Storage	156,374	50,000	-	806,374	93,824	743,824
345			Clean, Crate, and Package	16,924	-	-	22,001	16,924	22,001

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
	Other Shipping and Transportation Costs	Reactor Structure Fabrication	Load Truck for Shipment	846	-	-	1,100	508	762
			Load/Unload Truck for Subcontractor Lead Pour and Polyester Pour	1,015	-	-	1,320	1,015	1,320
35	**Engineering Services**								
351	Off-Site	MARVEL Engineering Support	Subcontract Engineering Support	-	-	-	566,050	-	566,050
		MARVEL Engineering Support	Subcontract Engineering Support FY 2024	-	-	-	215,726	-	215,726
		MARVEL Engineering Support	Subcontract Engineering Support-Spent Cost through Jan FY 2024	-	-	-	545,822	-	545,822
		MARVEL Engineering Support	Subcontract Engineering Support	-	-	-	275,000	-	275,000
		MARVEL Engineering Support	Subcontract Engineering Support	-	-	-	275,000	-	275,000
		MARVEL Engineering Support	Subcontract Engineering Support	-	-	-	145,000	-	145,000
		MARVEL Engineering Support/Purchase of Long Lead Procurement	Subcontract Engineering Support	-	-	-	150,000	-	150,000
		Reactor Structure Fabrication	Subcontractor General Requirements	115,386	37,449	-	199,567	115,386	199,567
			Subcontractor Testing	7,385	-	-	9,600	7,385	9,600
			Quality Inspections, Quality Engineering, and Document Control	75,426	-	-	98,054	75,426	98,054
352	On-Site	MARVEL Engineering Support	Applied Mechanics	19,629	-	-	19,629	11,777	11,777
			Mechanical Engineer	42,144	-	-	42,144	25,286	25,286
			Nuclear Reactor Engineer	15,804	-	-	15,804	9,482	9,482
			Nuclear Research Facility Engineer	46,698	-	-	46,698	28,019	28,019
			FY 2026 Engineering Support	332,963	-	-	332,963	199,778	199,778
			FY 2027 Engineering Support	166,482	-	-	166,482	99,889	99,889
			Quality	49,736	-	-	49,736	29,842	29,842
			Technical Relationship and Program	71,694	-	-	71,694	43,016	43,016
			Nuclear Reactor Engineer	40,001	-	-	40,001	24,001	24,001
			Other Technical Engineering Collaboration	22,506	-	-	22,506	13,504	13,504
			Nuclear Engineer	11,407	-	-	11,407	6,844	6,844
			Nuclear Research Facility Engineer	5,627	-	-	5,627	3,376	3,376

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
			Records Management/ Document Control	3,920	-	-	3,920	2,352	2,352
			Records Management/ Document Control	3,056	-	-	3,056	1,834	1,834
			Nuclear/Reactor Engineer	14,793	-	-	14,793	8,876	8,876
			BEA Engineering Support - Spent Cost Through Jan FY 2024	338,890	-	-	338,890	203,334	203,334
			Quality	13,816	-	-	13,816	8,290	8,290
			Technical Relationship & Program	29,873	-	-	29,873	17,924	17,924
			Nuclear Reactor Engineer	16,667	-	-	16,667	10,000	10,000
352	On-Site	MARVEL Engineering Support	Other Technical Engineering Collaboration	4,501	-	-	4,501	2,701	2,701
			Quality	13,816	-	-	13,816	8,290	8,290
			Technical Relationship and Program	29,873	-	-	29,873	17,924	17,924
			Nuclear Reactor Engineer	16,667	-	-	16,667	10,000	10,000
			Other Technical Engineering Collaboration	4,501	-	-	4,501	2,701	2,701
			Nuclear Engineer	11,407	-	-	11,407	6,844	6,844
			Nuclear Research Facility Engineer	5,627	-	-	5,627	3,376	3,376
			Records Management/ Document Control	3,920	-	-	3,920	2,352	2,352
			Records Management/ Document Control	3,056	-	-	3,056	1,834	1,834
			Nuclear/Reactor Engineer	14,793	-	-	14,793	8,876	8,876
			Quality	8,842	-	-	8,842	5,305	5,305
			Technical Relationship and Program	33,457	-	-	33,457	20,074	20,074
			Nuclear Reactor Engineer	10,667	-	-	10,667	6,400	6,400
			Other Technical Engineering Collaboration	3,151	-	-	3,151	1,891	1,891
			Nuclear Engineer	7,300	-	-	7,300	4,380	4,380
			Nuclear Research Facility Engineer	3,601	-	-	3,601	2,161	2,161
			Records Management/ Document Control	2,509	-	-	2,509	1,505	1,505
			Records Management/ Document Control	1,956	-	-	1,956	1,174	1,174
			Nuclear/Reactor Engineer	9,468	-	-	9,468	5,681	5,681
		MARVEL Fabrication	BEA Fabrication Support	285,940	-	-	285,940	171,564	171,564
36	**Project Management and Construction Management (PM/CM) Services**								
362	**PM/CM Services**		MARVEL Management and Integration	8,316,782	-	-	8,316,782	4,990,069	4,990,069
40	**Capitalized Training Costs**								

GN-COA		MARVEL Class-3 Cost Estimate (March 2024)		Cost (2023 USD)					
Account ID	**Account Title**	**High-Level Account**	**Item Description**	**Labor**	**Material**	**Equipment**	**Total (with Markup)**	**Adjusted Labor**	**Adjusted Total (with Markup)**
41	**Staff Recruitment and Training**	MARVEL Readiness	Training and Procedures	788,130	-	-	1,888,130	472,878	1,572,878
		MARVEL Readiness	BEA Operations	3,246,988	-	-	3,246,988	1,948,193	1,948,193
50	**Capitalized Supplementary Costs**								
54	**Decommissioning**		Deactivation, Decontamination, and Decommissioning	1,014,636	-	-	16,814,636	608,782	16,408,782
60	**Capitalized Financial Costs**								
61	**Escalation**		**-**				6,160,606		6,160,606
70	**Annualized Operations and Maintenance (O&M) Cost**								
71	**O&M Staff**	Operations	Maintenance FY 2028	446,335	-	-	446,335	267,801	267,801

The MARVEL team directly communicated the costs of some significant components for the cost data breakdown (see Table 3). The actual spent costs (Patterson 2024) up to Fiscal Year (FY) 2023 are broken down separately in Table 4. The breakdown of these costs into labor, material, equipment costs is not available. However, itemized costs related to INL activities that were mainly attributed to labor costs were adjusted, with the assumption that the cost of industry labor is 40% lower than that for INL. The total expenses ($39.7M) is reduced to $29.2M after adjusting the labor cost.

Another source for the cost data is a breakdown of costs associated with MARVEL but intended to remain a part of TREAT Microreactor Experiment Cell (TREX-C) for future use beyond the MARVEL reactor (see Table 5). The total for these expenses—$3.4M—is reduced to $3.1M after adjusting the labor cost.

Table 3. A breakdown of the actual costs that were obtained through communications with the MARVEL team.

GN-COA			
COA	**Account Title**	**Description**	**Total Cost ($)**
20	**Capitalized Direct Costs**		
22	**Reactor System**		—
221	Reactor Components	—	—
221.1	Reactor Vessel and Accessories	—	—
221.11	Reactor Support	Reactor Frame Structure	454,126
221.12	Outer Vessel Structure	Guard Vessel	941,382
221.21	Reactivity Control System	B_4C-Control Poison	400,000
221.31	Reflector	BeO (for the reflector)	3,200,000
222	Main Heat Transport System	—	—
222.2	Reactor Heat Transfer Piping System	PCS	1,691,583

Table 4. A breakdown of the actual spent costs up to FY 2023. The highlighted accounts are nonrecurring costs.

GN-COA					
COA	**Account Title**		**Description**	**Total Cost ($)**	**Adjusted Total Cost ($)**
10	**Capitalized Preconstruction Costs**				
15	**Plant Studies**	FY 2020	Regulatory and economic risk reduction: Draft and final Environmental Assessment (EA) for MARVEL, including scoping studies and technical studies/evaluation. Tribal and regulatory consultations.	136,507	81,904
			Draft and final TREAT SAR addendum for MARVEL project. Hazards analysis/accident scenarios to issue the draft SAR addendum.	286,502	171,901
			Regulatory and economic risk reduction: Support regulatory and design activities for MARVEL, specifically integrated multiphysics modeling and leverage of Kilopower Reactor Using Stirling Technology (KRUSTY).	96,157	57,694
		FY 2021	Draft and final EA for MARVEL, including scoping studies and technical studies/evaluation. Tribal and regulatory consultations.	99,215	59,529
			Draft and final TREAT SAR addendum for MARVEL project. Hazards analysis/accident scenarios to issue the draft SAR addendum.	206,425	123,855
			Draft and final TREAT SAR addendum for MARVEL project. Hazards analysis/accident scenarios to issue the draft SAR addendum.	1,238,547	743,128
			Participate in design and analysis of the MARVEL system plus perform transient and safety analyses. Feeds design first, then necessary SAR changes.	236,450	141,870
		FY 2022	TREAT SAR Addendum - INL (AT-22IN080505)	420,746	252,448
			Activity 1: MARVEL support – Los Alamos National Laboratory (LANL)	54,809	32,886
			Activity 2–5: MARVEL support - LANL	219,238	131,543
		FY 2023	TREAT SAR Addendum - INL (AT-23IN080504)	883,827	530,296
			Activity 2: Fuel qualification report	407,408	244,445
			Activity 3: Finish HALEU production at Y12	62,993	62,993
20	**Capitalized Direct Costs**				
22	**Reactor System**	—	—	—	—
226	Other Reactor Plant Equipment	FY 2023	Activity 2: Long lead procurement	760,495	760,495
25	**Initial Fuel Inventory**		—	—	—
254	First Core Fuel Assembly Fabrication	FY 2022	Activity 1: Fuel production/procurement support	404,322	404,322
			Activity 2: HALEU production at Y12	158,212	158,212
		FY 2023	Activity 1: Fuel fabrication labor support	424,359	254,615

GN-COA					
COA	**Account Title**		**Description**	**Total Cost ($)**	**Adjusted Total Cost ($)**
30	**Capitalized Indirect Services Cost**				
31	**Factory and Field Indirect Costs**	—	—	—	—
317	Field Shops	FY 2023	Reactor assembly and installation - INL (AT-23IN080509)	732,042	732,042
34	**Shipping and Transportation Costs**	—	—	—	—
341		FY 2023	Activity 4: HALEU shipment to TRIGA International (TI), (Romans, France)	438,724	438,724
		FY 2023	Activity 5: TN-BGC-1 shipping container recertification	219,260	219,260
35	**Engineering Services**	—	—	—	—
351	Off-Site	FY 2020	Activity 1: Fabrication of fuels and structural components	205,298	205,298
			Activity 2: Multiphysics model and simulation	112,256	67,354
		FY 2021	Microreactor Applications Test Bed - LANL	618,315	618,315
			Microreactor Applications Test Bed – Argonne National Laboratory (ANL)	14,094	14,094
		FY 2022	Reactivity control develop, design, and construct - INL (AT-22IN080509)	450,834	270,500
			Instrumentation and control development - INL (AT-22IN080510)	452,963	271,778
			Reactor assembly and installation - INL (AT-22IN080511)	92,883	92,883
			Microreactor Application Test Bed - ANL (AT-22AN080515)	20,732	20,732
		FY 2023	MARVEL support - LANL AT-23LA080506)	142,220	85,332
			Microreactor Application Test Bed - ANL (AT-23IN080511)	57,654	57,654
352	On-Site	FY 2020	Activity 2: Power conversion demonstration	162,688	162,688
			Activity 3: PCS testing	156,459	156,459
			Activity 4: Reactor control systems development	198,817	119,290
			Activity 5: Shutdown rod system development	198,817	119,290
			Activity 6: Fuel fabrication	315,851	315,851

GN-COA		Description		Total Cost ($)	Adjusted Total Cost ($)
COA	Account Title				
			Activity 7: Non-fuel fabrication and manufacturing	549,446	549,446
		FY 2021 (Microreactor Applications Test Bed - INL)	Primary coolant apparatus test - fab test article (BCWP = $912.7K)	3,242,605	3,242,605
			Primary coolant apparatus test - integral effects testing (Stirling engines)	403,390	403,390
			Interim design - preliminary design of eight major systems	611,884	367,131
			Fuel research and development	443,960	443,960
			Detailed design (continuation of interim design) - count toward conceptual design based on maturity	466,331	279,798
			Project management	395,826	237,496
		FY 2022	Activity 2: Interim design review	169,618	101,771
			Activity 3: Final design review	49,806	29,884
			Activity 4: Requirements traceability	173,798	104,279
			Reactor structure final design and construction - INL (AT-22IN080502)	3,072,037	1,843,222
			Power conversion installation - INL (AT-22IN080503)	68,809	68,809
			Primary coolant apparatus test - INL (AT-22IN080506)	1,462,880	1,462,880
		FY 2023	MARVEL management and integration - INL: Activity 2: Final design review	281,722	169,033
			MARVEL management and integration - INL: Activity 3: Interim design review	588	353
			MARVEL management and integration - INL: Activity 4: Requirements traceability	269,587	161,752
			Reactor structure final design and construction: Activity 1: Final reactor structure design	8,258,837	4,955,302
			Power conversion installation - INL (AT-23IN080503): Stirling engine - system design and procurement, consulting	373,075	373,075
			Primary coolant apparatus test - INL (AT-23IN080505)	2,376,753	2,376,753
			Reactivity control develop, design, and construct - INL (AT-23IN080507)	959,078	575,447
			Instrumentation and control development - INL (AT-23IN080508)	1,526,603	915,962

GN-COA				Total Cost ($)	Adjusted Total Cost ($)
COA	Account Title	Description			
36	**PM/CM Services**	—	—	—	—
362	On-Site	FY 2020	Microreactor Applications Test Bed - INL: Activity 1: Project management	54,229	32,538
		FY 2022	MARVEL management and integration - INL: Activity 1: Project management	1,322,449	793,469
		FY 2023	MARVEL management and integration - INL: Activity 1: Project management	1,411,597	846,958
40	**Capitalized Training Costs**				
41	**Staff Recruitment and Training**	FY 2022	Training and procedures - INL (AT-22IN080513)	234,782	140,869
		FY 2023	Training and procedures - INL (AT-23IN080510)	846,375	507,825

Table 5. A breakdown of costs associated with MARVEL but intended to remain a part of the TREX-C for future use beyond the MARVEL reactor. The highlighted accounts are nonrecurring costs.

GN-COA		Description	Total Cost ($)	Adjusted Total Cost ($)
COA	**Account Title**			
20	**Capitalized Direct Costs**			
21	**Structures and Improvements**	—	—	—
212	Reactor Island Civil Structures	Structural Upgrades	989,346	989,346
		Electrical	103,184	103,184
		HVAC	106,612	106,612
		Fire Protection Upgrades	49,107	49,107
		Procurements	880,601	880,601
214.7	Emergency and Startup Power Systems	Generator Subcontract (diesel generator)	225,179	225,179
		Installation of Generator	358	358
22	**Reactor System**	—	—	—
227	Reactor I&C	Instrumentation and Control	248,008	248,008
24	**Electrical Equipment**	—	—	—
244	Protective Systems Equipment	Radiation Monitoring System	1,627	1,627
30	Capitalized Indirect Services Cost			
35	**Engineering Services**	—	—	—
352	On-Site	Design	113,092	67,855
36	**PM/CM Services**	—	—	—
362	On-Site	Project Management	694,932	416,959

Finally, all the costs from Table 2, Table 3, Table 4, and Table 5 are aggregated in Table 6. To leverage these cost data for the cost estimation of other microreactors, scaling parameters were selected for each cost item and the cost per unit (e.g., $/kg) was calculated. The MARVEL design variables that were used to estimate the unit costs are listed in Table 1. Note that in this table, all the costs are aggregated without nonrecurring costs (which is around $31.7 millions).

Note that Table 6 is still not a comprehensive estimate due to missing costs, such as the cost of the shielding in the pit, the BeO for the CDs, and the fuel mining and enrichment.

Table 6. MARVEL costs combined from various sources and mapped to the GN-COA (nonrecurring costs were excluded).

GN-COA		Total Cost (Labor Adjusted) ($)	Description	Scaling			Unit Cost	
COA	**Account Title**			**Scaling Variable**	**Base Value**	**Unit**	**Value**	**Unit**
10	**Capitalized Preconstruction Costs**	5,216,860	—	—	—	—	—	—
15	Plant Studies	5,216,860	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
20	**Capitalized Direct Costs**	31,195,633	—	—	—	—	—	—
21	**Structures and Improvements**	3,077,199	—	—	—	—	—	—
212	Reactor Island Civil Structures	2,851,662	Preparing the pit before placing MRAVEL	Assuming that the cost (mapped from MARVEL) will not significantly change for microreactors with larger capacities. Other civil structure (such as the reactor building will scale up with the reactor footprint).				
214.7	Emergency and Startup Power Systems	225,537	Diesel Generator	Power (MWe)	0.03	MWe	7,517,900	$/MWe
22	**Reactor System**	17,811,509	—	—	—	—	—	—
221	**Reactor Components**	**9,804,413**	—	—	—	—	—	—
221.11	Reactor Support	1,196,316	—	Guard Vessel Mass	1587	**kg**	**754**	**$/kg**
221.11A	Reactor Frame Structure	454,126	—				**286**	**$/kg**
221.11B	Other Support Structure (Including Installation)	742,190	—				**468**	**$/kg**
221.12	Outer Vessel Structure	1,610,557	—				**1015**	**$/kg**
221.12A	Guard Vessel	941,382	—				**593**	**$/kg**

GN-COA		Total Cost (Labor Adjusted) ($)	Description	Scaling			Unit Cost	
COA	**Account Title**			**Scaling Variable**	**Base Value**	**Unit**	**Value**	**Unit**
221.12B	Guard Vessel–Related Structure Including Installation	669,175	—				**422**	**$/kg**
221.13	Inner Vessel Structure	317,648	Reactor internals and all the materials inside the vessel that are not mapped elsewhere				**210**	**$/kg**
221.21	Reactivity Control System	2,017,266	—	—	—	—	—	—
221.21A	B_4C-Control Poison	400,000	—	Mass of Rod Poison (in both the drums and control rod)	28	**kg**	14286	**$/kg**
221.21B	Reactivity Control System Fabrication	1,294,603	—	—	—		—	—
221.21C	Installation	322,663	—	—	—		—	—
221.31	Reflector	4,259,687	—	—	—	—	—	—
221.31A	Outer Radial Reflector (BeO)	3,200,000	—	Mass of BeO Reflector	318	**kg**	10063	**$/kg**
221.31B	Metallic Axial Neutron Reflector (Be)	850,000	—	Mass of Be	18.9		44,903	**$/kg**
221.31C	Installation	209,687	—	—	—		—	—
221.32	Shield Installation Cost	402,939	—	—	—	—	—	—
222	Main Heat Transport System	5,330,586	—	—	—	—	—	—
222.20	Reactor Heat Transfer Piping System	4,330,586	—	—	—	—	—	—
222.2A	PCS	1,691,583	—	Mass of PCSs (SS316H)	860	**kg**	1967	**$/kg**
222.2B	Primary Coolant System Structure Fabrication	2,431,871	—				2828	**$/kg**
222.2C	Other Structure Related to PCS	207,132	—	—	—	—	—	—
222.50	Initial Heat Transfer Fluid Inventory	1,000,000	Misc. Material Procurements (gallium and other materials)	—	—	—	—	—
226	Other Reactor Plant Equipment	775,876	—	—	—	—	—	—
227	Reactor I&C	1,897,554	—	Number of sensors	277	sensors	6850	**$/sensor**
228	Reactor Plant Miscellaneous Items	3,080	—	—	—	—	—	—
23	**Energy Conversion System**	132,044	—	—	—	—	—	—
232.10	Electricity Generation Systems	132,044	—	For larger microreactors, the Stirling engines are not used.			—	—

GN-COA		Total Cost (Labor Adjusted) ($)	Description	Scaling			Unit Cost	
COA	Account Title			Scaling Variable	Base Value	Unit	Value	Unit
24	**Electrical Equipment**	33,657	—	—	—	—	—	—
244	Protective Systems Equipment	1,627	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
246	Power and Control Cables and Wiring	32,030	—					
25	**Initial Fuel Inventory**	10,141,224	—	—	—	—	—	—
254	First Core Fuel Assembly Fabrication	10,141,224	—	—	—	—	—	—
254A	Fuel Production and Procurement	9,324,075	—	Mass of the fuel (UZrH)	145.3	kg	83,423	$/kg (note that the unit cost was multiplied by 1.3 (higher price for non-DOE customers).
254B	Other related activities	817,149	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
30	**Capitalized Indirect Services Cost**	7,202,608	—	—	—	—	—	—
31	**Factory & Field Indirect Costs**	1,656,640	—	—	—	—	—	—
317.00	Field Shops	1,656,640	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
33	**Startup Costs**	2,407,166	—	—	—	—	—	—
331.30	Initial Fuel Loading Operations	215,000	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
331.50	Test Runs	138,369	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
332.00	Demonstration Test Run	2,053,798	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
34	**Shipping and Transportation Cost**	1,923,914	—	—	—	—	—	—
341.00	Fuel Shipping and Transportation	1,899,493		Assuming that this cost does not significantly change for microreactors with larger capacities.				
345.00	Other Shipping and Transportation Costs	24,421	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
35	**Engineering Services**	797,929	—	—	—	—	—	—
351	Off-Site	307,221	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
352	On-Site	490,708	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
36	**PM/CM Services**	416,959	—	—	—	—	—	—
362	On-Site	416,959	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				
40	**Capitalized Training Costs**	4,169,765	—	—	—	—	—	—
41	**Staff Recruitment and Training**	4,169,765	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				

GN-COA		Total Cost (Labor Adjusted) ($)	Description	Scaling			Unit Cost	
COA	**Account Title**			**Scaling Variable**	**Base Value**	**Unit**	**Value**	**Unit**
50	**Capitalized Supplementary Costs**	16,408,782	—	—	—	—	—	—
54	**Decommissioning**	16,408,782	—	Assuming that the ratio between decommissioning cost and direct cost stays the same.				
60	**Capitalized Financial Costs**	6,160,606	—	—	—	—	—	—
61	**Escalation**	6,160,606	—	Assuming that the ratio between escalation cost and overnight cost stays the same.				
70	**Annualized O&M Cost**	3,915,898	—	—	—	—	—	—
71	**O&M Staff**	3,915,898	—	Assuming that this cost does not significantly change for microreactors with larger capacities.				

3. REACTOR PHYSICS AND ENGINEERING EVALUATIONS

A Liquid Metal Thermal Reactor (LMTR)[b] design was investigated. It is partially inspired by the MARVEL specifications discussed in the previous section. The LMTR core model was developed using the OpenMC (Romano et al. 2015) Monte Carlo neutron transport code. LMTR uses zirconium hydride pins in a lattice that is a mix of these moderating pins with TRIGA 30/20 fuel pins. Other aspects of the core include the use of sodium-potassium eutectic coolant and a BeO reflector and CDs made of beryllium metal with boron carbide absorbers.

3.1. Model Description

3.1.1. LMTR Key Design Parameters

The core presented in this work is centered around the constraints of a 20-MW_{th} core cooled by NaK eutectic and moderated by Zirconium Hydride (ZrH), dubbed the LMTR-20. Parametric studies (detailed later) led to the design of a C_6 symmetrical hexagonal lattice with 12 “rings,” resulting in the characteristics presented in Table 7. The core is composed of a mix of fuel rods and moderator rods, as depicted in Figure 3. Inlet temperature is set to 230°C based on the Experimental Breeder Reactor I (EBR-I) experience with operating NaK coolant (Lichtenberger 1953).

Table 7. Main parameters of the LMTR-20.

Parameter	Value
Power (thermal/electric, MW_{th}/MW_e)	20/6
Number of fuel pins	252
Number of moderator pins	79
Pin Pitch (cm)	3.275
Core flat-to-flat (m)	0.786
Coolant inlet temperature (°C/K)	230/503.15
Coolant outlet temperature (°C/K)	320/593.15

[b] In this report, the term 'Liquid Metal Thermal Reactor' refers to a reactor design similar to or based on the MARVEL design. Given the small capacity of the research reactor MARVEL (approximately 0.1 MW_{th}), its design is referred to as LMTR-0. A reactor that is 'MARVEL-like' but modified to increase the capacity to 20 MW_{th} is designated as LMTR-20.

The fuel (UZrH), more specifically TRIGA fuel, consists of a mixture of uranium metal and zirconium hydride. The uranium is U-235 enriched to a certain proportion, the zirconium is hafnium free, and the hydrogen (for the hydride) is kept at a certain ratio with respect to the zirconium. For instance, the fuel for MARVEL (which is also considered for the LMTR) is known as 30/20 TRIGA fuel, which is 30 wt% uranium metal with 20% enriched U-235 (commonly referred to as high-assay low-enriched uranium, or HALEU). The zirconium hydride component of the fuel commonly has a hydrogen-to-zirconium ratio of 1.5. Following these concepts, instead of defining UZrH directly—as is commonly done in other codes—the uranium-metal enrichment is specified (e.g., 20%), then the zirconium hydride's hydrogen-to-zirconium ratio is fixed at 1.5. A material specification based on the mix of these two materials is defined, with uranium metal being 30% of the weight. This allows for the easy parametric study of uranium enrichment, uranium metal weight fraction, and even the hydrogen-to-zirconium ratio. A main advantage of OpenMC over its alternatives is that its Python bindings allow for the use of highly scripted language—such as that detailed here--to perform such parametric studies.

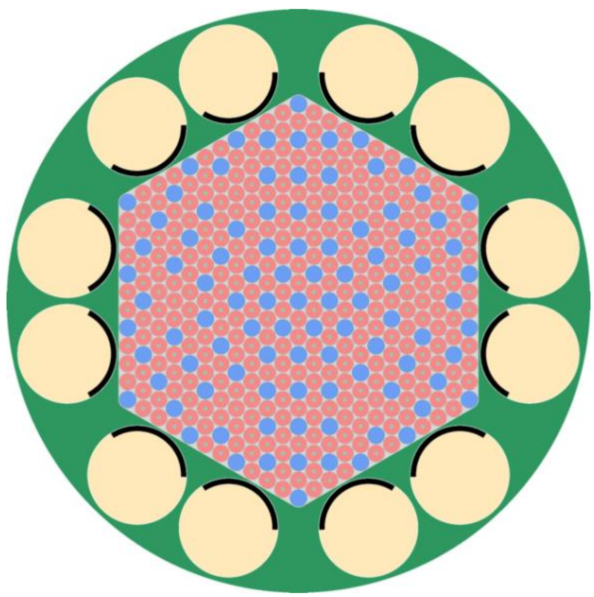

Figure 3. 2D view of the core lattice arrangement. The red circles are the TRIGA fuel pins. The blue circles are the moderator pins (zirconium hydride). The outer 12 circles are the CDs (beryllium in yellow and boron carbide in black). The outer green area is the BeO reflector.

3.1.2. Reactor Physics

The design of the core started with a test for criticality using a lattice with six "rings." Calculations of heat flux for a 20-MW_{th} reactor for a lattice of this size indicated that the heat flux was too high compared to the approximate calculated value for a typical sodium-cooled fast reactor (SFR), which is approximately 0.8 MW/m^2. Therefore, the number of rings was increased while keeping the power constant to match the 0.8 MW/m^2 heat flux which occurred when 12 rings were used for the lattice. Based on historical thermal limits, this size (12 rings) is effectively the minimum size of a credible reactor with the constraints imposed in this study.

Burnup calculations using 30/20 TRIGA fuel indicate that such a core operating at 20 MW_{th} would have a theoretical maximum operation time of 2,154 days (~5.9 years), as shown in Figure 4. Currently, this core configuration disregards the necessity of having burnable absorbers optimally placed to control reactivity to the point where the CDs are capable of fully controlling core excess reactivity. A feasibility check was performed whereby 3% erbium, the typical TRIGA fuel burnable absorber, was added to the fuel. A preliminary analysis shows that it is possible to make the reactor subcritical with enough integral burnable absorber pins; however, detailed fuel load optimization was outside the scope of this work. Changes in the hydride-containing pins were avoided for this design, as such changes would turn these pins into consumable parts, much like the fuel, a move that lacks a strong economic justification.

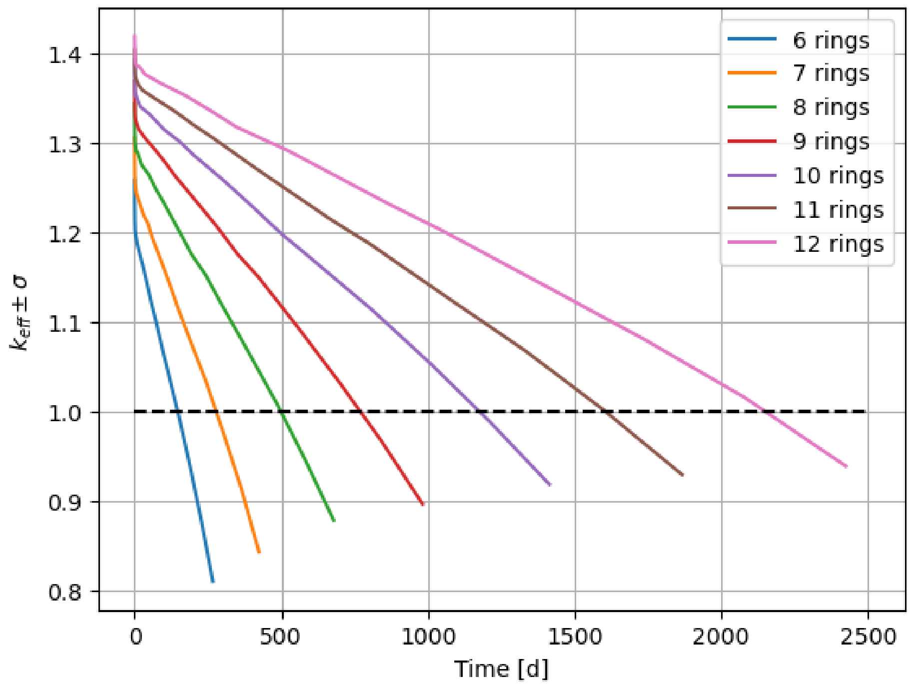

Figure 4. Parametric study of operational time by varying the number of rings in the core.

Figure 5 show other parametric studies performed by varying the lattice size. As lattice size increases, so does the number of fuel pins and the diameter of the core. There are competing economic factors at work, because as lattice size increases, neutron leakage decreases and operational time between refueling increases. Therefore, while the number of fuel pins and fuel cost increases, operational time also increases. The economical trade-off between longer cycle durations versus larger fuel inventory will require more detailed optimization.

Average heat flux in the core is one of the most important parameters for the design from a safety standpoint. For a fixed power design, heat flux decreases as the number of fuel pins increases. Here it is assumed that a heat flux that was compatible with previous experience of SFRs is adequate. As noted, SFRs tend to have a heat flux of approximately 0.8 MW/m^2, which can be calculated by dividing the power density of a typical SFR by the total fuel-pin surface area. The proposed core only reaches this heat flux level when its lattice size reaches 12 rings, as shown in Figure 5. This lattice size was therefore preferred and chose for this analysis. A smaller lattice size would require a lower power level to satisfy heat flux constraints before caring about expected trade-off between fuel cost and operational time (increasing the core size raises the capital cost of the fuel, but it leads to a lower annualized cost due to a decreased refueling frequency).

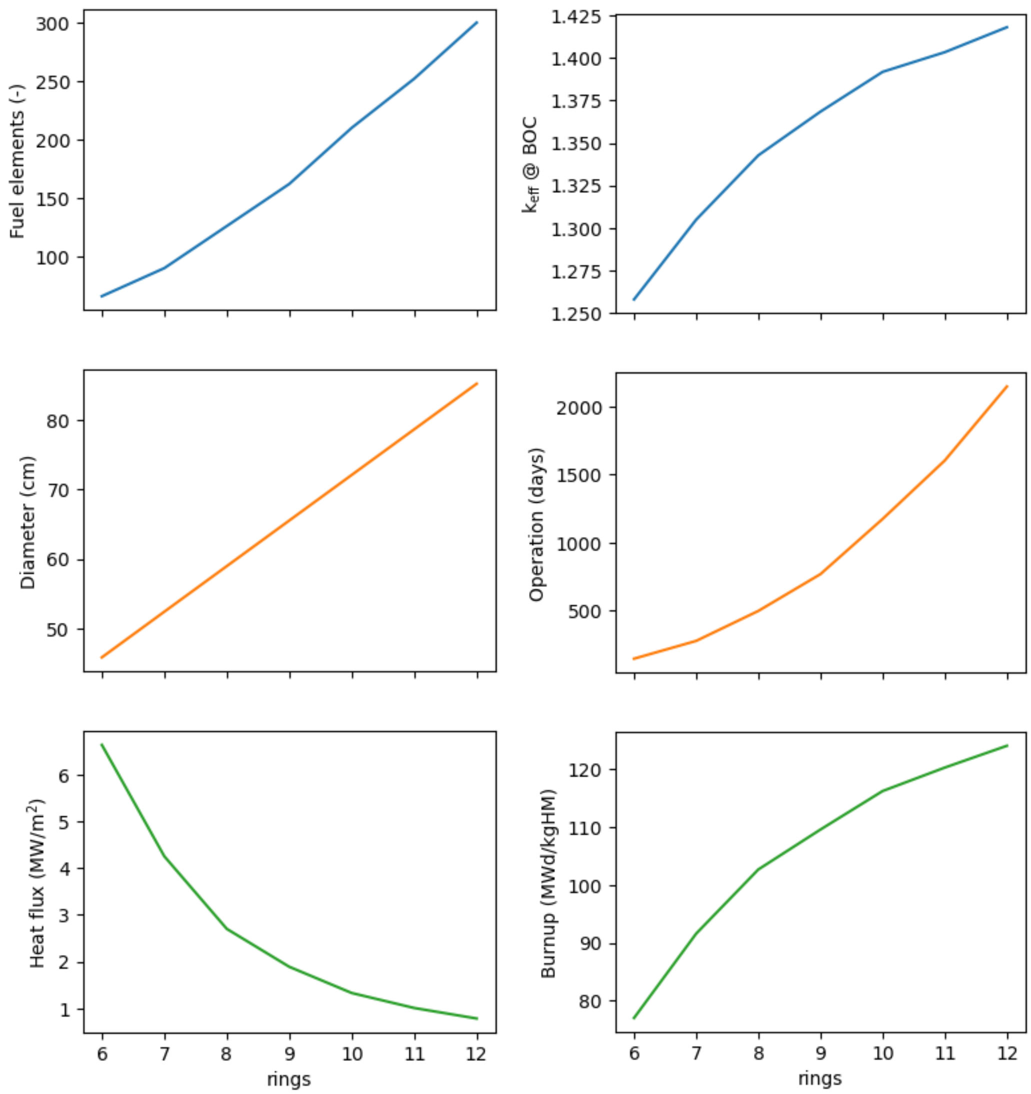

Figure 5. Parametric study of various quantities by varying the number of rings in the core. BOC stands for Beginning of the fuel cycle.

The theoretical burnup of the fuel elements in the core—up to 124 MWd/kgHM—is much higher than those reported by some in the literature (Keiser et al. 2023); however, it is just barely higher than the historical data on burnup and safety limits (GA Technologies 1987). In principle, there is no apparent reason why the fuel could not reach burnups higher than historical values. However, reaching the levels shown in this work would have to be demonstrated. For the core proposed in this work to be economically viable, high burnup levels will likely be necessary. Shielding Calculations

To house the MARVEL reactor within the TREAT Facility, the MARVEL team leverages the reactor shielding system (SHLD), the purpose of which is to limit radiation in the TREAT microReactor Experiment Cell (T-REXC). The shielding concept uses conventional materials to both moderate neutrons and attenuate gammas, which is especially important as T-REXC is designed to be used as a critical experiment facility for demonstrations beyond MARVEL. To do this, SHLD places the core within prefabricated steel cans where carbon steel and boron carbide within the steel can are used as absorbers and moderators, with a borated water-extended polyester (WEP) lining the wall of the pit is used to mitigate the neutron flux on the T-REXC concrete. A summary of the SHLD specifications within T-REXC is shown in Table 8.

Table 8. A summary of SHLD specs.

Parameter (Units)	Reported Value
Shielding in Vessel	
Guard Vessel Shielding Material	
Material	SS316H
Mass (MT)	0.18
Material	Natural B_4C powder
Mass (MT)	0.03
Secondary Cooling System Shielding Material	
Material	Carbon steel plates
Mass (MT)	2
Material	Natural B_4C powder
Mass (MT)	3.4
Shielding in Pit	
Pit Shielding Material	
Borated WEP	Borated WEP
Thickness (cm)	15.24

These specifications are designed to fulfill two operating requirements (Gerstner and Arafat 2023):

1. SHLD shall limit the radiation exposure of instrumentation in the upper confinement space to less than 1,336 rad/hr
2. SHLD shall prevent T-REXC concrete activation such that the dose rate is less than 0.5 mrem/hr at 30 cm from the structure 90 days after shutdown of the reactor.

The first requirement effectively maintains the operational capabilities of electrical instrumentation above the MARVEL core, though this is specific to the MARVEL core as there could feasibly be instrumentation location changes to limit the exposure. However, the second operating requirement is of particular interest as there has been ongoing discussion regarding microreactor capabilities for limiting soil and concrete activation, and thus questions surrounding the true cost for site preparation and decommissioning (Robert et al. 2024). This section will investigate the effect that using an LMTR design similar to MARVEL's will have on concrete activation.

3.1.2.1. Computational Environment

All calculations were performed with the Monte Carlo neutron transport code Serpent 2.2. (Leppänen et al. 2013). All calculations were run on Idaho National Laboratory high-performance computing systems using ENDF/B-VIII.0 cross-section libraries, decay libraries, photon libraries, spontaneous neutron-induced fission libraries, and appropriate S (α, β) libraries (Brown et al. 2018). Thermal scattering data for 900 K is not available for relevant materials, thus scattering data for 1,000 K was used instead. All calculations used the following bound scatterers: beryllium in BeO (Be-O), oxygen in BeO (O-Be), beryllium in beryllium metal (Be-Bem), hydrogen in zirconium hydride (H-Zr), and zirconium in zirconium hydride (Zr-H).

Depletion calculations were run with 1 million particles, with one hundred active and inactive cycles. Source calculations for activated concrete were run with 11 billion particles over 200 batches. Uncertainties are purely Monte Carlo neutron transport statistical uncertainty and do not propagate thermal scattering, cross-section uncertainties, or activated material definition uncertainties.

3.1.2.2. LMTR Core

The model used in this work is built from a previous model made for a generic reference liquid-metal-cooled UZrH-fueled core (Garcia, Bays, and Lindley 2024). The characteristics of the fuel are identical to those of the previous work, though the core geometry has been adjusted to accommodate a 20-MW_{th} system, for which all adjustments were made to radial core sizing and thus fuel mass. As a result, the core used in this study is identical to the core used in other portions of this study in terms of materials except for the fuel composition varies slightly. An annotated axial view of the core is shown in Figure 6.

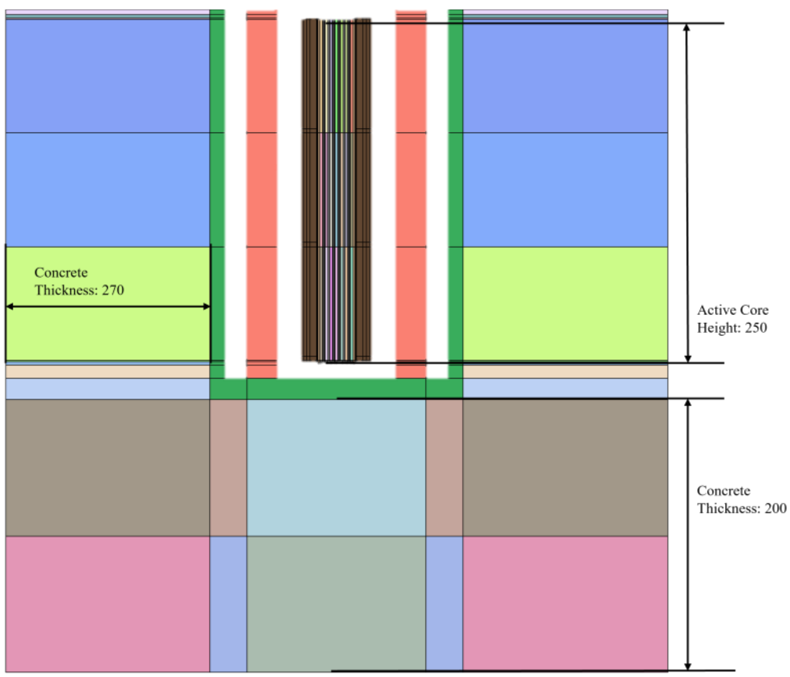

Figure 6. Dimensioned axial cross-section of the LMTR core in cm.

Though they are not shown due to the size of the simulation, the shielding layers and their thicknesses match those explored in other sections of this work. From a reactor-physics perspective, while the core is not one-to-one identical to what is explored in other sections of this report, the fuel definition and reflecting material provide a sufficiently close analog for exploring the impact that power variation has on shielding requirements. This is demonstrated with a core-average hardened thermal spectra, shown in Figure 7. This hardened thermal spectra is expected for a liquid-metal hydride core.

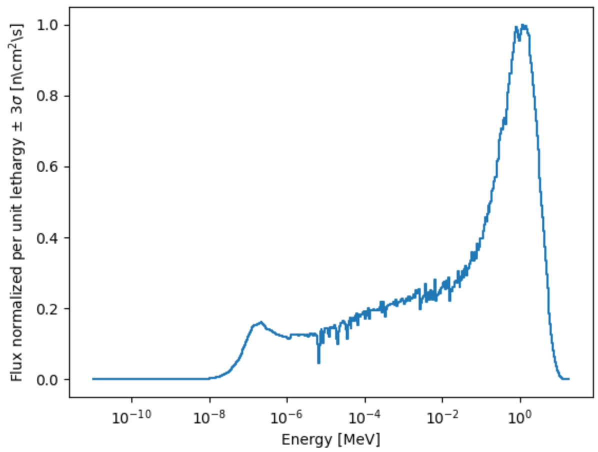

Figure 7. Hardened thermal spectra of an LMTR core.

3.1.2.3. Activation Analysis

As shown in Figure 6, the model is composed of the reactor, B_4C, layers of stainless steel (SS) 316H, borated WEP, and finally the concrete pit. Each fuel pin is treated as a unique material and further subdivided into three axial regions. Concrete is also subdivided into unique material zones to provide unique activated material definitions at various heights and radii of the pit. The core is depleted for 3 years at a 20-MW_{th} power rating to mimic a 3-year fuel cycle, though it is understood that the total core lifetime is 30 years at various WEP thicknesses. First, tallies were taken for each thickness at 0.5-, 1-, 2-, and 3-year intervals to provide sufficient data points for curve fitting to understand the evolution of dose as a function of core lifetime with respect to each WEP thickness. Second, the impact on WEP thickness was investigated by plotting 3-year concrete doses for each thickness to measure dose as a function of WEP thickness. Each tally was taken 30 cm above the opening of the pit with shielding and core removed. The reaction used for the tallies is photon dose for adipose tissue. The shielding and core were removed to investigate the activation of the concrete by itself rather than coupled with the core and shielding activation. An image of the tally location with the empty pit is shown in Figure 8.

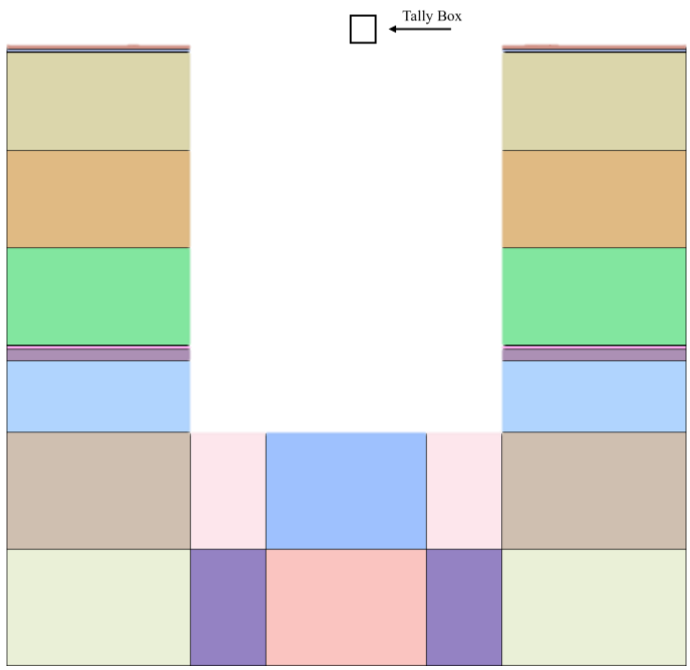

Figure 8. Emptied activated pit with tally designation.

3.1.2.4. Shielding Results

The resulting dose as a function of core lifetime for various WEP thicknesses is shown in Figure 9.

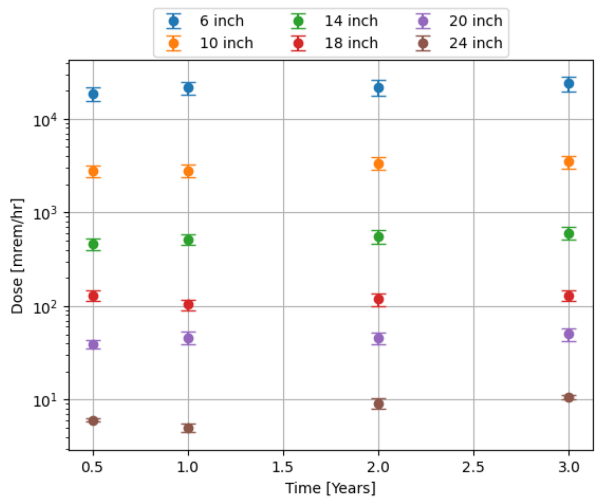

Figure 9. Dose 30 cm above pit for several thicknesses ± 3σ.

Figure 9 shows there is a significant reduction in dose above the pit as WEP thickness increases. The 6-inch configuration was used as the reference solution from which the relation between core lifetime and dose were derived, shown in Figure 10. The R^2 value is 0.8387 for the linear fit.

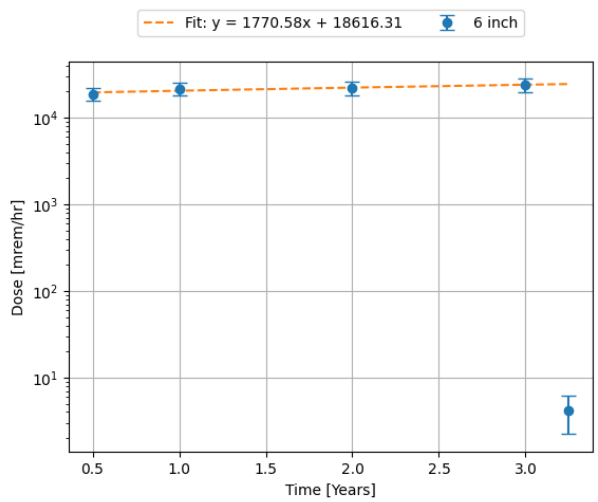

Figure 10. Dose 30 cm above the pit for 6-inch-thick WEP with decay dose rate, ± 3σ plotted.

The fit is assumed to be linear as a measure of built-in conservatism; more realistic dose behavior would be asymptotic due to short-lived activation products dominating the concrete composition post-activation. Furthermore, the 90-day decay period following shutdown decreased the dose to 0.0175% of its value following the 3-year depletion cycle. It is assumed that this decrease will be consistent over the 30-year design lifetime of the core. The final piece in determining the necessary thickness to maintain a concrete dose of 0.5 mrem/hr is understanding the relationship between WEP thickness and concrete dose immediately following shutdown. This relationship is shown in Figure 11 with a R^2 value of 0.9998.

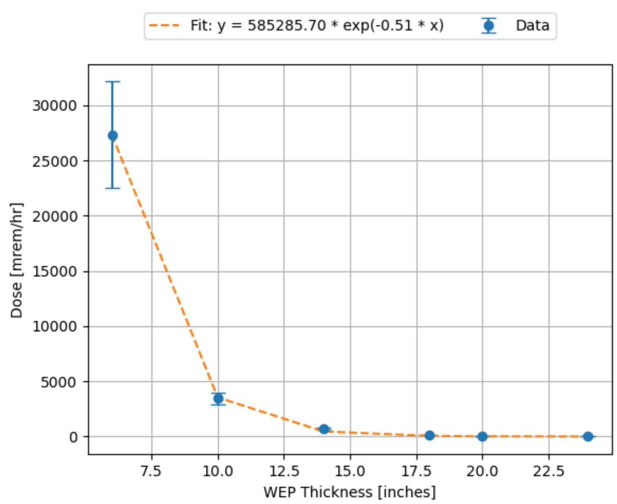

Figure 11. Dose rate immediately after shutdown as a function of WEP thickness, ± 3σ plotted.

Using the lifetime-to-dose fit and assuming a 6-inch-thick WEP, the dose at 30 years immediately following shutdown would be 7.2E4 mrem/hr. Utilizing the dose drop observed in Figure 10, to maintain a dose less than 0.5 mrem/hr following a 90-day decay period, the dose immediately after shutdown would need to be less than 28.5 mrem/hr. Finally, the relation shown in Figure 11 provides an attenuation coefficient for the WEP, thus the WEP thickness as a function of core lifetime can be determined by relating lifetime-to-dose and dose-to-thickness. This is derived in Equations 1–3 where D_o is dose rate immediately after shutdown, t is time in years, and x is the WEP thickness in inches.

$$D_o = 1770.58t + 18616.31 \quad (1)$$

$$28.5 = D_o e^{-0.51x} \quad (2)$$

$$\rightarrow x = \ln\left(\frac{1770.58t+18616.31}{28.5}\right) \cdot \frac{1}{0.51} \quad (3)$$

This relation is plotted in Figure 12, showing that the WEP must be between 12.5 to 15.5 inches thick depending on the lifetime of the core.

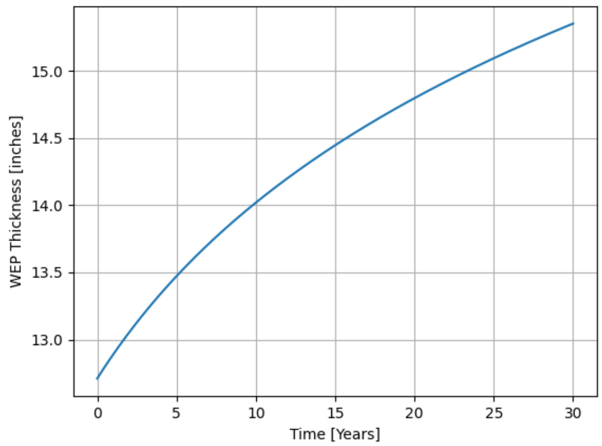

Figure 12. Required WEP thickness as a function of core lifetime.

3.1.2.5. Shielding Assessment Limitations

While this work incorporates conservative assumptions that would lead to a thicker WEP than might be necessary, there are other important considerations for future work. Notably, the concrete was developed without the presence of rebar, which is traditionally composed of steel and would be necessary for external accident safety considerations (plane impact, local explosion, etc.). Steel rebar would lead to a stronger source post-activation due to the presence of iron, although this could feasibly be mitigated with the use of fiberglass rebar reinforcement.

Additionally, the choice of concrete material definition will be a large contributor to the radioactivity of the concrete following shutdown. This is largely due to the calcium and iron content in the aggregate that is mixed in with the concrete, along with other impurities that can worsen the activation depending on its source (Robert et al. 2024). This work only considered using regular concrete, and more analysis should be done for concrete compositions that would be more site specific. Additionally, it is important to note that while concrete and instrumentation are the only shielding considerations at this time, much of the activation considerations will relate to the stainless-steel vessels themselves because they will contain large amounts of iron. Finally, there are other criteria worth considering for other potential microreactor concepts, such as 10 CFR § 20.1402, the "Radiological Criteria for Unrestricted Use," which states that a site-wide activation limit should not exceed 25 mrem/year. Notably, this criterion was not pursued in this work as it incorporates structural activation, such as that of concrete and soil, and residual radioactivity from groundwater sources, and it account for detriments such as transportation accidents that might result from decontamination and waste disposal. This criterion thus covers a rather large spread of analysis not feasible in this work and merits its own dedicated report.

For the purposes of this study, the lifetime and required WEP thickness were held constant even when performing parametric evaluations at power levels below 20 MW_{th}. This is a simplification for this stage in the work that can be improved upon in future work.

3.1.3. Balance of Plant Specifications

As part of completing the architecture of the LMTR, some components of the reactor structure and balance of plant were modeled. These components include heat exchangers, vessels, pumps, turbine-generator set, fixes shield, and reactor silo. The balance of plant components are designed for an air Brayton cycle. A sketch of the heat transfer loops and power block are presented in Figure 13, and a detailed presentation of the sizing and cost estimate of some components in the power plant follows.

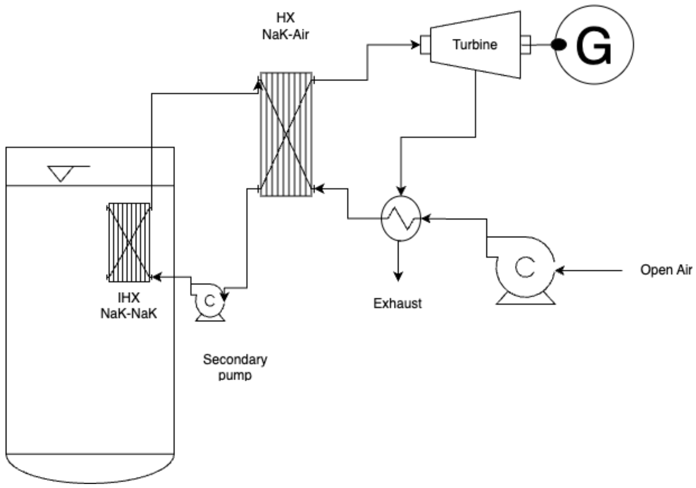

Figure 13. Sketch of the heat transfer loops and power block.

3.1.3.1. Intermediate Heat Exchanger

A printed circuit intermediate heat exchanger is suggested for the LMTR design. The selection of printed circuit heat exchanger (PCHE) is motivated by the compactness of its design. A semicircular channel type is used in this investigation. The modeling of the IHX requires assumptions about the temperature difference across the sides of the IHX. These assumptions are as follows.

$$Hot\ side\ T_{in} = 520°\boldsymbol{C}$$

$$Hot\ side\ T_{out} = 430°\boldsymbol{C}$$

$$Cold\ side\ T_{in} = 395°\boldsymbol{C}$$

$$Cold\ side\ T_{out} = 495°\boldsymbol{C}$$

Additional geometric assumptions for the IHX channel are presented here and are consistent with other PHCEs found in the literature (Lee 2014):

$$IHX\ channel\ diameter = 1.25\ mm$$

$$IHX\ channel\ pitch = 2.25\ mm$$

$$IHX\ channel\ length = 1\ m$$

$$IHX\ channel\ layer\ thickness = 3\ mm$$

Using the temperatures provided above, the log mean temperature difference across the IHX is calculated as:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} = 29.7\ K$$

$$\Delta T_1 = T_{h,in} - T_{c,out}$$

$$\Delta T_2 = T_{h,out} - T_{c,in}$$

The reported values for the overall heat transfer coefficient (U) of PCHEs range between 300–650 $\frac{W}{m^2K}$. A value of 500 $\frac{W}{m^2K}$ was selected for the analysis of the IHX. Based on this value the total heat transfer area required to perform the thermal duty is:

$$Total\ Heat\ Transfer\ Area = \frac{Thermal\ Load}{U\ \times LMTD} = 1{,}345.88\ m^2$$

The number of channels in the heat transfer is calculated by dividing the total heat transfer area by the heat transfer area available in a single channel, and, using the total number of channels and the volume of void, the mass of the IHX is calculated. It is found that the mass of the heat exchanger is linearly correlated with the reactor thermal power as follows:

$$IHX\ mass(tons) = 0.8 \times Reactor\ power\ (MWth)$$

For the LMTR-20 (Power = 20 MW_{th}), the number of channels is 349,020 and the mass is 16 tons.

3.1.3.2. NaK-Air Heat Exchanger (HX)

For compactness of design, a PCHE is suggested for the NaK-air heat exchanger. The NaK-CO_2 heat exchanger cost is calculated in a similar fashion to the IHX. Like the intermediate HX, the mass of the heat exchanger is linearly correlated with the reactor thermal power as follows:

$$IHX\ mass(tons) = 1.6 \times Reactor\ power\ (MWth)$$

For the LMTR-20 (Power = 20 MW_{th}), the HX mass is 32 tons

3.1.3.3. Primary and Secondary Pumps

Since the system is designed with a primary and secondary loops, there will be a pump that drives each loop. Assuming that the primary and secondary pumps have a head of 58 m, the inlet and outlet temperatures on the heat exchanger primary side are $520°C$ and $430°C$, respectively, and the secondary side inlet and outlet temperatures are $395°C$ and $495°C$, respectively. The pump mechanical power can be estimated as follows:

$$Primary\ pump\ mechanical\ power\ (kW) = 2.1514 \times Reactor\ thermal\ power\ (MW)$$

$$Secondary\ pump\ mechanical\ power\ (kW) = 1.984 \times Reactor\ thermal\ power\ (MW)$$

When the power is 20 MW_{th}, the mechanical powers of the primary and secondary pumps are 43 kW and 39.7 kW, respectively.

3.1.3.4. Reactor Silo

The reactor will be placed below grade and housed in a concrete silo. The silo is assumed to have annular geometry with a circular disc base. The inner diameter of the silo is assumed to be 2.4 m based on the container dimensions (i.e., 2.3-m width). The silo walls are assumed to have 2 m thickness. Hence, the outer diameter is 6.4 m and the volume of the circular disc (6.4 m diameter and 2 m thick) is 64.3 m^3.

The volume of the silo walls is dependent on the total height of the vessels. Since there are multiple vessels around the reactor, the total height is the reactor vessel height plus the height of the bottom part (ellipsoid shell) of the outer intake vessel. The volume of the vessel walls (outer diameter is 6.4 m, inner diameter is 2.4 m) is $27.6 \times total\ vessel\ height(m)$.

For the LMTR-20 reactor, the total lattice height is 78.6 cm, and the total vessel height is 2.614 m. Therefore, the total volume of the silo is 136.4 m^3.

3.1.3.5. Instrumentation and Control System

The number of sensors in the LMTR-0 (0.1 MW_{th}) is 277 and the number of sensors in larger microreactors is almost the same (255 sensors for the 6 MW_{th} MITR (de Candido et al. 2024)). Hence, it is assumed that the number of sensors does not significantly change with increasing the power.

3.1.4. Plant Layout Design

The plant layout is conceptualized as a series of structures that are the same size as transportation containers so they can be transported by standard means, or by means as standard as feasible. In Figure 14 (left), the reactor container is tilted lengthwise up on-site to bring the reactor to the vertical and to assist with natural circulation during decay-heat removal. This tilted container is put into a concrete pit that shields the ground soil from the reactor, which sits below grade, as shown in Figure 14 (right). The upper part of the reactor container, above grade, containing the IHX is connected through pipes to a second container that houses the balance of plant.

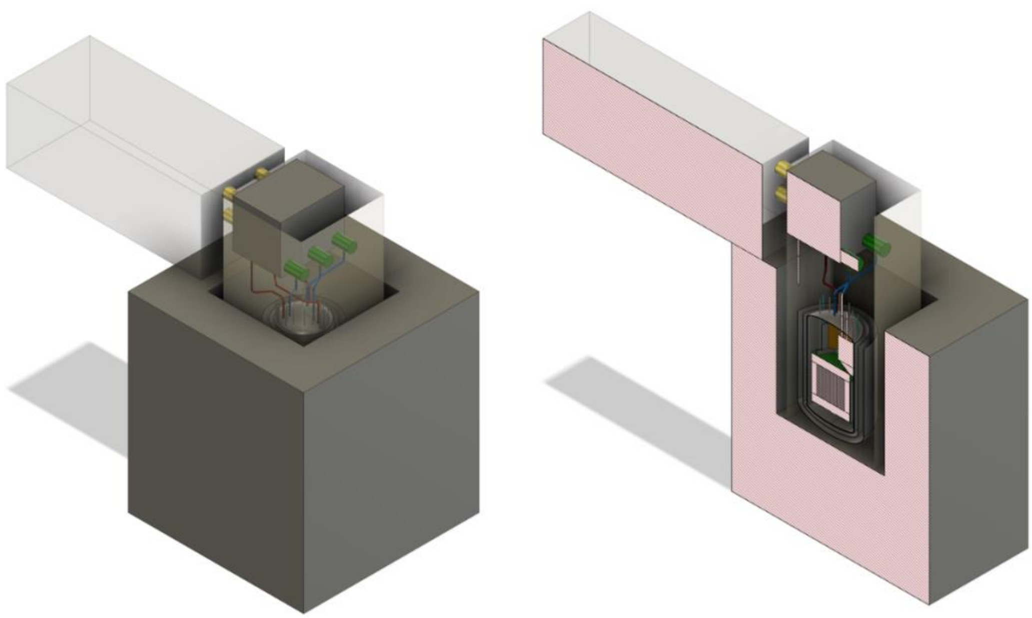

Figure 14. System overview with concrete base and separate containers (*left*) and cross section (*right*) of the system showing the reactor below grade inside the concrete pit. Not all dimensions are final or to scale.

The reactor container is essentially "a heat source in a container." The IHX could be connected to either a balance of plant or some other service that requires heat to operate. In Figure 15 (left) this IHX is represented by the box on top of the reactor. While this system has not been fully detailed, it is known that it will have to be compact to fit in a container. The current design considers a PCHE due to its size and robustness. In the drawing, the hot pipes come out of the reactor and enter the heat exchanger from below. The fluid comes out cold to the pumps (in green) and passes into the cold pipes in blue. The penetrations on top of the reactor vessel for these pipes are depicted in Figure 15 (right).

The multiple vessels around the reactor comprise the reactor vessel auxiliary cooling system (RVACS) and a guard vessel. The former is responsible for dissipating decay heat in all design basis accidents and transients, and the latter is responsible for containing sodium leaks and insulating the system under normal conditions. The intake and exhaust of the RVACS were not designed as part of this analysis, however; some piping with low-pressure drop must be added to connect the vessels to the outside of the container.

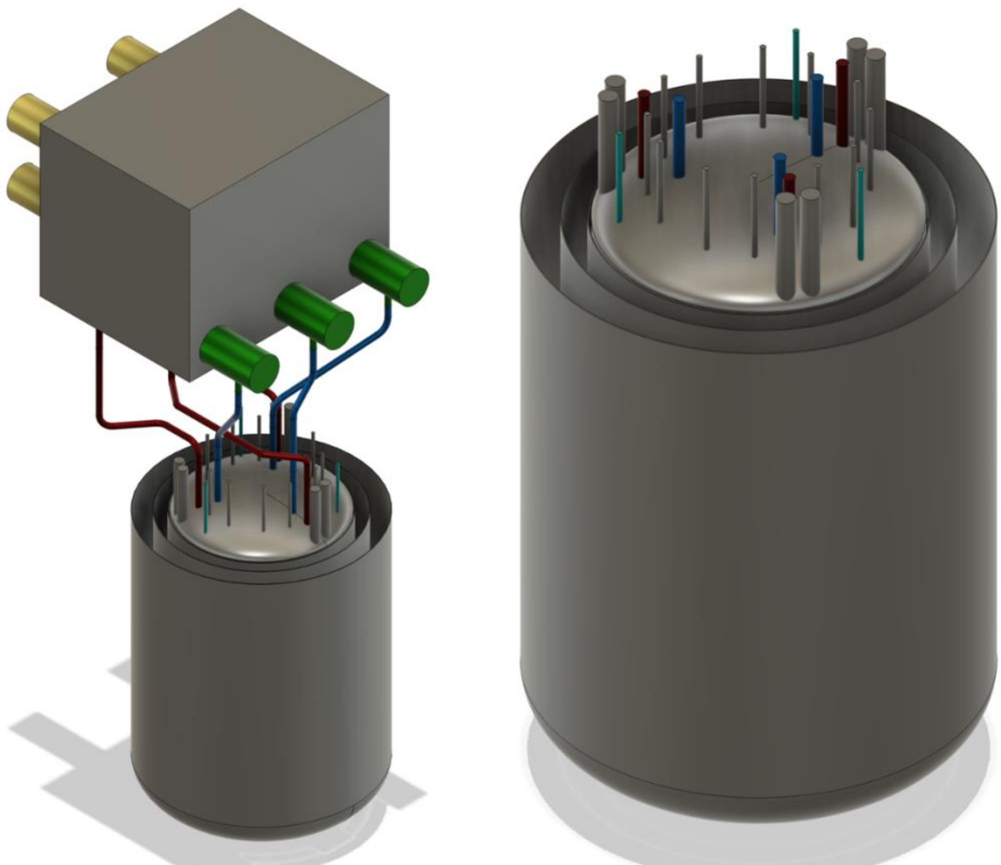

Figure 15. *Left*: zoomed-in view of the reactor and IHX, with pumps in green and pipes into the balance of plant container in yellow. *Right*: Zoomed-in view into the reactor, showing the multiple vessels responsible for the RVACS, sodium guard vessel, and main vessel, with pipe and pump shaft penetration. Red pipes are the hot side, blue pipes the cold side.

In Figure 16, the arrangement of the core, reflector, heat exchanger, baffles, and pump inside the reactor is visible. There are three heat exchangers and three pumps, therefore three circuits. There are hot and cold pipes and some extra pipes on top of the heat exchanger. These extra pipes are a provision for a decay-heat removal system based on the heat exchanger. The pumps are long shaft pumps; their motors are expected to be outside of the reactor but will actuate an impeller below the reactor core.

With the top reflector removed in Figure 16, the core components are more visible. There are two CDs per side of the lattice, so 12 in total. Like the pumps, they are also actuated by motors outside of the core. Naturally, the CDs use a different type of motor and mechanism that together actuates in both directions and with accuracy. As seen in Figure 17, the baffle on top of the core has a shape that approximates the hexagonal lattice, separating the cold and hot side. Additional baffles separating the three circuits would probably be beneficial; however, these were not designed at this stage of this work.

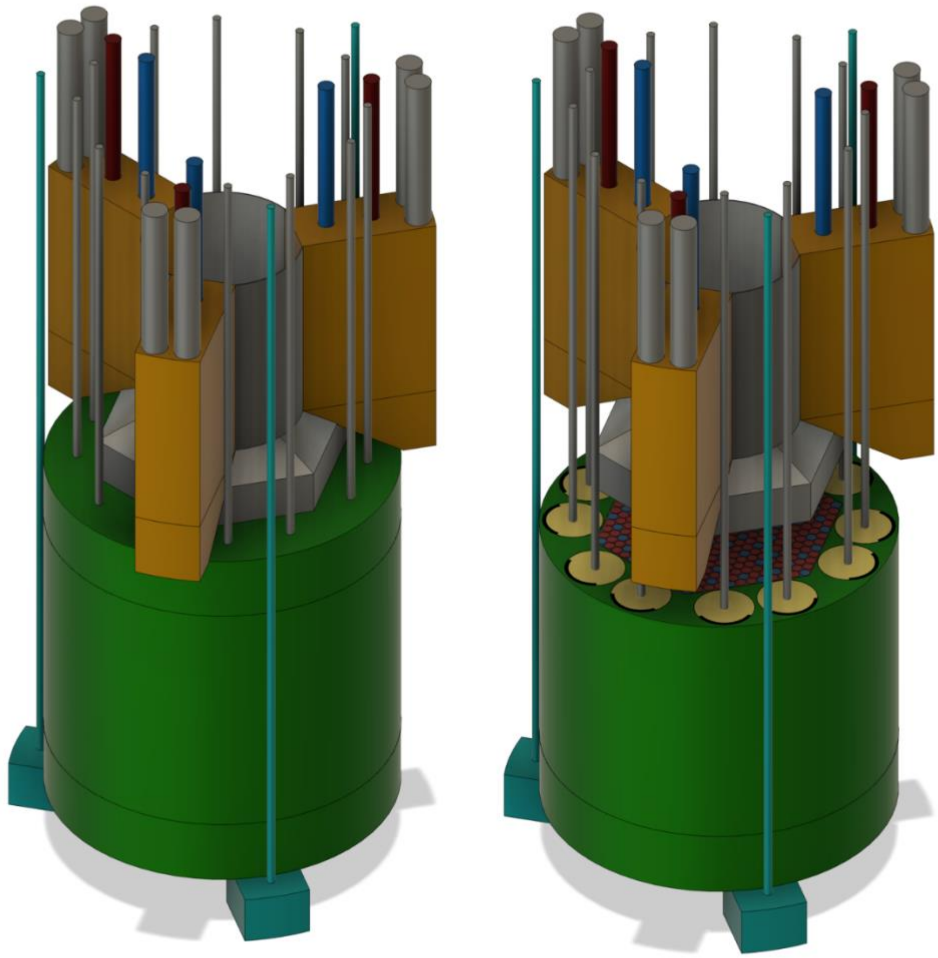

Figure 16. Reactor core with and without top reflector for exposition.

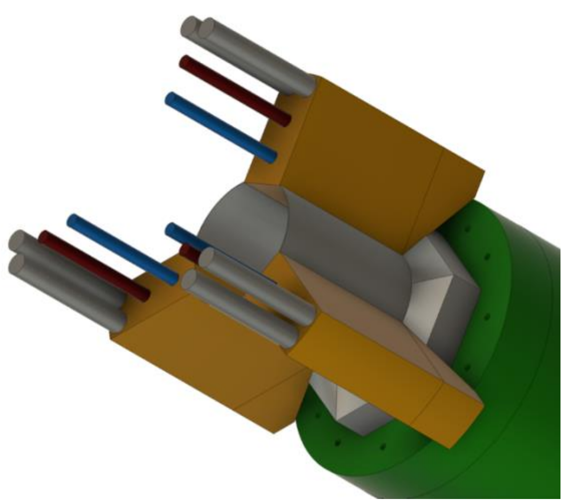

Figure 17. Zoomed-in view of the core heat exchangers and the baffles that separate the hot and cold side of the fluid domain.

Based on the CAD-generated dimensions and the concrete dimensions, the plant layout of the system could be devised. Approximated dimensions are shown in Figure 18. It is assumed that turbogenerator and instrumentation and control (I&C) systems fit within standard International Standards Organization (ISO) containers. Dimensions for the NaK storage tanks, the refueling area, the spent fuel storage area, and the radwaste area were also estimated. A summary of the baseline design variables is presented in Table 9.

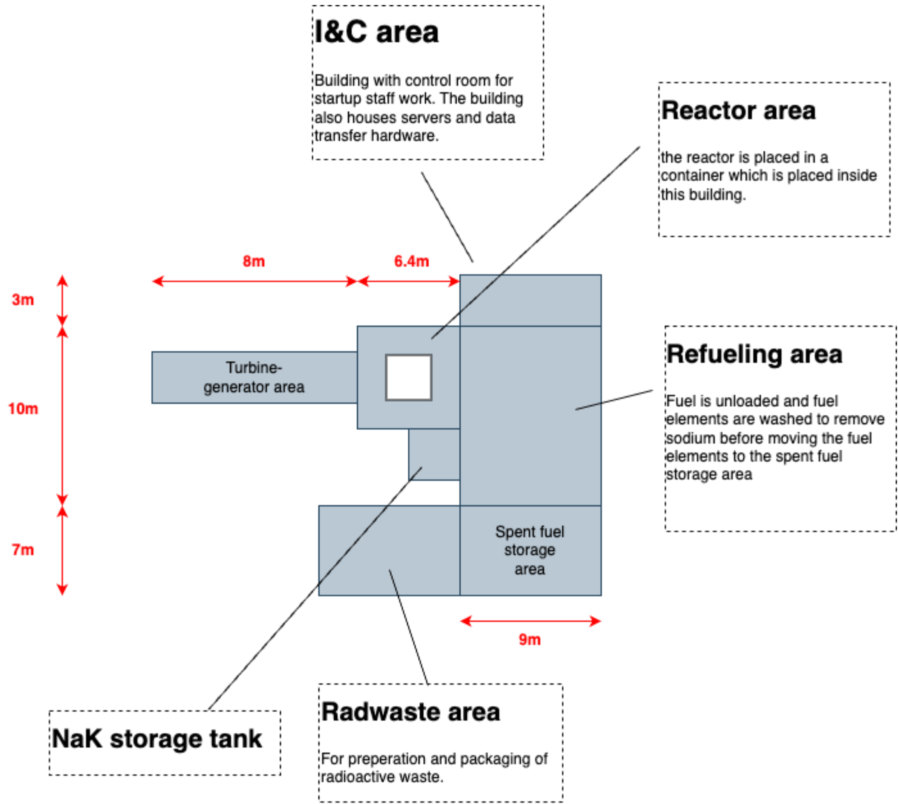

Figure 18. Suggested plan layout and area dimensions.

Table 9. LMTR-20 design parameters summary.

Variable	Value	Unit
Enrichment	19.8	wt%
Fuel	UZrH	
Uranium/Fuel weight	0.3	
UZrH weight	1154.54073	kg
Thermal efficiency	36.2	%
Power	20	MW_{th}
Power	7.24	MW_e
Coolant inlet temperature	230	°C
Coolant outlet temperature	320	°C
Number of fuel pins	252	pins
Number of moderator pins	79	pins

Variable	Value	Unit
Number of rings	12	rings
Fuel lifetime	5.9	years
Heat flux	0.8	MW/m^2
In-vessel shielding (B_4C) thickness	10.6	cm
WEP shield thickness	15.5 (39.37)	inch (cm)
Reactor lifetime	30	years
Primary pump head	58	m
Secondary pump head	58	m
Primary pump mechanical power	43	kW
Secondary pump mechanical power	39.6	kW
Silo’s volume (walls and base disc)	136.4	m^3
Lattice radius	39.3	cm
lattice height	78.6	cm
Reflector thickness	14	cm
Core radius (including the reflector)	53.3	cm
Vessel radius	213.6	cm
Vessel thickness	2	cm
Vessel volume (the walls and the bottom shell)	283,414	cm^3
Vessel SS mass	2,267.3	kg
Guard vessel radius	87.46	cm
Guard vessel thickness	0.5	cm
Guard vessel volume (walls and shell)	74,758	cm^3
Guard vessel mass	598	kg
RVACS cooling vessel thickness	0.3	cm
RVACS intake vessel thickness	0.3	cm
RVACS cooling vessel radius	92.5	cm
RVACS intake vessel radius	95.5	cm
Cooling vessel volume (wall and shell)	48,254	cm^3
Cooling vessel SS mass	386	kg
Intake vessel volume (wall and shell)	50,367	cm^3
Intake vessel SS mass	403	kg
Number of control drums	12	
Control drum radius	9	cm
Drum height	97.5	cm
Drum absorber layer (B_4C) thickness	1	cm

4. TECHNOECONOMIC EVALUATION MODEL

4.1. Detailed Bottom-Up Cost Estimation

4.1.1. Capitalized Preconstruction Cost (Account 10)

In this section, the cost of the LMTR-20 (20-MW_{th} reactor) is estimated. When appropriate, the unit costs from the LMTR-0 cost in Table 6 are utilized to estimate the costs of components in the LMTR-20 reactor. Since the LMTR-20 and LMTR-0 do not have the exact same design, some costs for the LMTR-20 are estimated independently. The cost of each item in the GN-COA is estimated, and the results for each item are summarized in Table 12

4.1.1.1. Land Cost (Account 11)

Since microreactors are likely to serve distant rural places, the cost of land needs to be taken into account. For this work, a land cost of $3,800/acre was taken from Abou-Jaoude (2024) and inflated to $4,084/acre to put the number into 2024 dollars. The next step is to calculate the area of the land required. Figure 17 shows a layout and plant areas for this analysis. The area occupied by the buildings (including gaps) is calculated to be:

$$Building\ areas\ including\ gaps = 468\ m^2$$

The total fenced area of the plant is assumed to be 4 times this building area. Thus:

$$Plant\ area = 1{,}782\ m^2 = 0.46\ acres$$

The total cost of land is therefore:

$$Land\ cost = \$1{,}888$$

It is assumed that the land cost is not sensitive to the reactor dimensions since the reactor and other components will be in ISO containers that have standard dimensions

4.1.2. Capitalized Direct Costs (Account 20)

4.1.2.1. Structures and Improvements cost (Account 21)

<u>Reactor's silo</u>

As explained in Section 3.1.3.4, the silo's dimensions are dependent on the container dimensions and the total vessel height. Since the total vessel height (height of the vessel wall and the bottom ellipsoid-shaped shell of the LMTR-20) is 2.61 m, the silo's volume is 136.4 m^3. According to Abou-Jaoude et al. (2021) concrete costs $917/$m^3$ (2017 USD). Using an inflation multiplier of 1.22, the cost of the reactor silo is estimated to be over $153K (or $1,119/$m^3$).

<u>Building's cost</u>

The construction cost for the LMTR-20 is calculated by determining the area occupied by the building and multiplying this figure by $300/$ft^2$ (Abou-Jaoude 2021). This area is the area of the rectangle covered by building edges with a 20% increase for each edge length (refer to Figure 18). The area is specifically calculated as:

$$Building\ area = (3 + 7 + 10) \times 1.2 \times (8 + 6.4 + 9) \times 1.2 = 674\ m^2$$

Applying the $300/$ft^2$ multiplier, the construction cost is calculated to be:

$$Construction\ cost = \$2{,}176{,}202$$

<u>Diesel Generator</u>

Another cost that is included from under the structures account from Table 6 is the cost of the diesel generator, which is \$7,517,900/MWe. It is assumed that the cost will scale with the reactor power (MWe) with a scaling exponent of 0.6. Therefore, the cost of the diesel generator for the LMTR-20 is estimated to be around \$6 millions.

4.1.2.2. *Reactor System's Cost (Account 22)*

The reactor system includes the reactor components, the heat transport system, the safety systems, the I&C, plus other equipment.

4.1.2.2.1. Inner and Outer Vessel and Support Structure

The first components are the reactor support structure and the guard vessel (outer vessel). For both, the costs are assumed to scale up linearly with the cost of the guard vessel. Because the microreactor (LMTR-20) is horizontal and would have an extra support structure, the cost for the support structure was doubled. Using the LMTR-0 guard vessel mass and cost, the costs of the reactor support and the outer vessel are estimated to be \$0.9 million and \$0.6 million, respectively.

Since LMTR-20 is a pool-type cooled reactor, the inner vessel is comparable to the PCS of LMTR-0, so the cost of the inner vessel scales up with the mass of the PCS (unit cost is \$1,967/kg). The mass of the inner vessel is 2,267 kg and is estimated to cost \$4.5 million.

4.1.2.2.2. Reactivity Control System

The cost of the reactivity control system is the cost of the control system fabrication, installation, plus the cost of the control drums (made of B_4C and BeO). The cost of drums is assumed to scale linearly with the mass of the B_4C and BeO, whereas the other costs are assumed to be the same as for the LMTR-0. The cost of B_4C per kilogram is available in Table 6, while the cost of BeO is assumed to be the same as the cost of the reflector in Table 6. Hence the cost of the reactivity control system is:

$$Control\ sys.cost = \$322{,}663 + \$1{,}294{,}603 + \$14{,}286 \times B4C\ mass + \$10{,}063 \times BeO\ mass$$

The CD specs, in the OpenMC simulation, are summarized in Table 7. The height of the drum is not defined in the OpenMC simulation, but it is assumed to be 1.24 times the core's active height (as it is for the LMTR-0). The absorber layer (B_4C) is 1 cm thick and covers only one-third of the drum. The volume of the drum absorber (B_4C) for one drum is 1,737 cm^3, or 208,445 cm^3 for all the drums (52.5 kg), and the volume of the drum reflector is 23,052 cm^3 per drum, or 276,622 cm^3 for all the drums (835.4 kg), so the total cost of the reactivity control system is estimated to be around \$10.8 millions.

4.1.2.2.3. Reflector

The reflector height is assumed to be the same as the control drum height. The reflector thickness is 14 cm, and the outer diameter is 106.6 cm. Therefore, the area occupied by the reflector equals the total area of the core minus the hexagonal lattice area and the area occupied by the CDs. It is estimated that the BeO reflector's area is 1,887 cm^2, and the reflector volume is 183,872 cm^3 (555 kg). Using the cost in Table 6 (\$10,063/kg), the cost of the reflector is around \$5.6 millions

4.1.2.2.4. Shielding

The thickness of the in-vessel shield (B_4C) is 10.16 cm and the inner diameter is the outer diameter of the reflector (106.6 cm). The height is the same as that of the vessel (213.6 cm). The volume is 782,041 cm^3, and the mass is 1.97 tons. Using the cost of B_4C (\$14,286/kg) in Table 6, the cost is estimated to be around \$28 millions.

The out-of-the-vessel WEP shielding thickness is estimated (in Section 0) to be 15.5 in. (39.37 cm). The WEP layer's inner radius is the outer radius of the intake vessel, plus the thickness of the intake vessel (95.8 cm), and the height is the same as total vessel height (vessel wall height plus the ellipsoid-shaped shell height), which is 261.4 cm. The volume of the WEP layer is calculated to be 7,463,735 cm^3.

The mass of the WEP's shield is 4.1 tons (note that we use 50% of the density to perform this calculation since the WEP layer is not fully made of WEP). According to a vendor quote, the WEP's cost is $600/ft^3 (or $20/kg), so the WEP's shield cost is estimated to be $82,000.

4.1.2.2.5. Primary and Secondary Pumps

The cost of the pumps according to Roosen, Uhlenbruck, and Lucas (2003) is:

$$Pump\ cost = 1{,}168\ P^{0.71}\left(1 + \frac{0.2}{1-\eta}\right),$$

where P is the pump mechanical power and η is the pump isentropic efficiency (assumed to be 80%). For the LMTR-20, the mechanical powers of the primary and secondary pumps are 43 kW and 39.7 kW, respectively (see Section 3.1.3.3). Hence the cost of the primary pump is $33,764, and the secondary $31,139.

4.1.2.2.6. Piping

Since the piping in the LMTR-20 and LMTR-0 are not comparable, the piping cost is not scaled from the LMTR-0. According to Ganda et al. (2019), a rough estimate of the piping cost is $20/kW (2017 USD), or $25/kW (2024 USD). Hence, the cost of the piping system of the LMTR-20 (36.2% thermal efficiency) is $181,000.

4.1.2.2.7. Heat Exchangers

From Sections 3.1.3.1 and 3.1.3.2, the masses of the IHX and the NaK-air HX are 16 and 32 tons, respectively. According to (Gezelius 2004) the PCHE cost is $192/kg (2024 USD), so the cost of the immediate HX and NaK-Air HX would be $3.072 million and $6.144 million, respectively.

4.1.2.2.8. RVACS Vessels

The RVACS system includes the cooling and intake vessels. Using the vessels' masses from Table 7, and assuming that the cost of stainless steel is $310/kg (2017 USD; taken from Ganda et al. 2019), or $378/kg (2023 USD), the costs of the cooling and intake vessels are estimated to be $146K and $152K respectively.

4.1.2.2.9. I&C Cost

As explained in Sec. 3.1.3.5, the LMTR-20 is estimated have the same number of sensors as MARVEL (277 sensors). The I&C cost has two components: the cost of the I&C plus an additional cost to account for the autonomous control. According to the Table 6, the cost per sensor is $6,850. Hence, the cost of the I&C system is estimated to be $1.9 millions

Using the model in de Candido et al. (2024), the additional cost of the I&C due to autonomous control is:

$$Cost\ of\ autonomus\ operation = 1.22 * Total\ I/O \times \$5000$$

Thus the autonomous operation cost is $1,689,700, and the total I&C cost is $3.6 millions

4.1.2.3. Energy Conversion System (Turbine): Account 23

For the turbine, cost data from the DOE microturbines fact sheet (2016) are leveraged to develop a correlation for the turbine cost. As shown in Figure 19, the turbine's cost as a function of the turbine's power is estimated via the following equation:

$$Turbine's\ cost = 6381.5 \times P(kW)^{0.8917}$$

For the LMTR-20 reactor (7.24 MW_e), the turbine's cost is estimated to be $17,646,219.

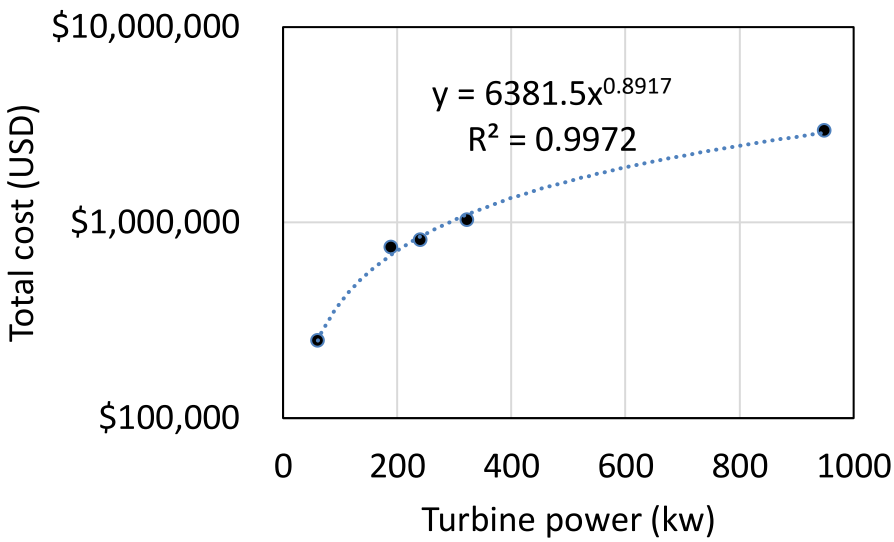

Figure 19. Microreactor turbine cost vs. turbine power.

4.1.2.4. Initial Fuel Inventory (Account 25)

The unit costs of uranium mining, conversion, and enrichment from Abou-Jaoude et al. (2024) and Dixon et al. (2017) are summarized in Table 10. Several parameters, such as separative work units (SWUs), were considered to calculate these costs (see Table 11)

Table 10. Fuel cost summary.

	Mean Cost (2022 USD)	Unit
Natural uranium	184	$/kg of natural uranium
Natural uranium conversion	15.1	$/kg of natural uranium
Enrichment	184.2	$/SWU
SWU premium multiplier	0.15	—

For the fuel fabrication, the cost is not scaled up directly from MARVEL. Instead, the correlation between the number of fuel pins and the total cost (as depicted in Figure 20) is utilized. From Figure 20, the total cost as a function of the fuel pins is

$$Fabrication\ Cost(\$) = 653{,}122 \times Number\ of\ fuel\ pins^{0.7054}$$

Considering that the mass of one fuel pin in MARVEL is 4.036 Kg and the cost for non-DOE customers is 30% higher, the fabrication cost equation can be modified to be

$$Fabrication\ Cost(\$) = 210{,}371.3 \times fuel\ mass(kg)^{0.7054}$$

Therefore, the cost of the fuel production will be around $30 millions

Table 11. Fuel calculations.

Parameter	Value	Calculation
Fuel (UZrH) Mass	1,154.5 kg	—
Enrichment	19.75 (wt%)	—
Uranium wt fraction (U: UZrH)	30 (wt%)	—
Uranium mass	346.3 kg	—
Natural uranium consumption	*14,683 kg*	Using the typical natural uranium assay of 0.71%, and the tail assay of 0.25%, the mass of the natural uranium is Uranium mass $\times \frac{Enrichment-0.0025}{0.0071-0.0025} =$
Tail waste	14,336 kg	$= Natural\ uranium\ consumption - uranium\ mass$
Enrichment kg-SWU	*14,236 kg*	The SWU requirement can be expressed as a function of the energy necessary to obtain a mass of product m_U of assay x_{Ut} from a feed m_{NatU} of assay x_{NatU}, and with tails of mass m_t and assay x_t is given by the expression: $W_{SWU} = m_U \times V(x_U) + m_t \times V(x_t) - m_{NatU} \times V(x_{Nat})$ m_U, m_t, m_{NatU} $are\ the\ masses\ of\ Uranium, tail\ waste,$ $and\ the\ natural\ uranium$ where $V(x)$ is the value function defined as: $V(x) = (2x-1)\ln\left(\frac{x}{1-x}\right)$ x_U, x_t, x_{Nat} $are\ the\ enrichment, the\ tail\ assay\ of$ 0.25%, $and\ the\ natural\ uranum\ assay\ of$ 0.71%.

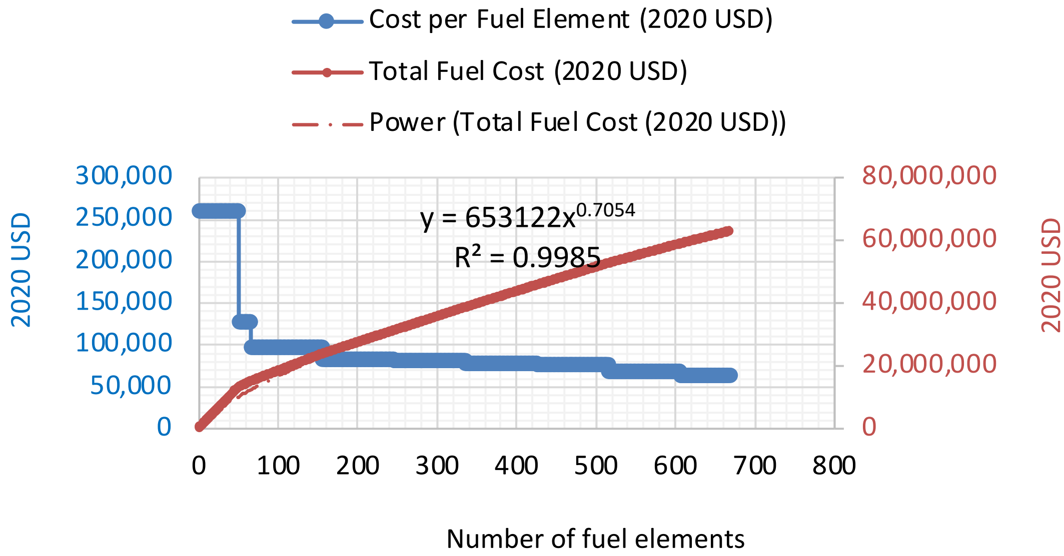

Figure 20. Fuel cost change when more fuel elements are purchased (Hanna and Abou Jaoude 2023).

4.1.3. Capitalized Indirect Costs and Financial Costs (Accounts 30 and 60)

Assumptions are made to estimate the indirect costs for each subaccount as follows.

- The factory and field indirect costs (account 31) are assumed to be the same as those for the LMTR-0.
- The factory and construction supervision (account 32) cost is not available. Therefore, it is assumed that the cost of this account relative to the cost of the structure direct cost (account 21) is the same as the ratio between the factory and field indirect cost and the reactor system's cost (account 22). Currently, this ratio is 0.027.
- The startup costs are assumed to be the same as those for LMTR-0.
- The shipping and transportation costs include international shipping, so it is assumed that for the LMTR-20 this cost would be 50% less than the cost for the LMTR-0.
- The engineering, Project Management and Construction Management (PM/CM) services are assumed to be the same as those for the LMTR-0.

For the financial costs, these assumptions are made:

- The interest cost was estimated assuming a 6% interest rate and a 4-year construction duration.

4.1.4. Annualized O&M Costs (Account 70)

Operational costs for microreactors can be lumped into four main constituents: (1) reactor operations, (2) plant security, (3) equipment maintenance, and (4) refueling. Multiple deployment arrangements can be conceived for microreactors. If refueling and servicing are conducted outside of the site at a centralized facility, this will undoubtedly impact the operational costs of a microreactor. For this work, it is assumed that there will be a simplified arrangement for refueling activities to be conducted at the site. This is in-line with the original MARVEL design on which the LMTR-20 design is based (fuel loading operations are to be conducted at the TREAT cell where it is housed). Based on these assumptions, this section will quantify the operational costs for the LMTR-20 concept.

Microreactor operational expenses can be greatly improved by automating the O&M activities (de Candido et al. 2024). Instead of opting for a fully autonomous system, de Candido et al. (2024) highlighted how it may be beneficial to only rely on a digital system to operate the system during steady-state operations. The reactor would be shut down in the event of a transient and would rely on an external operator to travel to the site and restart operations. Assuming a similar arrangement for this work, the associated costs for such a system can be estimated.

4.1.4.1. Operators Cost (Startup)

The reactor startup team is responsible for starting up the reactor after a shutdown for refueling or after a non-anticipated shutdown. To calculate the Full-Time Equivalent (FTE) required for this team a few assumptions need to be established:

- A startup team of two members working for 2 weeks (for refueling or due to an unanticipated shutdown)
- A 5.7-year cycle length for the LMTR-20 so 1 startup is expected each 5.7 years after refueling
- Assuming that one unanticipated shutdown every year, one startup will be required per year (not including the startup after refueling).

Using $178,500/FTE, the annual cost of the startup team is more than $16K

4.1.4.2. Remote Monitoring

It is assumed that the reactor will be operated autonomously, which will require some operator action only in case of emergency or maintenance or refueling. It is assumed here that the cost of one person monitoring reactors (24/7 monitoring) equals 5 FTEs and according to (de Candido et al. 2024), it is assumed that one person can monitor 20 reactors so the cost of monitoring per year per reactor is around $44K.

4.1.4.3. Security Staff

The next step is to compute security requirements for the microreactor. Several studies have attempted to better understand security requirements for microreactors (Gateau, Todreas, and Buongiorno 2024). Due to the lack of current regulatory guidance on this question, it remains unclear if microreactors may be allowed to operate with zero staff present, relying only on an external rapid-response team. For simplicity here, it is assumed that it will be required to have a single staff present at all times. Assuming an 8-hour shift and accounting for off days, etc., securing the reactor 24/7 will require 5 FTEs and it is assumed that a single security staff is required for each 2 reactors so the cost of one reactor per year is around $446K.

4.1.4.4. Maintenance (Capital Plant Expenditure)

To calculate the maintenance cost, the economics-by-design approach (Abou-Jaoude et al. 2021) suggests 1% of capital cost (in particular the reactor system, the energy conversion system, and the electrical equipment) for maintenance cost. This leads to $0.8 million for maintenance per year.

4.1.4.5. Decommissioning

The Nuclear Regulatory Commission requires a plant licensee to guarantee the availability of funds for decommissioning a nuclear power plant. This cost can be secured through a trust fund (for example, in which the licensee deposits a certain amount of money in the fund annually to obtain the target decommissioning cost at the end of the power plant’s life). Assuming a known decommissioning cost, the annual cost for the licensee can be estimated (Abou-Jaoude 2024)

$$Annual\ payment = \frac{Decommissioning\ cost \times AR}{1-(1+AR)^{n}},$$

where AR is the annual return (assumed to be 4.75%), and n represents the number of years a payment will be put into the trust (30 years in this work). To calculate the annual payment, the total decommissioning cost needs to be calculated. According to a World Nuclear Association report (2023), the decommissioning cost of a nuclear power plant is in the range of 9–15% of the total capital cost. As a conservative assumption and keeping in mind that microreactor technology has not been built, the decommissioning will be assigned a value of 15% the total capital cost.

4.1.5. Annualized Fuel Cost (Account 80)

4.1.5.1. Refueling

It is assumed that refueling will be a 2-week on-site process requiring five staff members. For a 5.7-year fuel lifetime, the average number of refueling days per year is 2.5. Hence, the cost of refueling per year is:

$$Annual\ cost\ of\ refueling\ process = \$6{,}013$$

4.1.5.2. Additional Fuel

The cost of the fuel is the same as the capital cost but distributed over the plant's lifetime. The fuel lifetime for the LMTR-20 is 5.7 years, and the refueling period is assumed to be 2 weeks, so the core needs to be refueled five times over the 30-year plant lifetime. It is assumed that 5 persons will conduct the refueling process.

4.1.5.3. Spent Fuel Management

To take into account the spent fuel disposal cost, a $1/MW$_e$hr figure was used (Abou-Jaoude et al. 2024). The annual spent fuel cost can be calculated as:

$$Spent\ fuel\ cost = 1\ \left[\frac{\$}{MW_e hr}\right],$$

$$Thermal\ power \times \eta \times CF \times 365.25 \times 24$$

where η is the power plant efficiency (assumed to be 36.2%). The capacity factor is estimated based on the refueling period (5.7 years) and assuming the refueling takes 2 weeks. One unanticipated shutdown per year is assumed with down time of 2 weeks. The estimated capacity factor is around 95%.

4.2. Summary of LMTR-20 Cost Breakdown

Table 12 provides a detailed breakdown of the cost for the proposed LMTR-20 based on the correlations from previous estimates. This table includes the scaling variables used to adjust the cost for each account, along with the unit costs (in $/kg or $/MW) applied in the cost estimation.

Key economic figures are summarized at the end of Table 12. For a well-executed, baseline first-of-a-kind deployment of the LMTR-20, the overnight construction cost (OCC) is projected to be approximately $14,500 per kilowatt electrical (kWe), or around $19,800 per kWe when fuel costs are included. Including interest, the total capital investment (TCI) is estimated to exceed $22,000 per kWe. This results in a levelized cost of energy (LCOE) of $325 per megawatt-hour (MWh). While this LCOE is relatively high compared to that of large nuclear reactors, it is expected to decrease due to the potential for the factory fabrication and mass production of microreactors. Additionally, the faster construction time of microreactors will contribute to higher learning rates. Further details on the cost of the NOAK reactor are discussed in Section 5.3.

Table 12. The LMTR-20 cost breakdown.

Account ID	Account Title	Scaling			Unit Cost		Estimated Cost (USD 2023)
		Scaling Variable	Value	Units	Value	Units	
10	**Capitalized Preconstruction Costs**						**5,218,748**
11	**Land Cost**	**Plant Area**	**0.46**	**acres**	**4,084**	**$/acre**	**1,888**
15	**Plant Studies**	**No Scaling**			**—**	**—**	**5,216,860**
20	**Capitalized Direct Costs**						**131,634,692**
21	**Structures and Improvements**						**11,246,430**
212	Reactor Island Civil Structures	—	—	—	—	—	5,182,025
212A	Pit Preparation (Coordination and mods)	No Scaling					2,851,662
212B	Reactor Silo (Concrete)	Concrete Volume	138	m^3	1,119 (Abou-Jaoude et al. 2021)	$/m³	153,863
212C	Reactor Building	Area Covered by the building	7255	ft^2	300	$/ft²	2,176,500
214	Buildings to Support Main Function	—		—	—	—	15,632,973
214.7	Emergency and Startup Power Systems	Power (MWe)	7.24	MW_e	837,625	$/$MW_{th}$	6,064,405
22	**Reactor System**						**63,899,534**
221	Reactor Components						50,552,239
221.1	Reactor vessel and accessories	—		—	—	—	5,967,943
221.11	Reactor support	Mass of the guard vessel	598	kg	754	$/kg	901,784
221.12	Outer vessel structure	Mass of the guard vessel	598	kg	1,015	$/kg	606,970
221.13	Inner vessel structure	Mass of the primary cooling system	2267	kg	1,967	$/kg	4,459,189
221.2	Reactor control devices	—	—	—	—	—	10,773,911
221.21	Reactivity control system	—	—	—	—	—	10,773,911
221.21A	Reactivity Control System Fabrication	—	—	—	—	—	1,294,603
221.21B	installation	—	—	—	—	—	322,663
221.21C	CDs (B_4C)	B_4C Mass	52.5	kg	14286	$/kg	750,015
221.21D	CDs (BeO)	BeO Mass	835.4	kg	10,063	$/kg	8,406,630
221.3	Non-fuel core internals						33,810,385
221.31	Reflector	BeO Reflector Mass	555	kg	10,063	$/kg	5,584,965
221.32	Shield						28,225,420
221.32A	In-vessel shield (B_4C)	B_4C Mass	1.97	tons	13,793	$/kg	28,143,420
221.32B	Out the vessel shield (WEP)	WEP’s mass	4.1	tons	20	$/kg	82,000

Account ID	Account Title	Scaling			Unit Cost		Estimated Cost (USD 2023)
		Scaling Variable	Value	Units	Value	Units	
222	Main Heat Transport System						9,461,903
222.1	Fluid Circulation Drive System (Pumps)	—	—	—	—	—	64,903
222.1A	Primary Pumps	Pump Mechanical Power	43	kW	785	$/kW	33,764
222.1B	Secondary pumps		39.7	kW	784	$/kW	31,139
222.2	Reactor Heat Transfer Piping System	Electric Power	7.24	MW	25	$/kW	181,000
222.3	Heat Exchangers	—	—	—	—	—	9,216,000
222.3A	Immediate Heat Exchanger	HX Mass	16	tons	192	$/kg	3,072,000
222.3B	NaK to Air Heat Exchanger	HX Mass	32	tons	192	$/kg	6,144,000
223	Safety Systems						298,242
223.2	Reactor Cavity Cooling System	—	—	—	—	—	298,242
223.2A	RVACS (Cooling Vessel)	Mass of the Cooling Vessel	386	kg	—	—	145,908
223.2B	RVACS (Intake Vessel)	Mass of the Intake Vessel	403	kg	—	—	152,334
227	Reactor I&C						3,587,150
227A	I&C Baseline Cost	Number of Sensors	277	Sensors	6,850	$/ sensor	1,897,450
227B	I&C Autonomous Control				6,100		1,689,700
23	**Energy Conversion System**	— —	—	—	—	—	**17,646,219**
232	Energy Applications	— —	—	—	—	—	17,646,219
232.1	Electricity Generation Systems (Turbines)	Reactor Power	7.24	MW_e	2,437	$\$/kW_e$	17,646,219
24	**Electrical Equipment**	Assuming that this cost does not significantly change for microreactors with larger capacities			—	—	**33,657**
25	**Initial Fuel Inventory**	— —	—	—	—	—	**37,493,070**
251	First Core Mining	Natural Uranium Consumption	14,683	kg	184	$/kg Natual Uranium	2,701,672
252	First Core Conversion			kg	15.1		221,713
253	First Core Enrichment	Enrichment kg-SWU	14,236	kg	212	$/kg-SWU	3,329,737
254	First Core Fuel Assembly Fabrication	—	—	—	—	—	31,239,948
254A	Fuel Production and Procurement	Fuel Mass	1154.5	kg			30,422,799
254B	Other Related Activities	Assuming that this cost does not significantly scale.			—	—	817,149
26	**Miscellaneous Equipment (Cranes)**	**—**			**—**	**—**	**1,000,000 (Abou-Jaoude 2023)**

Account ID	Account Title	Scaling				Unit Cost		Estimated Cost (USD 2023)
		Scaling Variable		Value	Units	Value	Units	
30	**Capitalized Indirect Services Cost**							6,532,223
31	**Factory and Field Indirect Costs**	—	—	—	—	—	—	**1,656,640**
32	**Factory and Construction Supervision**	—	—	—	—	—	—	**291,572**
33	**Startup Costs**	—	—	—	—	—	—	**2,407,166**
34	**Shipping and Transportation Costs**	—	—	—	—	—	—	**961,957**
35	**Engineering Services**	—	—	—	—	—	—	**797,929**
36	**PM/CM Services**	—	—	—	—	—	—	**416,959**
60	**Capitalized Financial Costs**	—	—	—	—	—	—	**17,883,735**
62	**Interest**	—	—	—	—	—	—	**17,883,735**
70	**Annualized O&M Cost**	—	—	—	—	—	—	**1,659,884**
71	**O&M Staff**	—	—	—	—	—	—	**506,957**
711	On-site Operators	—	—	—	—	—	—	16,082
712	Remote Monitoring Technicians	—	—	—	—	—	—	44,625
713	Security Staff	—	—	—	—	—	—	446,250
75	**Capital Plant Expenditures**	—	—	—	—	—	—	**815,794**
78	**Annualized Decommissioning Cost**	—	—	—	—	—	—	**337,132**
80	**Annualized Fuel Cost**	—	—	—	—	—	—	**6,315,425**
81	**Refueling Operations**	—	—	—	—	—	—	**5,973**
81	**Additional Nuclear Fuel**	—	—	—	—	—	—	**6,248,845**
83	**Spent Fuel Management**	—	—	—	—	—	—	**60,607**
OCC ($)								143,069,881
OCC ($/kW)								19,761
OCC excluding initial fuel load cost ($/kW)								14,582
TCI ($)								160,953,616
TCI ($/kW)								22,231

Account ID	Account Title	Scaling			Unit Cost		Estimated Cost (USD 2023)
		Scaling Variable	Value	Units	Value	Units	
Annualized Cost ($)							7,975,308
Annualized Cost ($/MWh)							132
LCOE ($/MWh)							325

The cost breakdown of the FOAK LMTR-20 is shown in Figure 21. Direct costs account for approximately half of the Levelized Cost of Electricity (LCOE), while annualized fuel costs represent around 30% of the LCOE. Note that direct costs include the initial fuel load, which constitutes 30% of the direct costs, highlighting that fuel costs are a major driver for the microreactors. This finding is consistent with previous research by Abdalla Abou Jaoude (2021). A more detailed analysis of the cost drivers is shown in Figure 22. In addition to fuel and reactor system costs, which are the primary cost drivers, interest accrued during construction are also identified to be large contributors. Additionally, the turbine and civil work (structures) have substantial impacts on the overall cost of the LMTR-20.

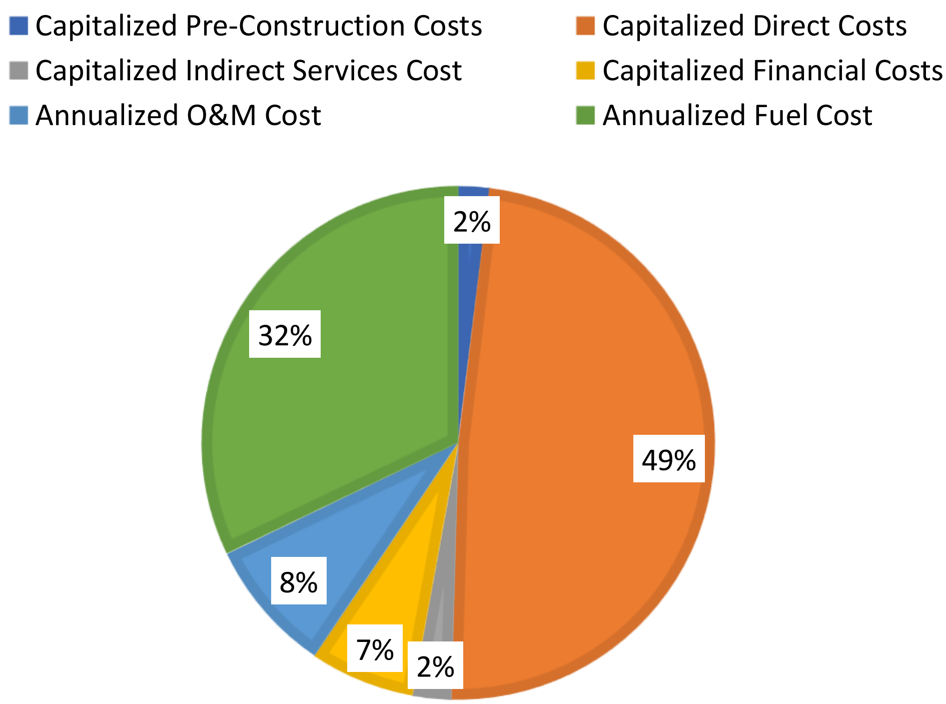

Figure 21. LMTR-20 FOAK levelized Cost ($/MWh) Breakdown. The contribution of each cost to the LCOE is presented as a presentage.

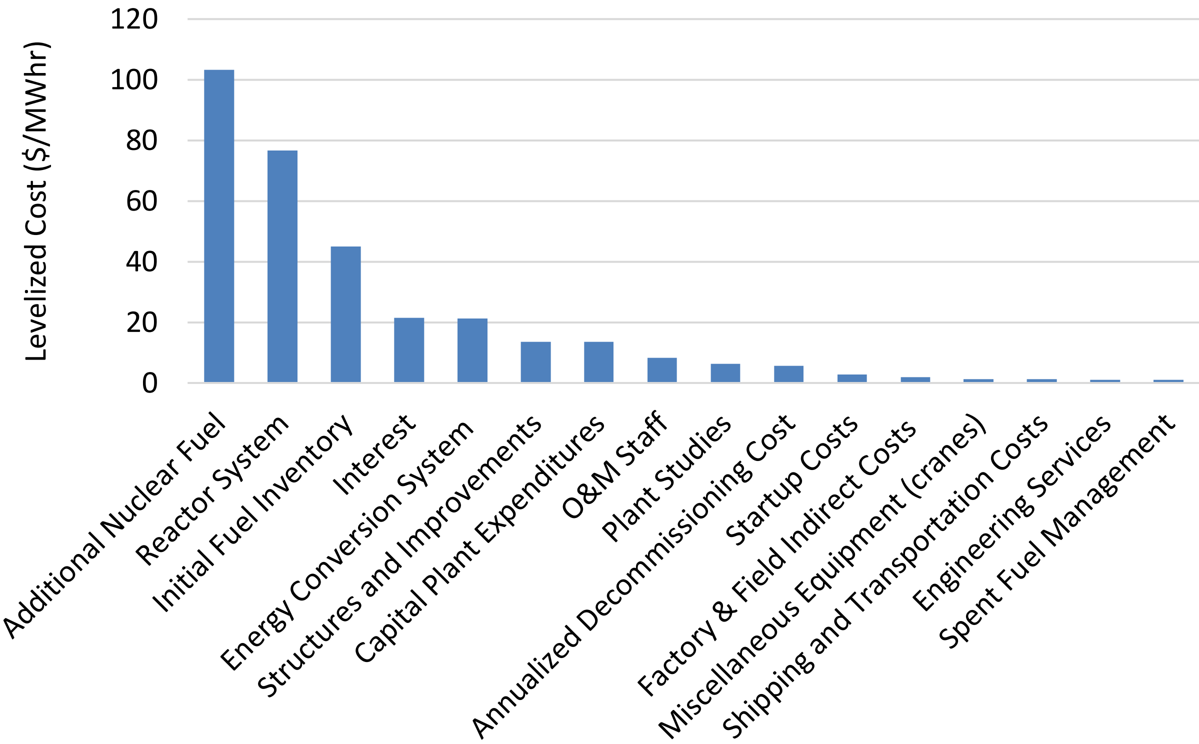

Figure 22. FOAK LMTR-20 Cost drivers.

5. POTENTIAL PATHWAYS FOR COST-COMPETITIVE MICROREACTORS

5.1. Implementing Economics-by-Design Methodology

To identify and understand how a change in core design can impact the costs of a microreactor, a new tool that couples the reactor design calculations with the economic equations was developed. In this new tool, the OpenMC neutronics code was coupled with cost equations that are mainly based on the MARVEL cost. Figure 23 demonstrates the overall coupling process.

Using the MARVEL costs (mapped to the GN-COA) and the MARVEL design parameters, cost equations for each cost item were developed. Using OpenMC, the fuel lifetime and the heat flux are estimated. Both the inputs and outputs of OpenMC feed the cost equations (based on MARVEL data) to estimate the cost of a new LMTR reactor. OpenMC and the cost equations are fully coupled so a change in the core design (e.g., enrichment, power, reflector thickness, etc.) directly changes the operational lifetime and the MARVEL-like reactor cost.

Besides the inputs and outputs from OpenMC, the cost equations are also fed other relevant or economic parameters (such as the interest rate, construction period, refueling period, etc.). Using this new tool, it can be shown how the reactor design specifications directly affect capital cost, annualized cost, and the LCOE.

Examples showing the impact of the design on cost are presented in the following section.

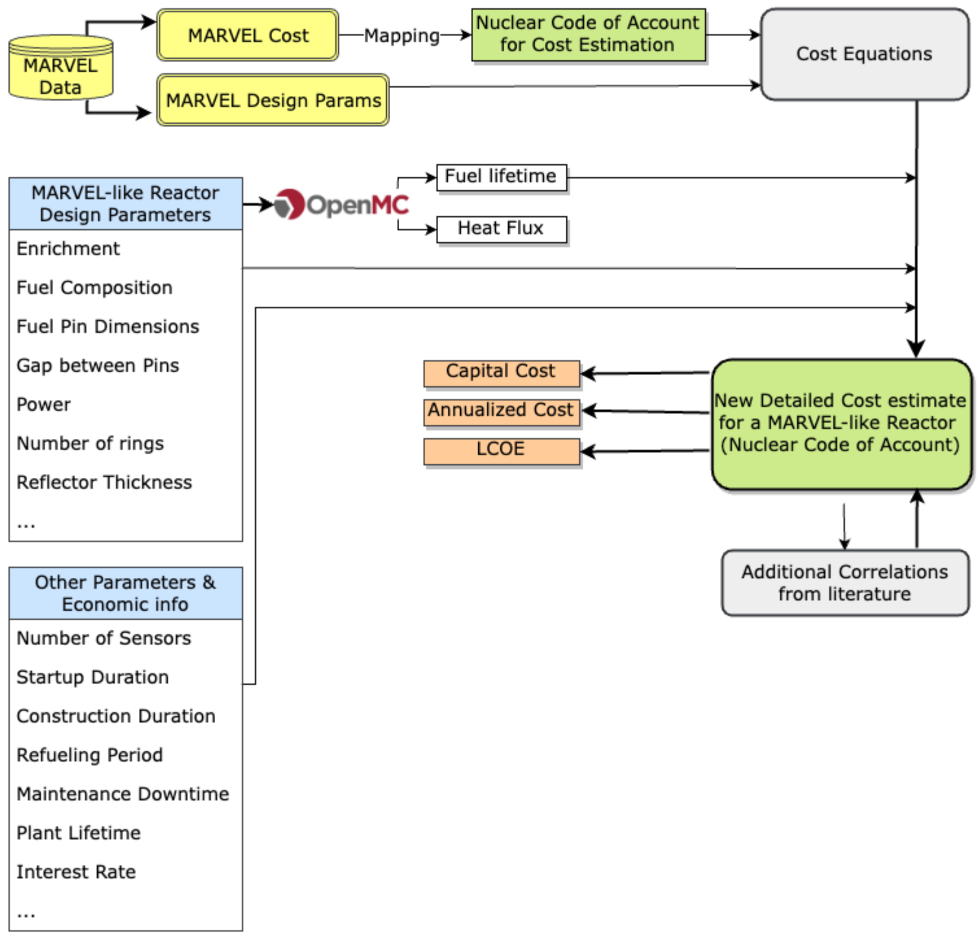

Figure 23. Neutronics-Economics Framework: Leveraging the MARVEL microreactor project data and coupling OpenMC (neutronics) with cost equations (economics) to estimate the capital cost, annualized cost, and LCOE of an LMTR reactor.

5.2. Parametric Studies of Design Considerations

In this section, we examine the impacts of design changes on economic figures of merit, such as TCI (Total Capital Investment) and LCOE (Levelized Cost of Electricity). These parametric studies are facilitated by a new tool that integrates neutronic analysis (conducted in OpenMC) with cost equations using the framework shown in Figure 23. An example of a parametric study using this tool is illustrated in Figure 24, which demonstrates the effect of reactor power on economic performance metrics. As depicted in Figure 24 increasing reactor power from 1 MWe to 7 MWe results in a significant extension of the refueling interval (or fuel lifetime), extending it by approximately 100 years for the same core design (with the same amount of fuel and 20 wt% enrichment). As anticipated, higher-power reactors are more economical. Specifically, increasing the power to 7 MWe reduces the levelized capital cost ($/kW) by a factor of 20, bringing it down to about $22,000/kWe. This power increase (from 1 MWe to 7 MWe) also lowers the LCOE from $4,000/MWh to less than $340/MWh.

Another parametric study examines the impact of enrichment on reactor cost (see Fig Figure 25). Increasing the enrichment from 5% to 20% extends the refueling interval by more than 5 years. Although this higher enrichment raises the capital cost by approximately 5%, it significantly reduces the levelized annualized cost ($/MWh) by a factor of 15. Consequently, the LCOE decreases from around $3,000/MWh to $325/MWh. These analyses are intended to showcase the flexibility of the framework developed. Other parametric studies that can be conducted to design variables range from the number of fuel pins to the reflector thickness, to operational considerations. These are left for future work.

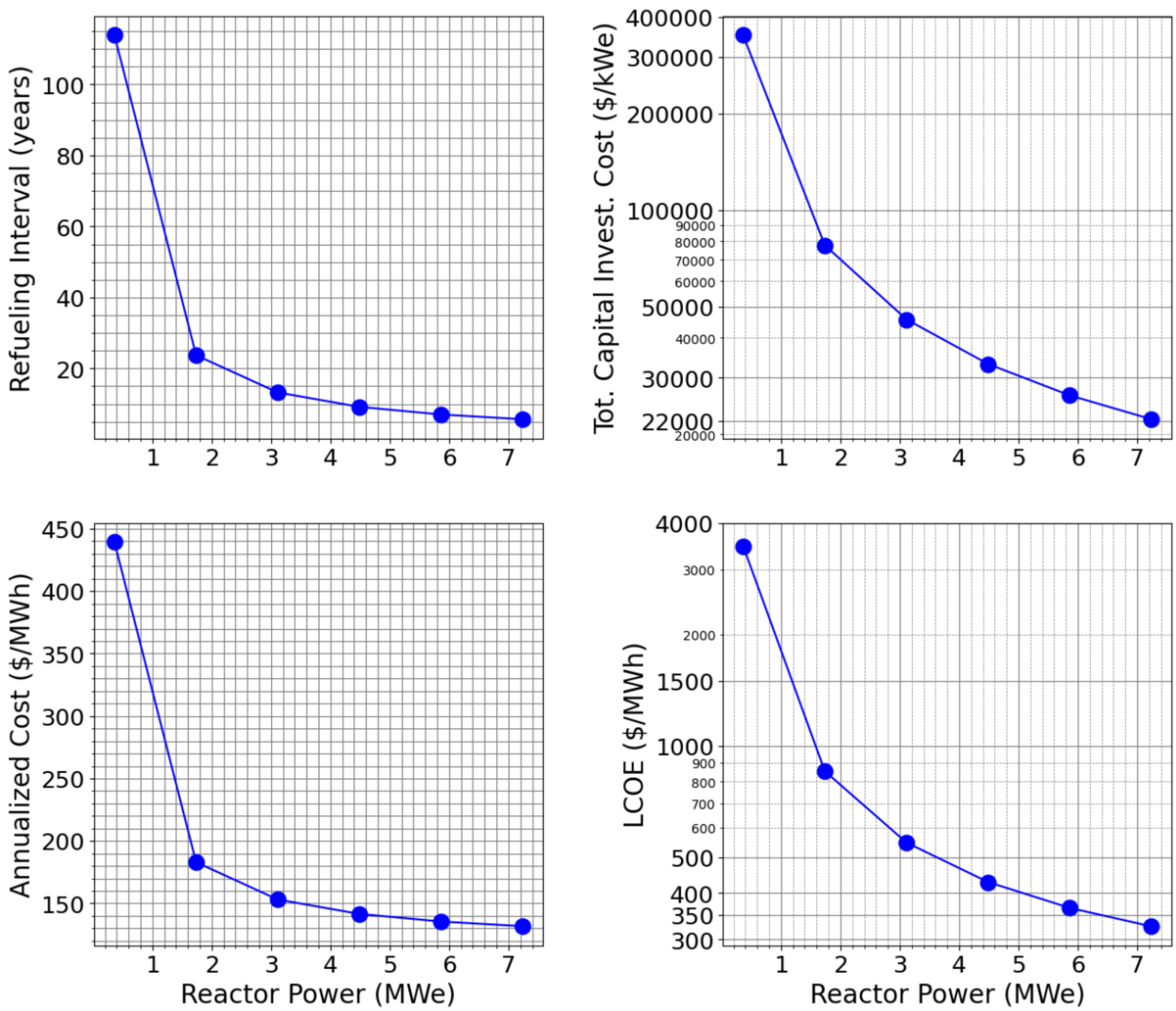

Figure 24. Economic figures of merit dependence on the reactor power.

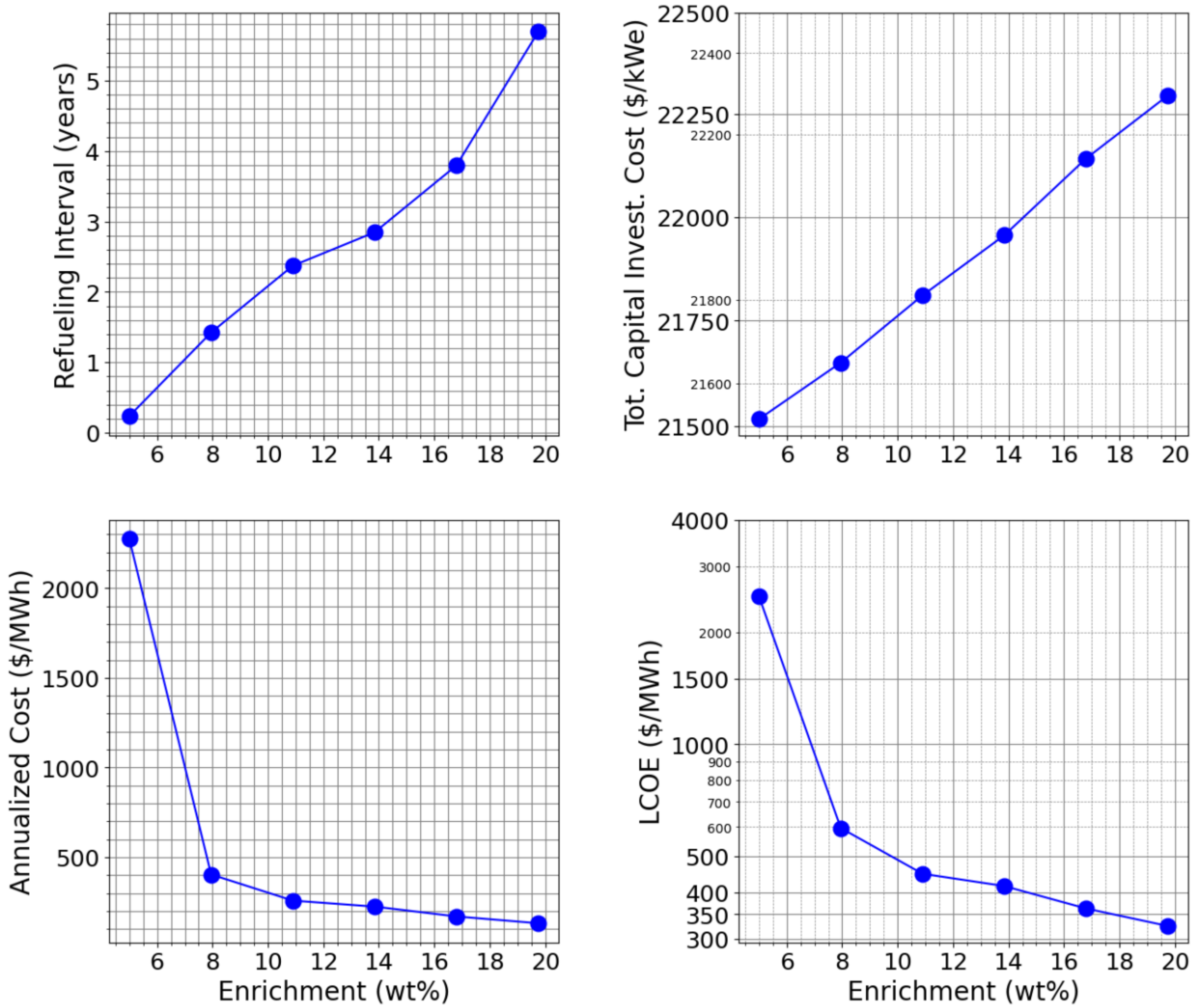

Figure 25. Economic figures of merit dependence on enrichment.

5.3. Impact of Mass Production

Microreactors are planned to be factory produced, and their economics can be improved by applying mass production. Additionally, microreactors offer a simplicity in their plant design, allowing for ease of construction. This work attempts to capture the factory fabrication and learning effects on the LMTR-20 LCOE.

To capture how mass production might influence the LMTR-20, a factory production of 10 reactor units per year is assumed. This assumption follows the work of Abou-Jaoude (2023), in which the influence of mass production on factory-fabricated microreactor equipment is assessed. The publication stated that equipment produced through factory-fabricated mass production would cost 30% than non-mass-produced equipment. To consider the influence of mass production on the LMTR-20, a multiplier of 30% was applied to accounts with factory-fabricated equipment. In addition, it is assumed that fuel can be mass produced for microreactors, and the same multiplier (i.e., 30%) was applied to account 254, which corresponds to the first core fuel assembly fabrication. Table 13 is a summary of the accounts to which the factory fabrication was applied.

To capture the influence of learning on construction activities of LMTR-20, the learning rate equation was applied to estimate the NOAK cost compared from the reference FOAK costs.

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

where LR is the learning rate, and N is the total number of constructed units. In studying the influence of learning on the LMTR-20, 8% and 20 units are assumed for LR and N, respectively. The learning rate value is based on the recommendation of Abou-Jaoude et al. (2024) for large reactor learning rates. The factor $(1 - LR)^{\log_2 N}$ is calculated to be ~70%, which as applied as a multiplier to the cost of site activities for the LMTR-20. Table 13 summarizes the accounts to which the learning rate model was applied.

Table 13. Overview of adjustment factors for a mass-produced version of the LMTR-20.

Account	Mass Production Multiplier Type	Multiplier Value
214.7, 221.11, 221.12, 221.13, 221.21A, 221.B, 222.1A, 222.1B, 222.2, 222.3A, 222.3B, 223.2A, 223.2B, 227A, 227B, 232.1, 24, 254, 26, 31, 82	Factory-production rate	0.3
212A, 212B, 32, 33, 35, 36	On-site learning	0.7
11, 15, 221.21C, 221.21D, 221.31, 221.31, 221.32, 251, 252, 253, 34, 41, 62, 71, 75, 78, 81, 83	None	1.0

Based on these assumptions, the cost for mass-produced microreactors can be estimated. Applying the multipliers shown above, the results in Table 14 were obtained. The mass-produced microreactor is referred to as an NOAK estimate for convenience. An OCC reduction of 57% was calculated by shifting to an assembly-line production that deploys 10 microreactors per year. Similarly, the O&M costs drop by 62% for the NOAK case.

Table 14. Cost adjustment for mass-produced microreactors.

Account ID	**Account Title**	**First-of-a-Kind Estimated Cost (2023 USD)**	**NOAK Estimated Cost (2023 USD)**
10	**Capitalized Pre-Construction Costs**	**5,218,748**	**5,218,748**
11	**Land Cost**	**1,888**	**1,888**
15	**Plant Studies**	**5,216,860**	**5,216,860**
20	**Capitalized Direct Costs**	**131,318,910**	**48,271,430**
21	**Structures and Improvements**	**11,246,430**	**7,872,501**
212	Reactor Island Civil Structures	5,182,025	3,627,418
212A	Pit preparation (coordination and mods)	2,851,662	1,996,163
212B	Reactor silo (concrete)	153,863	107,704
212C	Reactor Building	2,176,500	1,523,550
214	Buildings to Support Main Function	6,064,405	4,245,083
214.7	Emergency and Start-up Power Systems	6,064,405	4,245,083
22	**Reactor Components**	**63,899,534**	**19,169,860**

221	Reactor vessel and accessories	50,552,239	15,165,672
221.1	Reactor vessel and accessories	5,967,943	1,790,383
221.11	Reactor support	901,784	270,535
221.12	Outer vessel structure	606,970	182,091
221.13	Inner vessel structure	4,459,189	1,337,757
221.2	Reactor control devices	10,773,911	3,232,173
221.21	Reactivity control system	10,773,911	3,232,173
221.21A	Reactivity Control System Fabrication	1,294,603	388,381
221.21B	Installation	322,663	96,799
221.21C	Control Drums (B4C)	750,015	225,005
221.21D	Control Drums (BeO)	8,406,630	2,521,989
221.3	Non-fuel core internals	33,810,385	10,143,116
221.31	Reflector	5,584,965	1,675,490
221.32	Shield	28,225,420	8,467,626
221.32A	In vessel shield (B4C)	28,143,420	8,443,026
221.32B	Out the vessel shield (WEP)	82,000	24,600
222	Fluid circulation drive system (pumps	9,461,903	2,838,571
222.1	Fluid circulation drive system (pumps	64,903	19,471
222.1A	Primary pumps	33,764	10,129
222.1B	Secondary pumps	31,139	9,342
222.2	Reactor Heat Transfer Piping System	181,000	54,300
222.3	Heat Exchangers	9,216,000	2,764,800
222.3A	Immediate heat exchanger	3,072,000	921,600
222.3B	Nak to Air heat exchanger	6,144,000	1,843,200
223	Reactor Cavity Cooling System	298,242	89,473
223.2	Reactor Cavity Cooling System	298,242	89,473
223.2A	RVACS (Cooling Vessel)	145,908	43,772
223.2B	RVACS (Intake Vessel)	152,334	45,700
227	I&C baseline cost	3,587,150	1,076,145
227A	I&C baseline cost	1,897,450	569,235
227B	I&C autonomous control	1,689,700	506,910
23	**Energy Conversion System**	**17,646,219**	**5,293,866**
232	Energy Applications	17,646,219	5,293,866
232.1	Electricity Generation Systems (turbines)	17,646,219	5,293,866
24	**Electrical Equipment**	**33,657**	**10,097**
25	**Initial Fuel Inventory**	**37,493,070**	**15,625,107**
251	First Core Mining	2,701,672	2,701,672
252	First Core Conversion	221,713	221,713
253	First Core Enrichment	3,329,737	3,329,737
254	First Core Fuel Assembly Fabrication	31,239,948	9,371,985
254A	Fuel Production and Procurement	30,422,799	9,126,840
254B	Other related activities	817,149	245,145
26	**Miscellaneous Equipment (cranes)**	**1,000,000**	**300,000**

30	**Capitalized Indirect Services Cost**	**6,532,223**	**4,198,487**
31	**Factory & Field Indirect Costs**	**1,656,640**	**496,992**
32	**Factory & Construction Supervision**	**291,572**	**204,100**
33	**Startup Costs**	**2,407,166**	**1,685,016**
34	**Shipping and Transportation Costs**	**961,957**	**961,957**
35	**Engineering Services**	**797,929**	**558,550**
36	**PM/CM Services**	**416,959**	**291,871**
60	**Capitalized Financial Costs**	**17,883,735**	**2,411,386**
62	Interest	17,883,735	2,411,386
70	**Annualized O&M Cost**	**1,659,884**	**887,634**
71	**O&M Staff**	**506,957**	**506,957**
711	Operators	16,082	16,082
712	Remote Monitoring Technicians	44,625	44,625
713	Security Staff	446,250	446,250
75	**Capital Plant Expenditures**	**815,794**	**244,738**
78	**Annualized Decommissioning Cost**	**337,132**	**135,939**
80	**Annualized Fuel Cost**	**6,315,425**	**1,941,233**
81	**Refueling Operations**	**5,973**	**5,973**
82	**Additional Nuclear Fuel**	**6,248,845**	**1,874,654**
83	**Spent Fuel Management**	**60,607**	**60,607**
OCC		**143,069,881**	**57,688,665**
OCC($/kw)		**19,761**	**7,968**
OCC excluding initial fuel load cost ($/kW)		**14,582**	**5,810**
TCI ($)		**160,953,616**	**60,100,052**
TCI ($/kW)		**22,231**	**8,301**
Annualized Cost ($)		**7,975,308**	**2,828,867**
Annualized Cost ($/MWh)		**132**	**47**
LCOE ($/MWh)		**325**	**119**

Mass producing the LTMR concept leads to an overall reduction of the LCOE by 61% to $146/MWh. While this generation cost is more elevated than production costs for the U.S. grid, it is in line with retail prices. If microreactors are able to bypass the grid and provide electricity directly to industry users at these price points, they can be expected to compete beyond narrow niche markets where prices are exceedingly elevated. To assess the economic competitiveness of the LMTR-20 microreactor, the FOAK and NOAK costs (LCOEs) are compared with wholesale electricity prices (EIA 2023) and retail prices (EIA 2022), as shown in Figure 26 and Figure 27.While both FOAK and NOAK costs are relatively high compared to the average wholesale electricity price, the NOAK LCOE may be competitive with electricity prices in some states. Compared to the retail price, the NOAK cost matches the median price while the FOAK cost maybe acceptable in remote markets. While it remains unclear if microreactors may be able to sell electricity at a retail level (both from a nuclear and electricity market regulatory perspective), the analysis does indicate that there is potential value in microreactor deployment beyond niche applications.

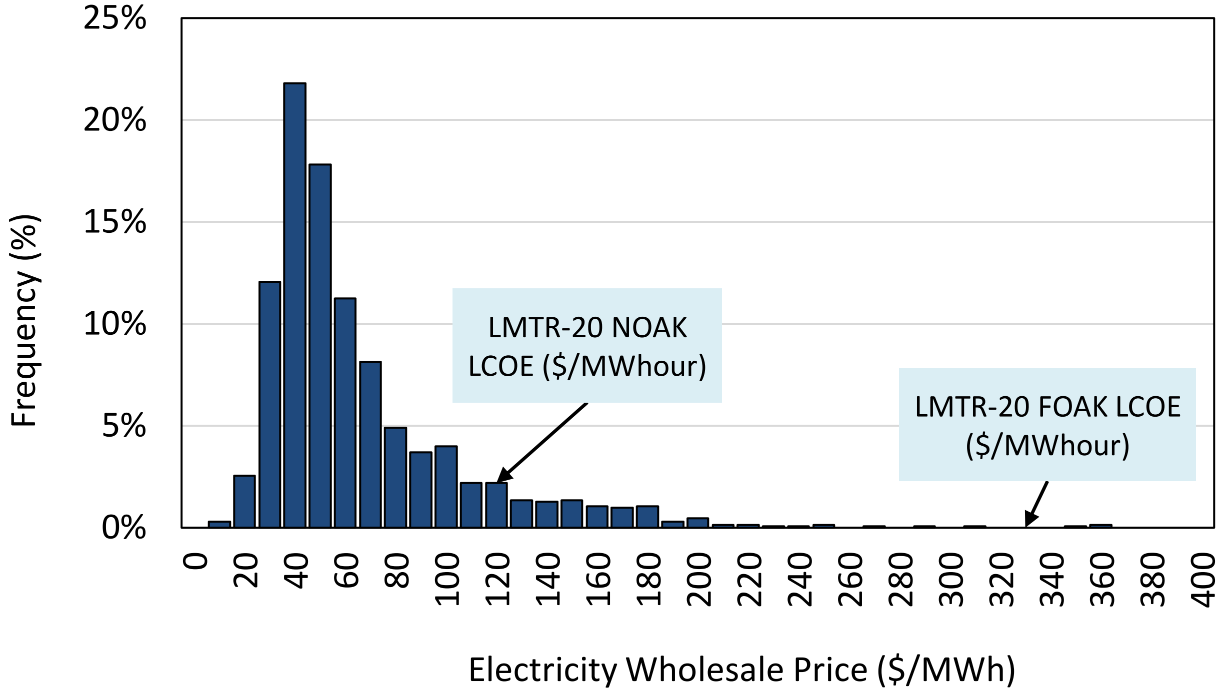

Figure 26. The LCOE of the LMTR-20 FOAK and NOAK reactor compared to the wholesale electricity price distribution (in 2023).

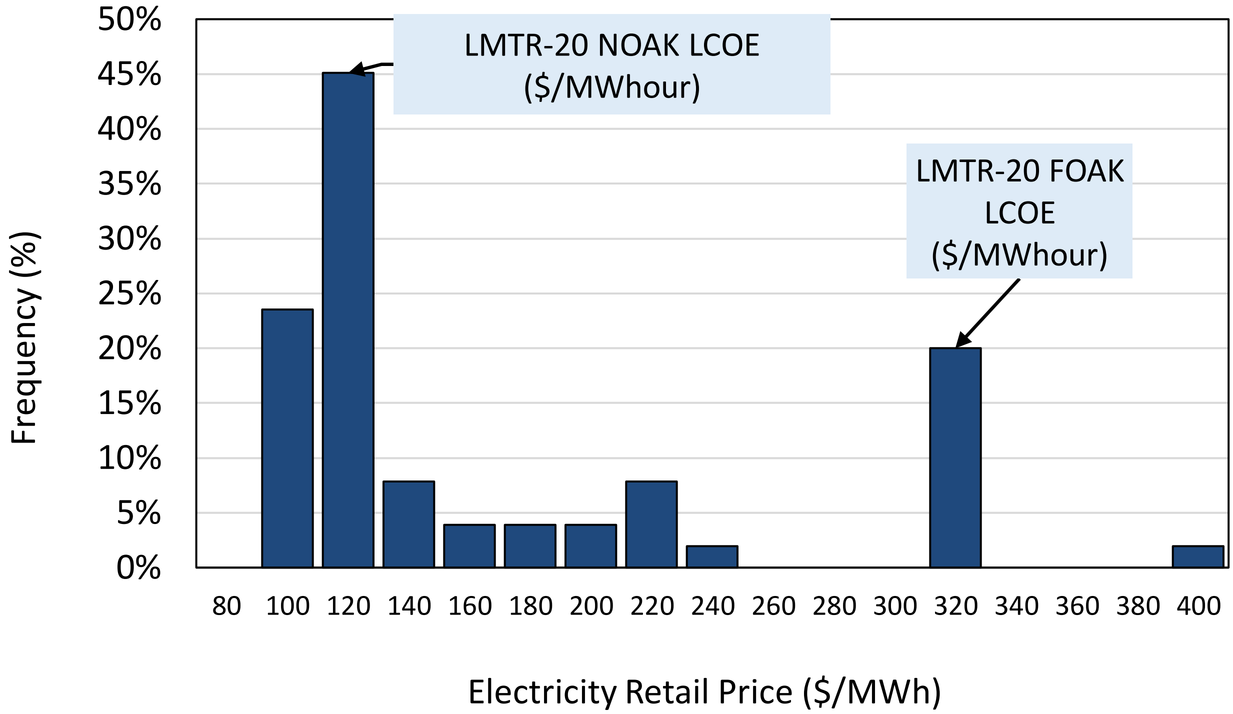

Figure 27. The LCOE of the LMTR-20 FOAK and NOAK reactor compared to the retail electricity price distribution.

For the LMTR-20 NOAK reactor, the cost breakdown (in Figure 28 and Figure 29) is similar to that of the FOAK reactor (in Figure 21 and Figure 22), with direct costs and fuel costs being the primary cost drivers. However, for the NOAK reactor, the cost of interest becomes less significant due to the expected shorter construction duration, which reduces the overall cost of interest. In general, the biggest contributors to the costs are (in order): the annualized refueling costs, the reactor system, the initial fuel inventory, structures and buildings, operating staff, then energy conversion systems. This provides some targeted areas of focus for future cost reduction analyses.

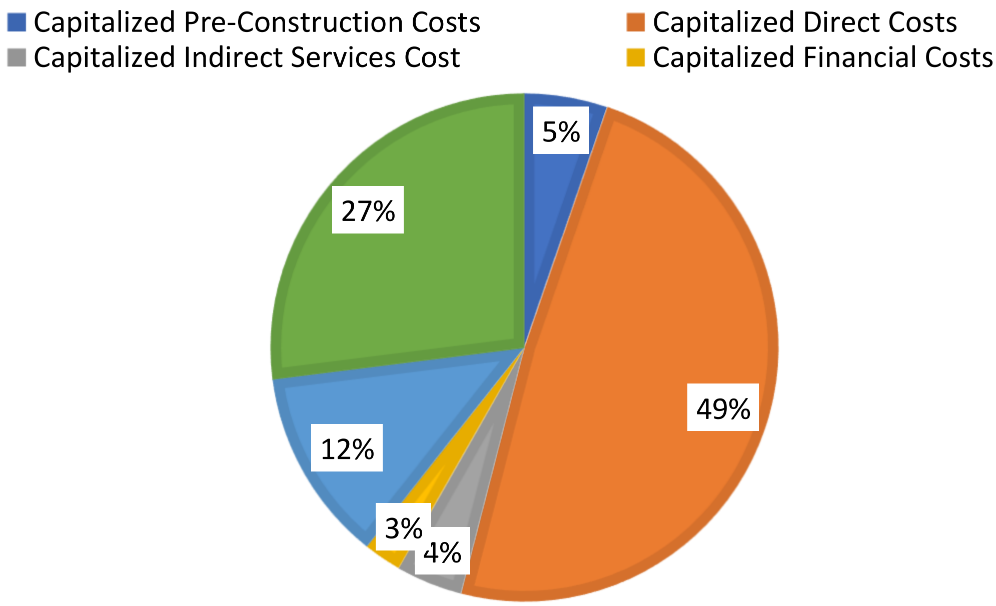

Figure 28 LMTR-20 NOAK levelized Cost ($/MWh) Breakdown. The contribution of each cost to the LCOE is presented as a percentage.

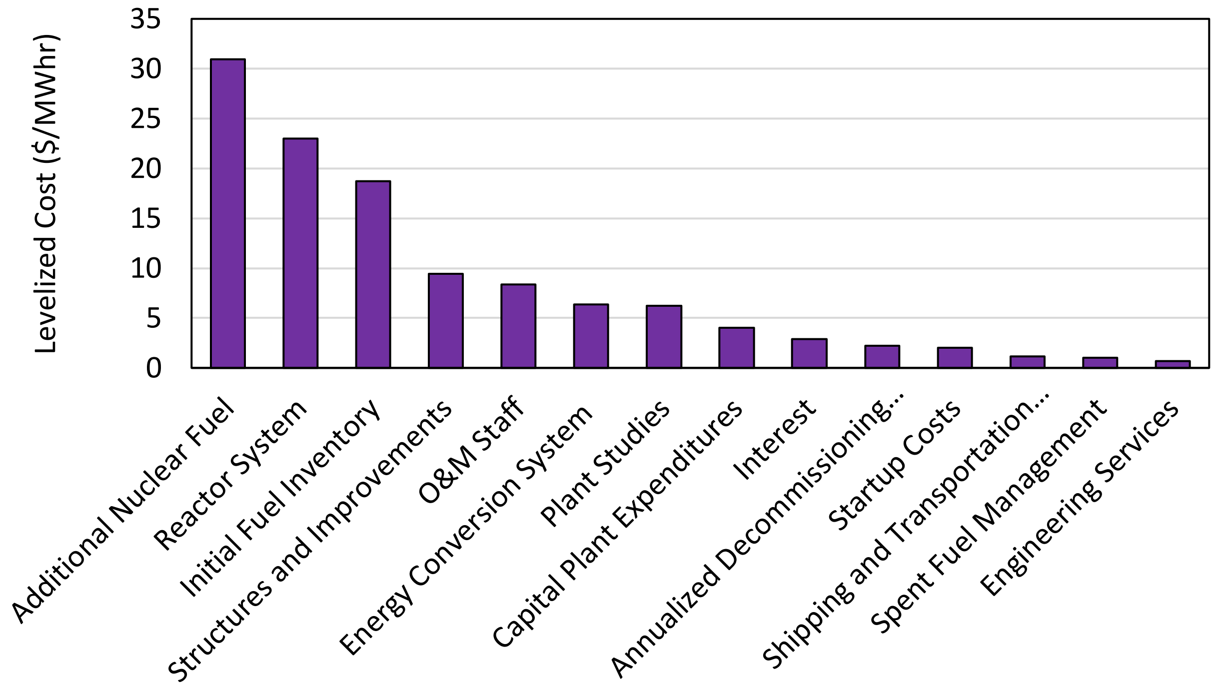

Figure 29. NOAK LMTR-20 Cost drivers.

6. CONCLUSION

This report developed a detailed and transparent technoeconomic model for a commercially representative microreactor. The Microreactor Applications Research, Validation, and EvaLuation (MARVEL) demonstration was used as a starting point because detailed design information was readily available alongside a comprehensive cost estimate. All the data obtained from the MARVEL program were laid out and transposed to a Code of Account framework. This MARVEL cost estimate is expected to be an invaluable database for stakeholders to leverage for subsequent technoeconomic assessments.

Because the MARVEL reactor was never intended to be commercially viable, an economics-by-design approach was followed to devise new reactor specifications based on the demonstration. For that reason, a holistic framework was developed that can link physical constraints to economic considerations. The starting point for the framework is a simplified OpenMC model for evaluating the reactor physics considerations of potential design changes (e.g., fuel inventory needs, depletion calculations, impact of moderators). The framework was augmented with thermal hydraulics considerations to spec the balance of plant components and ensure that the design configuration operates within reasonable limits (namely fuel burnup and average pin power limits). Then, simplistic shielding calculations were performed to project soil doses at the end of life and quantify the required level of shielding in the reactor. CAD models and 2D plant layouts were then built to ensure that physical constraints were met. While the analysis is not comprehensive, it provides some assurances that the considered design configurations are bound by physical constraints. Using these tools, a new reference reactor design, the Liquid-Metal Thermal Reactor (LMTR)-20, was established.

The next step in the analysis was to develop detailed bottom-up cost estimates for the design variant. Cost equations were formulated primarily based on MARVEL data. For instance, vessel costs were normalized per unit mass and the LMTR-equivalent costs were adjusted based on this consideration. Cost components that are missing from the MARVEL estimate (e.g., land costs, structure costs) were estimated using the assumptions outlined in this report. It is important to note that regulatory and operational requirements are still unclear at this phase, and the assumptions should be viewed as best estimates. Using the derived cost correlations, a detailed breakdown of the projected cost for the LMTR-20 was generated. This should be interpreted as the cost for a well-executed first-of-a-kind reactor. The new model is expected to prove useful for energy-mix models and microgrid assessments that are interested in considering the technoeconomics of microreactors.

Lastly, the reference LMTR-20 cost models were leveraged to conduct parametric studies and project Nth-of-a-kind costs for a mass-produced reactor. With the physics-economics framework, it becomes easy to conduct sensitivity analyses to evaluate the impact of design variables on cost. For instance, reducing the reactor power output by half led to around 50% increase in the levelized costs of electricity. Also, increasing the enrichment from 5 to 19.75% reduces the LCOE by a factor of 15.

To then evaluate Nth-of-a-kind costs for the reference model, the findings from a previous study on microreactor mass production was used. The study estimated that a dedicated assembly line producing 10 units per year would result in a 70% cost reduction compared to a stick-built design. Based on this (and assuming a more modest learning rate for site-based activities), a levelized cost of energy in the ~$150/MWh range was deemed achievable. While this generation cost is relatively high, by virtue of their size, microreactors can be envisaged to be directly embedded with end users. If possible, from a regulatory standpoint, this would enable selling electricity at retail levels, bypassing the grid and associated transmissions costs. At these costs of electricity, microreactors can be expected to be more broadly competitive beyond remote markets and could have the potential to upend energy economics more broadly. However, several legal and regulatory hurdles would need to be overcome before this could be implemented.

In summary the report provided four key outputs that are expected to be invaluable to Department of Energy Microreactor Program stakeholders:

- A tabulated cost estimate for the MARVEL microreactor demonstration
- A framework linking physics-based tools (including OpenMC) to cost estimation algorithms for technoeconomic analysis and optimization
- A transparent detailed technoeconomic model for a reference microreactor design (LMTR-20) that can be used in energy-mix models
- A cost projection for commercial microreactors that indicates that this class of nuclear reactor may be able to compete beyond niche applications.

Future work can be expected to further refine the analysis conducted here. Namely, several approximations in the reactor physics and shielding models could be refined further. The impact of fuel cost (e.g., alternate fabrication approaches, higher burnup configurations), in particular, should be investigated further in light of its large contribution to total cost. Refueling costs were also not robustly captured and could be more refined. Thermal hydraulics calculations could be performed with a dedicated tool (e.g., one from the Nuclear Energy Advanced Modeling and Simulation program) and account for transient scenarios that can impact design specifications. A source term model could also help inform technoeconomic trade-offs between the required number of barriers versus the power output and land size of a microreactor. The software that was built to couple reactor physics analysis with cost considerations could be refined further and released publicly. Lastly, the framework used here could be expanded to also consider different design variants that are more actively being pursued by the private sector (e.g., heat-pipe-based designs, or TRISO-fueled concepts). This would provide a useful capability for vetting different design options for certain applications and help better guide the research-and-development priorities in the Microreactor Program toward the most promising technological innovations from an economics standpoint.

7. REFERENCES

AACE. 2020. "Cost Estimate Classification System - As Applied in Engineering, Procurement, and Construction for the Process Industries: Recommended Practice No. 18R-97." American Association of Cost Estimators International.

Abou-Jaoude, A., et al. 2023. "Assessment of Factory Fabrication Considerations for Nuclear Microreactors." *Nuclear Technology*, 209 (11): 1697–1732. https://doi.org/10.1080/00295450.2023.2206779.

Abou-Jaoude, A., Y. Arafat, A. Foss, and B. Dixon. 2021. "An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept." INL/EXT-21-63067, Rev. 000, Idaho National Laboratory, Idaho Falls, Idaho. https://doi.org/10.2172/1811894.

Abou-Jaoude, Abdalla, et al. *Meta-Analysis of Advanced Nuclear Reactor Cost Estimations*. No. INL/RPT-24-77048-Rev001. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2024.

Brown, D. A., et al. 2018. "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data." *Nucl. Data Sheets*, 148: 1–142. doi: 10.1016/j.nds.2018.02.001.

Buongiorno, J., B. Carmichael, B. Dunkin, J. Parsons, and D. Smit. 2021. "Can Nuclear Batteries Be Economically Competitive in Large Markets?" *Energies*, 14: 4385. https://doi.org/10.3390/en14144385.

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

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

DOE, *Combined Heat and Power Technology Fact Sheet Series*. 2016, U.S. Department Of Energy

EIA. *US Electricity Profile 2022*. 2022; Available from: https://www.eia.gov/electricity/state/.

EIA. *Wholesale Electricity and Natural Gas Market Data*. 2023; Available from: https://www.eia.gov/electricity/wholesale/.

Finch, B., *MARVEL Demonstration Project/ INL Project Number: 33526*, in *Class-3 Cost Estimate*. 2024, Idaho National Laboratory.

Forsberg, C., A. Foss, and A. Abou-Jaoude. 2022. "Fission Battery Economics-by-Design." *Progress in Nuclear Energy*, 152: 104366. https://doi.org/10.1016/j.pnucene.2022.104366.

Froese, S., N. C. Kunz, and M. V. Ramana. 2020. "Too Small to Be Viable? The Potential Market for Small Modular Reactors in Mining and Remote Communities in Canada." *Energy Policy*, 144: 111587. https://doi.org/10.1016/j.enpol.2020.111587.

GA Technologies. 1987. "Safety Evaluation Report on High-Uranium Content, Low-Enriched Uranium-Zirconium Hydride Fuels for TRIGA Reactors." NUREG-1282.

Ganda, F., E. Hoffman, T. A. Taiwo, T. K. Kim, and J. Hansen. 2019. "Report on the ACCERT Cost Algorithms Tool." ANL/NSE-19/10.

Garcia, S., S. Bays, and B. Lindley. 2024. "Generic Sodium-Potassium-Cooled Thermal Microreactor Reference Design with Sizing-Burnup Tradeoff Study." in *Nuclear Power Plants: Other Advanced Reactors*, Las Vegas, NV: American Nuclear Society, June: 226–235. doi: doi.org/10.13182/T130-44230.

Gateau, E., N. Todreas, and J. Buongiorno. 2024. "Consequence-Based Security for Microreactors." *Nuclear Engineering and Technology*, 56: 1108–115.

Gerstner, D., and Y. Arafat. 2023. "MARVEL 90% Final Design Report." INL/RPT-23-74280, Idaho National Laboratory, Idaho Falls, ID, doi: 10.2172/2208844.

Gezelius, Knut. Design of compact intermediate heat exchangers for gas cooled fast reactors. Diss. Massachusetts Institute of Technology, 2004.

Hanna, B., and A. Abou Jaoude. 2023. "Microreactor Cost Estimation Incorporating MARVEL Information." INL/RPT-23-03702, Idaho National Laboratory, Idaho Falls, Idaho.

Hashemian, H. M. "Nuclear power plant instrumentation and control." *Nuclear Power–Control, Reliability and Human Factors, InTech* (2011): 49-66.

Keiser Jr., D., et al. 2023. "Post Irradiation Examination of a Uranium-Zirconium Hydride TRIGA Fuel Element." *Frontiers in Energy Research*, 11: 1106601.

Lichtenberger, H. V., et al. Experimental Breeder Reactor (Progress Report, April 1, 1951 Through January 31, 1953). No. ANL-5023. Argonne National Lab.(ANL), Argonne, IL (United States), 1953.

Lee, Youho, and Jeong Ik Lee. "Structural assessment of intermediate printed circuit heat exchanger for sodium-cooled fast reactor with supercritical CO2 cycle." Annals of Nuclear Energy 73 (2014): 84-95.

Leppänen, J., M. Pusa, T. Viitanen, V. Valtavirta, and T. Kaltiaisenaho. 2015. "The Serpent Monte Carlo Code: Status, Development And Applications in 2013." *Ann. Nucl. Energy*, 82: 142–150. https://doi.org/10.1016/j.anucene.2014.08.024.

Lovering, J. 2023. "A Techno-Economic Evaluation of Microreactors for Off-Grid and Microgrid Applications." *Sustainable Cities and Society*, 95: 104620. https://doi.org/10.1016/j.scs.2023.104620.

Moore, M., P. Sanongboon, D. Zekveld, J. Abols, A. Siddiqui, and C. Deir. 2021. "Small Modular Reactor (SMR) Economic Feasibility and Cost-Benefit Study for Remote Mining in the Canadian North: a Case Study Ashlea Colton on Behalf of Megan Moore." Ontario Power Generation, Canadian Nuclear Laboratories (CNL), MIRARCO, Mining Partner.

Nuclear Energy Institute. 2019. "Cost Competitiveness of Micro-Reactors for Remote Markets." April. https://www.nei.org/resources/reports-briefs/cost-competitiveness-micro-reactors-remote-markets.

Patterson, M. W. 2024. "Breakdown of Cost and Scope Growth through 90% Final Design." INL/RPT-24-14160, Idaho National Laboratory, Idaho Falls, Idaho.

Robert, D., A. Horwood, M. Philips, S. Bays, and T. Knight. 2024. "Activation Analysis of Soils and Materials Under Small Transportable Reactors with Severe Shielding Weight Restrictions," in *Portable and Propulsion Reactors*, Las Vegas, NV: American Nuclear Society, 483–92.

Romano, P. K., et al. 2015. "OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development." *Annals of Nuclear Energy*, 82: 90–97.

Roosen, P., S. Uhlenbruck, and K. Lucas. 2003. "Pareto Optimization of a Combined Cycle Power System as a Decision Support Tool for Trading Off Investment vs. Operating Costs." *International Journal of Thermal Sciences*, 42 (6): 553–60.

Shirvan, K., et al. 2023. "UO2-Fueled Microreactors: Near-Term Solutions to Emerging Markets." *Nuclear Engineering and Design*, 412: 112470. https://doi.org/10.1016/j.nucengdes.2023.112470.

Shropshire, D., and B. Geoffrey. 2021. "Global Market Analysis of Microreactors." INL/EXT-21-63214, Idaho National Laboratory, Idaho Falls, Idaho.

Stewart, W. R., and K. Shirvan. 2022. "Capital Cost Estimation for Advanced Nuclear Power Plants." *Renewable and Sustainable Energy Reviews*, 155: 111880.

Subramanian, D. V., A. Haridas, D. S. Kumar, A. J. Arul, and P. Puthiyavinayagam. 2018. "Neutron Attenuation Studies with Borated Polyethylene Slabs Containing 30% Natural Boron and Its Comparison with Hydrogenous Materials." *Indian J. Pure Appl. Phys.*, 56 (8): 583–86.

World Nuclear Association. 2023. "Economics of Nuclear Power." World Nuclear Association. Updated September 29. https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power#:~:text=Decommissioning%20costs%20are%20about%209,less%20to%20the%20generation%20cost.