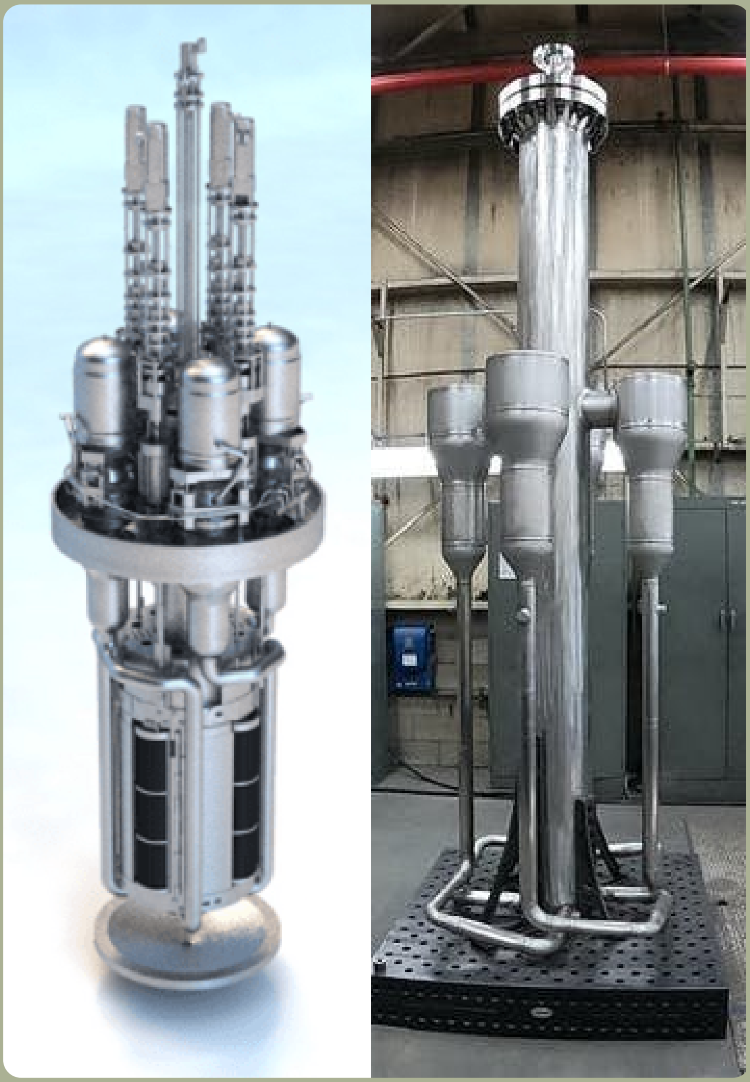
Nuclear Microreactors: Potential for Satisfying Advanced Nuclear Research Needs and Providing Low-Carbon Energy for WPI



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WPI

Nuclear Microreactors: Potential for Satisfying Advanced Nuclear Research Needs and Providing Low-Carbon Energy for Campus

An Interactive Qualifying Project

Submitted To:
The Faculty of Worcester Polytechnic Institute
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Abstract

This report addresses the technical, regulatory, economic, and political feasibility of deploying the MARVEL nuclear microreactor (MR) at Worcester Polytechnic Institute (WPI) for nuclear research and low-carbon energy. We evaluate MARVEL's technology, WPI's energy needs, infrastructure capabilities, and research priorities to determine suitability and potential benefits. An economic analysis examines costs, savings, and funding opportunities. Safety considerations, including radiation, waste, and emergency preparedness, are rigorously assessed against regulations and standards. The report provides recommendations on the viability, challenges, and implications of MR implementation to inform WPI's energy planning and research endeavors while prioritizing environmental sustainability goals.

Acknowledgements

We are immensely thankful to our advisors, Professors Derren Rosbach, PhD, and David Medich, PhD, for their invaluable guidance, unwavering support, and open communication throughout the duration of this project. Their consistent willingness to provide assistance and meaningful insights made the past six weeks a truly enriching experience.

We would also like to express our sincere appreciation to Omer Rona, a team member who made valuable contributions but was unable to finish the project with us. As well as all our interviewees, namely Norbert Hugger, Professor David Adams, a representative of WPI Facilities, and a representative for the Nuclear Regulatory Commission. Their contributions and insights were invaluable to the success of this project.

Our gratitude also extends to the members of the WPI Green Team and the Office of Sustainability, who kindly incorporated us into their events, allowing us to interact with the community during WPI sanctioned events. Furthermore, we would like to thank all the individuals from the WPI community who were willing to take time from their day to provide their valuable insights and perspectives regarding micro reactors. Their input played a crucial role in shaping this project. Thank you all for your support and cooperation, which allowed this project to come to light.

Executive Summary

Project Statement

Our Interactive Qualifying Project (IQP) conducts a comprehensive analysis of the technical, regulatory, economic, and political feasibility of deploying the cutting-edge MARVEL microreactor at WPI. This report leverages the work of previous IQPs, insights from existing research by Professor David Medich and Mr. Norbert Hugger, and new information obtained through various methods to explore the feasibility of deploying MARVEL. These preliminary assessments will provide a foundation to aid the deployment of MR technology at WPI.

Potential benefits of deploying MARVEL include creating new opportunities for advanced nuclear research and training aligned with WPI's academic mission, as well as reliable carbon-free electricity and heat to support sustainability goals. However, deploying a new type of reactor brings uncertainties that are carefully analyzed in the economic, infrastructure, and regulatory sections. By synthesizing technical evaluations, regulatory analysis, economic analysis, and community engagement strategies, the project delivers actionable recommendations on whether and how WPI can optimally pursue the deployment of MARVEL for advanced research and low carbon energy.

Introduction

Nuclear Microreactors promise opportunities for advanced nuclear research alongside low-carbon energy production. This study evaluates the technical, regulatory, economic, and political feasibility of deploying the MARVEL MR at WPI. MARVEL's potential benefits include reliable, low-carbon electricity and heat generation as well as opportunities for cutting-edge research and training. We assess potentially significant hurdles, including technical challenges, safety considerations, regulatory issues, economic costs and benefits, and political ramifications.

Our multifaceted analysis covers reactor design, siting, operations, and safety protocols; licensing pathways; cost assessments; public engagement strategies; environmental impact; and sustainability. Weighing advantages and challenges, this study offers recommendations on whether and how an MR could optimally serve WPI's needs for research capabilities, sustainable energy, and emissions reductions.

Objectives

The core objective of this study is to evaluate the technical, regulatory, economic, and political feasibility of deploying MARVEL at WPI for research purposes and for low-carbon energy, ultimately providing valuable recommendations. To this end, we identified five objectives:

1. Assess the technical feasibility of MARVEL in terms of research, power and safety.
2. Assess regulatory feasibility of deploying MARVEL for research and power with a class 104(c) license.
3. Analyze economic regulatory restrictions and Code of Accounts for MARVEL deployment.
4. Examine the political feasibility of deploying MARVEL.
5. Formulate recommendations addressing the viability, challenges, and implications of deploying an MR for energy and research, focusing on regulatory obstacles, facility and infrastructure requirements, and public engagement strategies.

Methods

To assess the feasibility of deploying MARVEL, we employed qualitative methods including literature reviews and regulatory analysis, expert interviews, and community surveys. We evaluated MARVEL's design, operation, safety, and potential for infrastructure integration through in-depth interviews with WPI's MARVEL research team, as well as a representative from the Department of Facilities, and WPI's Radiation Safety Officer (RSO).

The campus facility assessments identified necessary upgrades for siting and operating MARVEL. Regulatory feasibility centered on reviewing applicable state and federal regulations and legislation, with insights gained from an interview with an Nuclear Regulatory Commission (NRC) representative. Economic costs and benefits were analyzed by using an industry-standard Code of Accounts model and by assessing potential regulatory restrictions. Community engagement strategies examined public attitudes toward nuclear power through a photo response survey at campus events, research on local opinions regarding nuclear, and analysis of stakeholder backgrounds and policy positions.

Finally, technical details, feasibility evaluations, and community feedback were synthesized to formulate comprehensive recommendations for WPI regarding if and how to optimally pursue the MARVEL reactor for sustainable energy, research capabilities, and alignment with institutional goals.

Results and Discussion

Our technical assessment found that MARVEL's design incorporates inherent safety features like passive cooling capabilities and automated shutdown protocols that put the reactor in a secure inoperative state during emergencies or power disruptions. Stringent safety measures including robust shielding, personnel access controls, and comprehensive training programs would be required. While MARVEL's compact size is advantageous for siting, a new dedicated facility with concrete shielding would need to be constructed, likely requiring around three years for design, approvals, and construction. Its high neutron flux offers promising potential for cutting-edge research applications and hands-on nuclear training opportunities aligned with WPI's academic programs. MARVEL could provide minor, supplemental heating for campus by integrating its thermal output with existing steam distribution networks, though regulatory hurdles exist around connecting its electrical output to the local grid.

On the regulatory front, significant legal uncertainties remain around transporting an operational reactor, loaded with fuel, from the factory to campus. WPI could pursue a Class 104 (c) license but may encounter regulatory economic restrictions on revenue from energy sales. The forthcoming 10 CFR Part 53 regulations for Advanced Reactors (ARs) may indeed allow more flexibility. MARVEL is unlikely to violate the economic restrictions of the Class 104 license, though the applicability of many potential cost categories is unknown and requires a proper, more detailed economic analysis.

Public engagement efforts including a photo response survey at campus events revealed overwhelming majority support for deploying MARVEL, with more than 83% of participants either somewhat, or strongly, in favor. However, a small opposition of around 8.5% remained. Best practices from literature emphasize the importance of early, transparent, two-way communication tailored to stakeholder groups. Innovative tools such as virtual reality could aid public understanding. Building a physical mockup of the reactor facility could also serve as an effective visual and educational resource.

While our results demonstrate MARVEL's overall technical viability for providing carbon-free energy and research capabilities, there remain significant regulatory ambiguities, economic uncertainties, and political issues to resolve prior to deployment. Based on our findings we developed recommendations that inform both a full feasibility assessment and MARVEL's deployment.

Recommendations

Our recommendations outline a comprehensive approach for addressing the technical, regulatory, economic, and political issues we identified. The highest priority recommendations are:

1. Recommendation: find a Project Manager and search for a project management team.
   To ensure efficient, parallel progress during feasibility studies and deployment we strongly recommend the appointment of a centralized, experienced, and full-time Project Manager (PM) or PM team.
2. Recommendation: seek regulatory clarity from the NRC and INL
   The feasibility of deploying MARVEL and of using MRs to supply meaningful amounts of low-carbon energy to campus depends on resolving several regulatory issues and uncertainties. We strongly recommend their resolution.
3. Recommendation: fully characterize potential dangers of MARVEL
   MARVEL must be physically safe for Worcester Polytechnic Institute (WPI) to consider deploying it, not only for those in the Emergency Planning Zone, but for those living nearby. We recommend exploration of existing theoretical and computational safety analyses as well as ensuring access to experimental data upon its availability.
4. Recommendation: Develop strategies for gauging community perspectives on having MARVEL on campus
   Community perspectives are an important factor in deploying MARVEL, making strategies for building public awareness, trust, and acceptance important precursors to public engagement. We recommend conducting archival research to investigate any documented nuclear-related activities, public engagement efforts, or debates in the Worcester area to understand historical views of the local public toward nuclear technologies.

Conclusion

This study found MARVEL to be technically feasible for neutron research and power integration testing at WPI, given its high neutron flux and compact design. However, serious potential roadblocks exist regarding legal, economic, and political feasibility. Regulatory viability hinges on future policies around transporting operational reactors, as well as requirements around reactor revenue and manufacturing. An economic feasibility assessment requires characterizing unspecified costs against potential benefits and funding sources. Politically, community engagement is needed to properly gauge sentiments around deploying a nuclear reactor in Worcester.

Moving forward will require synchronizing technical progress with resolving feasibility roadblocks in parallel - identifying potential sites while finalizing shielding, initiating licensing while resolving regulatory hurdles, updating economic assessments as details emerge, and proactively addressing public perceptions. A dedicated team should comprehensively evaluate MARVEL's overall viability across all dimensions.

Even an unfavorable assessment provides valuable insights, while a positive outcome could pave the way for WPI to be a pioneer in sustainable, Gen. IV nuclear energy solutions. Diligent efforts toward MARVEL's responsible deployment align with WPI's sustainability commitments and leadership in innovative technologies.

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0.2 Acronyms

AC	Annualized Costs	55
AEA	Atomic Energy Act	24
AFC	Annualized Financial Costs	55
AOC	Annualized Operations and Maintenance (O&M) Cost	54
AOOC	Annual Owning and Operating Cost	26
AR	Advanced Reactor	4
ASC	Annualized Fuel Cost	54
BUA	Bottom-Up Analysis	28
BWR	boiling water reactor	18
CDC	Capitalized Direct Costs	29
CFC	Capitalized Financial Costs	83
CFR	Code of Federal Regulations	9
CIC	Capitalized Indirect Services Cost	29
COA	Code of Accounts	29
COC	Capitalized Owner's Cost	82
COL	Construction and Operating License	25
CP	Construction Permit	24
CPC	Capitalized Pre-Construction Costs	29
CSC	Capitalized Supplementary Costs	82
DC	Design Certification	26
DOD	Department of Defense	32
DOE	Department of Energy	27
DOT	Department of Transportation	27
DWM	Demilitarize Western Massachusetts (MA)	75
EMWG	Economic Modelling Working Group	29
EOL	end-of-life	
ER	Environmental Report	25
ESP	Early Site Permit	25
EPZ	Emergency Planning Zone	51

FOAK	first-of-a-kind	32
FPR	Fuel Performance Report	84
FSSP	Final Status Survey Plan	
FSSR	Final Status Survey Report	
G4	Gen. IV	
GECOA	Gen. IV International Forum Economic Modelling Working Group Code of Accounts	29
GIF	Gen. IV International Forum	29
HALEU	high-assay low-enriched uranium	19
HP	heat pipe	21
HWR	Heavy Water Reactor	18
I&C	instrumentation and controls	22
INL	Idaho National Laboratories	20
IQP	Interactive Qualifying Project	2
ITAAC	Inspections, Tests, Analyses, and Acceptance Criteria	25
LCoE	levelized cost of electricity	30
LCWNRF	Leslie C. Wilbur Nuclear Reactor Facility	62
LEU	low-encriched uranium	18
LWR	Light Water Reactor	56
MA	Massachusetts	13
MAPA	Massachusetts Peace Action	59
MARVEL	Microreactor Applications Research Validation and EvaLuation	20
MHA	Maximum Hypothetical Accident	76
MMR	Micro-Modular Reactor	44
MR	microreactor	16
MW	megawatt	31
NESEB	nonenergy services, or energy, or both	46
NEI	Nuclear Energy Institute	
NFFCWM	Nuclear Free Future Coalition of Western MA	59
NPP	nuclear power plant	27
NR	nuclear reactor	24

NRC	Nuclear Regulatory Commission	3
OECD	Organization for Economic Cooperation and Development	17
OL	Operating License	24
O&M	Operations and Maintenance	13
PM	Project Manager	5
PM/CM	Production and Construction Management	82
PUF	Production and Utilization Facility	24
PWR	Pressurized Water Reactor	18
PWR-12	PWR-12	30
R&D	research and development	19
REP	Regulatory Engagement Plan	
RR	Research Reactor	36
RSO	Radiation Safety Officer	3
SAR	Safety Analysis Report	25
SMR	Small Modular Reactor	21
SNM	Special Nuclear Material	83
TCIC	Total Capital and Investment Cost	30
TDA	Top-Down Analysis	28
TRIGA	Training, Research, Isotopes, General Atomics	20
UCS	Union of Concerned Scientists	59
UIUC	University of Illinois Urbana-Champaign	36
US	United States	21
USNC	Ultra-Safe Nuclear Corporation	44
VO&M	variable Operations and Maintenance	80
WP	White Paper	45
WPI	Worcester Polytechnic Institute	5

Chapter 1

Introduction

Addressing climate change while meeting growing energy demands requires exploring innovative, carbon-free power sources. Microreactors have emerged as a promising technology that could sustainably satisfy both energy needs and enable advanced nuclear research. This study conducts a comprehensive feasibility analysis to assess the technical, regulatory, economic, and political viability of implementing the MARVEL microreactor (MR) for sustainable, low-carbon energy for WPI.

Potential benefits of MARVEL include reliable, low carbon electricity and opportunities for cutting-edge nuclear science research and training. Deploying MARVEL, however, will require careful evaluation of potentially significant technical hurdles, regulatory issues, economic factors, political ramifications, and safety considerations.

Our technical analysis examines reactor design, siting requirements, and operation. Our consideration of federal and state regulations covers the nuances of current and future licensing pathways and frameworks. Our economic analysis comprehensively assesses potential costs and regulatory restrictions. Our research into public engagement strategies and public perceptions of nuclear spans literature and includes a photo response survey. As relevant, our study will analyse safety protocols, environmental impact, and sustainability.

By comprehensively weighing the advantages and challenges, our research can inform WPI's strategic energy vision and sustainability commitments. Our findings will offer concrete recommendations on if and how a MR could optimally serve WPI's interdependent needs for sustainable energy, advanced research capabilities, and carbon emission reductions.

Chapter 2

Background

2.1 Nuclear Power

Nuclear fission reactors harness immense energy by splitting uranium atoms apart. This controlled nuclear chain reaction produces heat that is typically harnessed to generate steam, to spin turbines, and create electricity (Breeze, 2017). The fission process begins when a neutron strikes and breaks apart a heavy atomic nucleus like uranium-235 or plutonium-239, releasing tremendous energy and additional neutrons to sustain the reaction (De Sanctis et al., 2016). Nuclear power offers potential benefits such as carbon-free electricity generation and energy security, especially for nations lacking fossil fuel resources. Synonymous with nuclear power's potential for energy, however, are concerns about radioactive waste disposal, abuse in military applications, and meltdowns like those at Chernobyl and Fukushima.

Between its benefits and drawbacks, the future of nuclear power remains uncertain. Issues with public perception, competition from renewables like solar and wind, and research into safer nuclear fusion technologies cloud its outlook. Indeed, from 2004 to 2013, global nuclear electricity generation declined from 2,738TWh (16% of total) to 2,478TWh (11%). In 2015 it was 2,441TWh, roughly 10% of worldwide electricity production. However, within Organization for Economic Cooperation and Development (OECD) countries, nuclear provided 19% of total electricity - nearly double the global share, underscoring divergent attitudes. Ultimately, nuclear power's trajectory depends on weighing its risks and benefits against those of other energy sources. Technological advances, policy decisions, and energy market dynamics will all shape nuclear's complex, evolving role in our transitioning global energy economy (Breeze, 2017).

2.2 Nuclear Reactors

Nuclear reactors are classified based on several criteria, primarily their design, fuel type, and purpose. An important design element is the coolant: Pressurized Water Reactors (PWRs) and boiling water reactors (BWRs) utilize water as both the coolant and neutron moderator, while Heavy Water Reactors (HWRs) rely on heavy water (Han and Zhong, 2024). Reactors are also distinguished by their fuel cycle – thermal reactors sustain fission using low-energy thermal neutrons, whereas fast reactors leverage high-energy fast neutrons. Furthermore, they are delineated by their core purpose, with power reactors dedicated to electricity generation and research reactors focused on scientific experimentation and radioisotope production. Each reactor type has presents unique advantages and challenges, creating a multifaceted landscape for nuclear energy applications.

Research reactors are smaller than power reactors, both physically and in terms of power output, typically ranging from a few kilowatts to around 100MW of thermal power. They have simpler designs, operate at lower temperatures, and require less fuel compared to large power reactors. However, many research reactors utilize highly enriched uranium fuel – up to 93% U-235 – raising nuclear proliferation concerns. A key application of research reactors is the production of the medical radioisotope technetium-99m through neutron irradiation of highly enriched uranium targets to generate molybdenum-99 as a fission product (of Sciences et al., 2016). Efforts are underway to transition from highly enriched to low-encriched uranium (LEU) targets and explore alternative molybdenum-99 production methods, including power reactors. Despite their modest size, research reactors play a vital role in radioisotope supply for nuclear medicine, as well as in training and scientific experimentation (of Sciences et al., 2016).

2.2.1 Microreactors

Nuclear MRs are very small reactors generally producing less than 50MWe ("Modular construction and overview on its potential advantages and constrains in the project management perspective", n.d.). These tiny reactors are being explored as a potentially nimble alternative to small modular reactors (50-300MWe) or massive conventional nuclear plants around 1,000MWe. Key prospective advantages include modular factory construction enabling faster, cheaper production, and rapid transportable deployment to remote sites or disaster zones ("Modular construction and overview on its potential advantages and constrains in the project management perspective", n.d.). Additionally, MRs offer greater energy resilience and independence for isolated military bases or off-grid communities. Some designs even propose inherently safer operations through passive cooling systems and infrequent refueling requirements.

However, significant technical and regulatory hurdles remain before MRs can become a commercial reality. A particular challenge is the limited availability of high-assay low-enriched uranium (HALEU) fuel required by many designs, which is not yet produced commercially. Use of HALEU also heightens nuclear security and weapons proliferation concerns (U.S. Government Accountability Office, 2020). Novel fuel compositions pose additional challenges around radioactive waste handling and disposal. Moreover, the regulatory framework needs to be revised or newly developed to adequately govern these radically smaller reactor designs. Protracted design certification timelines could further delay deployment (U.S. Government Accountability Office, 2020).

While the potential benefits are intriguing, there are some reservations about its safety and proliferation risks of spreading HALEU-fueled MRs, especially to unstable regions. Overall, MR technology remains nascent and has yet to be proven in testing and production. Substantial research and development (R&D), testing, and policy groundwork is required before any credible path to widespread deployment can be considered. Key logistical and security questions around managing a decentralized network of MRs must also be addressed through in-depth policy analysis and public discourse.

2.3 Current State and Design of Microreactors

2.3.1 Gen. IV microreactors

Fourth generation micro nuclear reactors have gained considerable attention due to their potential advantages over traditional large-scale nuclear reactors. The distinguishable Gen. IV criteria are passive safety and use of excess heat for other applications, increased efficiency, or reduction of long-term waste. A variety of designs have emerged, including molten salt reactors, high-temperature gas-cooled reactors, heat pipe-cooled reactors, and liquid metal-cooled reactors. Leading companies, such as Westinghouse, Oklo, Ultra-Safe Nuclear Corporation, Terrestrial Energy, and X-energy, are at the forefront of developing these technologies (Reyes-Ramírez et al., 2023).

Initially confined to research at national laboratories and universities, MRs are now increasingly being explored for commercial power generation applications. Potential use cases include providing power to remote communities, mining operations, military bases, industrial facilities, or as a backup power source in urban areas. Leading companies developing these MRs are actively working towards deploying their first micro reactor prototypes or demonstration units in the coming years, potentially as early as the late 2020s (Reyes-Ramírez et al., 2023).

Despite their potential advantages, micro nuclear reactors face challenges hindering widespread commercialization, including demonstrating their safety, security, and economic viability compared to other energy sources or larger nuclear reactors. Additionally, the regulatory framework for licensing and deploying these advanced reactors is still evolving, with organizations like the Nuclear Regulatory Commission (NRC) in the United States working to establish specific licensing processes.

2.3.2 The MARVEL Reactor

The Microreactor Applications Research Validation and EvaLuation (MARVEL) project, led by Idaho National Laboratories (INL), aims to develop an innovative, compact, Gen. IV MR for rapid demonstration of various technologies, applications, and capabilities (Hanna Bishara Hanna et al., 2023). With an anticipated lifetime of two to eight years, MARVEL will provide opportunities to conduct research in MR physics, operations, autonomous control systems, regulatory processes, and diverse applications like thermal storage, water purification, district heating, and grid integration (“INL’s microreactor: A MARVEL machine - Nuclear Engineering International”, n.d.).

Emphasizing rapid deployment and cost minimization, MARVEL’s design incorporates proven technologies and components (Hanna Bishara Hanna et al., 2023). The 100kWt (operated at 85 kWt) reactor employs a unique combination of innovative and proven engineering solutions. The core consists of 36 cylindrical Training, Research, Isotopes, General Atomics (TRIGA) HALEU zirconium hydride fuel elements enriched to 19.75% U-235 (Parry, 2020). Reactivity control is achieved through four rotating beryllium control drums with boron carbide poison sectors and a central absorber rod (Parry, 2020). The core is moderated by hydrogen and reflected radially and axially by graphite, beryllium, and beryllium oxide materials.

For efficient heat removal, MARVEL uses sodium-potassium eutectic as the primary coolant, transferring heat to a lead-bismuth eutectic intermediate loop - both driven by natural convection forces allowing inherent safety (“INL’s microreactor: A MARVEL machine - Nuclear Engineering International”, n.d.). The power conversion system features four Stirling engines with a combined 20kWe output, sufficient for a 100,000 square foot office building (“INL’s microreactor: A MAR-

VEL machine - Nuclear Engineering International", n.d.). The overall reactor structure is compact at 3m tall and 1m wide, with a projected weight under 10 United States (US) tons, allowing easy transport.

MARVEL reached "90% final" design in September 2023, but supply chain challenges have delayed its operation from late 2024 to 2025-2026 ("INL's microreactor: A MARVEL machine - Nuclear Engineering International", n.d.; "MARVEL microreactor start-up now expected in 2027, as fuel fabrication begins", n.d.). Testing is underway on a full-scale non-nuclear Primary Coolant Apparatus Test prototype to validate thermodynamic models (Hanna Bishara Hanna et al., 2023). Once operational at INL, MARVEL will operate autonomously while integrated into the lab's first nuclear microgrid ("INL's microreactor: A MARVEL machine - Nuclear Engineering International", n.d.). With inherent self-regulation and autonomous load-following operation, MARVEL positions itself as a robust, potentially revolutionary solution for reliable power generation and research initiatives. INL is open to collaborations leveraging MARVEL for external technology demonstrations ("INL's microreactor: A MARVEL machine - Nuclear Engineering International", n.d.).

2.3.3 eVinci Microreactor by Westinghouse

Westinghouse Electric Company's eVinci MR is an innovative Small Modular Reactor (SMR) designed for delivering safe, clean, and reliable power generation ("eVinci Microreactor | Westinghouse Electric Company", n.d.). Operating on a fast-critical reactor system with a once-through LEU fuel cycle, this reactor is designed to function as a nuclear battery, capable of autonomously operating for over 10 years without refueling (Hernandez et al., 2019). It is a 15MWt fission reactor with an electric power output of 5MWe and heated water power output of 8MW. As determined in a previous study, eVinci could power all of WPI's main campus in terms of electricity and nearly all of the main campus in terms of heated water (Coelho et al., 2022, p. 38).

eVinci's solid core, composed of a 316-stainless steel monolith with drilled fuel and heat pipe (HP) channels, ensures compactness and efficiency. However, studies indicate suboptimal performance in terms of discharge burnup and waste management compared to current US fuel cycle standards (Hernandez et al., 2019). Modifications to the core configuration, such as using a silicon carbide monolith, have been proposed to address these issues. Additionally, environmental concerns regarding high natural resource demand and waste generation have been raised, highlighting the need for further optimization (Hernandez et al., 2019). Despite challenges, the eVinci

MR offers a promising solution for clean and reliable energy production, with ongoing research aimed at improving its performance and sustainability.

2.3.4 Comparison Between eVinci and MARVEL

While both the eVinci and MARVEL MRs show innovative designs for compact nuclear power generation, they differ in some key areas. The eVinci is designed for longer-term autonomous operation of about 8 years without refueling, utilizing a compact solid steel core. However, studies suggest potential drawbacks in discharge burnup, waste management, and high resource demands compared to current standards. In contrast, MARVEL prioritizes rapid deployment, with a lifecycle as short as two years, using proven component technologies. Its compact, transportable design under 10 tons is well-suited for research across reactor operations, control systems, and novel applications like thermal storage. Though MARVEL has a shorter anticipated lifetime, it allows inherent self-regulation and autonomous load-following.

One key challenge MARVEL faces is supply chain delays pushing operation from late 2024 to 2025-2026. The eVinci design has not yet entered production, so its timeline remains uncertain as well. Despite these challenges, both MRs offer promising solutions - eVinci for long-term reliable clean power, and MARVEL for pioneering MRs research and demonstrations.

2.3.5 Challenges Facing Microreactor Development

The realization of microreactors' full potential is hindered by various challenges. A significant obstacle stems from the uncertainty surrounding development costs and lack of established regulatory frameworks tailored to these small-scale nuclear systems (Stevens et al., 2023). This ambiguity contributes to perceived risks and costs, potentially impeding widespread adoption and commercial viability. MRs also face unique technical hurdles related to instrumentation and control systems, communication methods, and operational protocols for remote operation scenarios (Stevens et al., 2023). Developing robust instrumentation and controls (I&C) systems, ensuring reliable communication between remote centers and reactor sites, and navigating regulatory landscapes are formidable tasks.

Fuel development poses another significant challenge, as microreactors require optimized fuel forms for their smaller size and operating conditions (Testoni et al., 2021). However, limited progress has been made in this area, hindering advancements in fuel design, fabrication techniques, and fuel cycle strategies. The absence of well-defined regulatory standards for microreactor fuel further exacerbates this issue (Stevens et al., 2023).

Overcoming these obstacles is crucial for realizing microreactors' potential. Addressing uncertainties in development costs, establishing tailored regulatory frameworks, advancing instrumentation and control systems, improving communication methods, and driving fuel development requires collaborative efforts and targeted research initiatives. By tackling these challenges comprehensively, stakeholders can pave the way for successful microreactor deployment across diverse applications.

2.3.6 Applications and Operational Benefits of Microreactors

MRs offer promising applications across various sectors, including the defense industry, remote civil power generation, industrial applications, and space exploration. In defense applications, microreactors serve as robust, safe, and highly adaptable power sources well-suited for deployment at Main Operating Bases and Forward Operating Bases, reducing training requirements and operational burdens. They also contribute to the growth of new national capabilities with export potential, technological advancement in nuclear energy, and align with defense initiatives for energy transition and achieving net-zero emissions targets ("Microreactor", n.d.).

For remote civil power generation, microreactors provide long-lasting, clean energy solutions to isolated microgrids and strategic locations with limited access to traditional power sources, alleviating pressure on existing infrastructures and enhancing energy security. In remote industrial settings, microreactors offer a continuous and safe energy supply, ensuring reliability for industries with heavy power usage and high energy demands, facilitating grid independence, and supporting clean energy commitments ("Microreactor", n.d.; "Microreactors", n.d.).

Furthermore, microreactors present promising opportunities for space exploration, providing power and propulsion for spacecraft and enabling surface power for planetary exploration missions. Their self-contained and power-dense design makes them particularly suitable for operating in harsh space environments, supporting persistent and resilient power needs for extended space missions ("Microreactor", n.d.). Microreactors demonstrate immense potential across various applications, offering reliable, clean, and highly versatile energy solutions tailored to diverse operational requirements.

2.4 Federal Legislation and Regulation on Nuclear reactors

The US Federal Government maintains the CFR, which is “the codification of the general and permanent rules published in the Federal Register by the departments and agencies of the Federal Government” (“Code of Federal Regulations (Cfr), 1996 to Present” n.d.). The CFR provides the actual implementation of the standards set forth in legislation. In the context of nuclear regulations, the Atomic Energy Act (AEA) of 1954 (and any amendments) is the relevant piece of legislation. The CFR is subdivided into Titles, Parts, Sections, and Paragraphs. Title 10 concerns energy, and covers federal regulations for nuclear energy. An example CFR citation is “10 CFR 50.21 (c)”, which references Paragraph “c”, of Section 21 (Class 104 Licenses), of Part 50 (Domestic Licensing of Production and Utilization Facility (PUF)), of Title 10 (Energy), of the CFR.

2.4.1 Existing Regulatory Landscape

Existing nuclear regulations are in 10 CFR, and nuclear reactor (NR) licensing frameworks are defined in its Parts 50 and 52. They were designed for water-cooled reactors, but are the only existing licensing frameworks, and as such are still in use today for ARs; to be clear, there is no existing framework for ARs. Parts 50 and 52 require the Licensee to obtain permission to construct the NR facility and permission to operate it. Part 50 separates those steps, while Part 52 combines them.

10 CFR Part 50

10 CFR 50 (henceforth also known as “Part 50”) concerns “Domestic Licensing of Production and Utilization Facilities” (“Code of Federal Regulations (Cfr), 1996 to Present” n.d.). In accordance with AEA §103 and 104, Part 50 defines the Class 103 and Class 104 reactor licenses. The Class 103 license is for “commercial and industrial facilities” (10 CFR 50.22). The Class 104 license is relevant and is covered in Section 2.5.1.3.

Regardless of license, Part 50 requires the applicant to obtain a Construction Permit (CP) and an Operating License (OL). The CP allows the applicant to begin constructing the reactor facility. The CP application requires, among other things, a review of “safety and environmental aspects..., planned location, and [the chosen] NRC’s licensing process”, along with public hearings and a “preliminary design” of the reactor and its facility (Owusu et al., 2018, p. 3). The CP must be obtained for the applicant to apply for an OL. With the OL, the applicant can “load fuel and begin operating the plant" (Owusu et al., 2018, p. 3). The OL application requires a "final mandatory [public] hearing... [and compliance with] all safety and environmental requirements" (Owusu et al., 2018, p. 3).

Separating the CP and OL can be useful for "novel reactor designs", such as ARs, because it creates a built-in path for submitting design changes (Garcia, 2023, p. 31). If an issue arises during construction, the applicant can update the design in the OL application. This separation creates two issues, however. First, when beginning construction with only a "preliminary design", applicants often iterate that design "as they go along[,] ultimately resulting in a large amount of reworking... due to a potential lack of compliance with regulations that is only determined during the construction process" (Owusu et al., 2018, p. 4). Second, by requiring a second round of hearings – possibly years-long – for the OL, "this leaves completed plants idle while facing economic pressures from construction costs" (Owusu et al., 2018, p. 4).

10 CFR Part 52

10 CFR 52 concerns "Licenses, Certifications, and Approvals for Nuclear Power Plants" (10 CFR). Specifically, it "governs the issuance of early site permits, standard design certifications, combined licenses, standard design approvals, and manufacturing licenses for nuclear power facilities" licensed as commercial or industrial facilities. Under Part 52, applicants apply for a COL instead of the CP and subsequent OL as in Part 50. When applying for the COL, applicants typically apply for an Early Site Permit (ESP) and submit a standard DC as part of "pre-application review" (Owusu et al., 2018, p. 5). The ESP "resolves site safety, environmental protection, and emergency preparedness issues independent of a specific nuclear plant design"; these requirements are generally satisfied with a Safety Analysis Report (SAR) (Garcia, 2023, p. 33). The DC is "irrespective of a specific site" and covers "the design basis, the limits on operation, and a safety analysis of structures, systems, and components of the facility" (Garcia, 2023, p. 36). An Environmental Report (ER) is also necessary. The ESP and DC not only allow "applicants to get early feedback on any licensing issues" but suffice for submission with the COL application (Owusu et al., 2018, p. 5).

Once the Construction and Operating License (COL) is granted, applicants can construct the plant. Then, after the NRC "verifies that the required Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC)... have been met", fuel can be loaded and the plant can operate (Owusu et al., 2018, p. 5). The COL application requires "complete design and site information", and thus “prevents the design-as-you-build approach and allows for immediate operation of the plant once construction and testing are complete” (Owusu et al., 2018, p. 5). For traditional LWRs and reactor “designs that can lean on previous experiences”, Part 52 “is particularly useful” because the ESP and Design Certification (DC) will be well-defined (Garcia, 2023, p. 33). However, “considerable [wasted] effort and potential for delay may occur if the application is submitted before detailed design is complete” (Kauffman, 2023, p. 15).

Class 104 License

10 CFR 50.21 defines the Class 104 license outlined by Section 104 of the AEA. The License applies to “medical therapy and research and development [nuclear] facilities”, and is the only license for Research Reactors (10 CFR 50.21). An RD facility consists of “a production or utilization facility, which is useful in the conduct of research and development activities of the types specified in section 31 of the [Atomic Energy] Act”, and which meets certain technical operational limits (10 CFR 50.21 (c)).

A Class 104-licensed facility is subject to certain “cost recovery requirements” to which the Licensee must adhere (Brooks, 2022, p. 7). The first requirement is imposed by 10 CFR 50.22, which defines the Class 103 license pursuant to Section 103 of the AEA. Though 50.22 covers commercial reactors, it stipulates that an RD facility “is deemed to be for industrial or commercial purposes” – in other words, not a Class 104 facility – if more than 50% of its annual “owning and operating” costs have been “devoted to the production of materials, products, or energy for sale or commercial distribution, or to the sale of services” (10 CFR 50.22). Notably, this requirement excludes sales from “research and development or education or training” (10 CFR 50.22).

The second requirement is imposed AEA 104 (c), requiring that “sales of nonenergy services, energy, or both,” not constitute more than 75% of the Annual Owning and Operating Cost (AOOC) of the facility (AEA 104 (c)). In addition, energy sales cannot constitute more than 50% of AOOC. Notably, and similarly to the first requirement, sales of “research and development or education and training” are excluded (AEA 104 (c)). Stated simply:

1. You can’t spend more than 50% worth of AOOC on “production of materials, products, or energy for sale or commercial distribution, or to the sale of services” (10 CFR 50.22).
2. You can’t realize more than 75% worth of AOOC from “sales of nonenergy services, energy, or both”, and you can’t realize more than 50% of AOOC from “sales of energy” (AEA 104 (c)).

2.4.2 Regulatory Future for Advanced Reactors

Owusu et al., from INL, offer several recommendations for agencies of federal government to develop a licensing process for MRs, adopting the NRC's goal to "not [negatively] influence the path to microreactor development, demonstration, and commercalization". Many of these recommendations are non-trivial, including for the NRC to "address [a] lack of definitive data and support of risk informed decision-making concepts" (Owusu et al., 2018, p. iv), for the Department of Energy (DOE) to "implement multi-step Phenomena Identification and Ranking Table[s]" to identify the technologies necessary to be in compliance with future licenses (Owusu et al., 2018, p. v), and for the Department of Transportation (DOT) to develop "new shipping packages for safe transport" (Owusu et al., 2018, p. v). Regarding transport of HALEU fuels, the estimated time frame for "establish[ing] the commercial fuel-cycle infrastructure" is at least seven to nine years from time of writing (Owusu et al., 2018, p. 18).

A 2021 report from INL lists R&D activities, about MRs themselves, important to AR stakeholders. Some of the most important are, in no particular order:

> Transportation and storage of new and post-use reactor modules • Remote monitoring and autonomous control and protection systems • Advanced manufacturing materials and qualification processes • Fuel qualification • Waste disposal certainty • ASME code case development • Standardized NRC regulatory guides • Oversight and inspections • Staffing levels • Physical security • Digital instrumentation and control systems • Part 53 licensing approach • Siting and emergency planning • Efficient licensing process • Operator licensing • Inspection and oversight activities • Emergency preparedness • Physical security • Aircraft impact • Environmental reviews • Licensing fees • Generic licensing • Probabilistic Risk Assessment • Quality assurance. • Staffing, training, and qualification requirements • Autonomous and remote operations • Population • related siting considerations • Operating experience • Industry codes and standards • End-of-Life determination • Control room design • Seismic and other natural phenomena hazards. (Christensen et al., 2021, pp. 4–5)

Clearly, there is work to be done.

A 2023 Master's Thesis from MIT recommends that the MR community work within existing regulations. Action from Congress that would constitute a regulatory "overhaul... is inefficient and highly improbable" (Garcia, 2023, p. 36). Even the upcoming 10 CFR Part 53 from the NRC, which tries to allow for a "technologically inclusive landscape", focuses mostly on NRs with thermal output in gigawatts, and SMR designs are assumed to be similar to traditional nuclear power plants (NPPs) (Garcia, 2023, p. 36).

2.5 Economic Analysis of MRs

At the time of writing, there are no commercially available Gen. IV MRs. This fact, compounded by the experimental nature of some Gen. IV technology, results in “considerable uncertainties” about their economic viability (Black et al., 2023, p. 3). There is consensus that the economic competitiveness of MRs relies on their mass production. As to how the other characteristics of MRs affect their economic costs and benefits, there are varying opinions and analytical approaches, reflecting both optimistic and pessimistic outlooks.

2.5.1 Analytical Approaches

There are two analytical approaches for determining the lifecycle costs of Gen. IV MRs: the Top-Down Analysis (TDA) and the Bottom-Up Analysis (BUA). The TDA scales down the characteristics and costs of large NPPs to approximate those of MRs. It is usually implemented in the early project stages, particularly when the reactor design has not been thoroughly laid out (EMWG, 2007, p. 37).

The process begins with a “reference design” (EMWG, 2007, p. 37). Cost estimations for the MR begin with the “costs of systems and equipment” for this design. For “indirect and supplementary costs... standardized factors or formulas [are used]” (EMWG, 2007, p. 37). Specific “cost-scaling equations... are equipment specific and must be developed by the designers and cost estimators working jointly” (EMWG, 2007, p. 37). While the TDA lacks detail, its abstract overview of costs makes it easier for designers and estimators “to optimize designs such that the lowest LUEC can be realized” (EMWG, 2007, p. 38).

The BUA calculates costs “on a component-by-component basis for a given new nuclear design” (Black et al., 2023, p. 5). All “components for reactor construction, delivery, and installation” are accounted for, and scaling factors are applied to each component (Black et al., 2023, p. 5). The BUA “is usually implemented as projects near construction, which implies the reactor design is essentially complete” (EMWG, 2007, p. 37). To start, the process requires “a detailed baseline design with layout diagrams for all major systems” (EMWG, 2007, p. 37). This design must have “very detailed items, such as equipment lists, commodity quantity estimates based on drawings or direct from conceptual three-dimensional design models" (EMWG, 2007, p. 37). A BUA "requires a staff of at least a dozen engineers and estimators" (EMWG, 2007, p. 37).

The Gen. IV International Forum's GIF Economic Modelling Working Group (EMWG) has put forth a Code of Accounts (COA) model for Gen. IV ARs. A code, or chart, of accounts is an accounting tool which defines categories for all types of transactions that can occur in a system. When estimating costs for that system, filling out cost estimates for each category, and their subcategories, necessarily leads to a comprehensive estimate. The Gen. IV International Forum Economic Modelling Working Group Code of Accounts (GECOA) goes into great detail, providing nine top-level cost categories with three subsequent digits of specification. A BUA based on the GECOA would apply "unit prices and unit labor-hour rates" and consult "project execution plans [and]... the construction schedule" (EMWG, 2007, p. 37).

2.5.2 Gen. IV International Forum Economic Modelling Working Group Code of Accounts Model

The top-level accounts of the Gen. IV International Forum (GIF) EMWG's COA model are listed below:

Account Number	Cost Name	Running Total
10	Capitalized Pre-Construction Costs (CPC)	-
20	Capitalized Direct Costs (CDC)	**Direct Cost**
30	Capitalized Indirect Services Cost (CIC)	-
31-34	Field Indirect	**Total Field Cost**
35-39	Field Management	**Base Construction Costs**
40	Capitalized Owner's	-
50	Capitalized Supplementary	**Overnight Construction Cost**
60	Capitalized Financial	**Total Capital and Investment Cost**
70	Annualized operations and maintenance	-
80	Annualized Fuel	-
90	Annualized Financial	-

The accounts are numbered such that as they increase, the cost categories grow more abstract and encompass more of the project's costs. The running total grows to eventually yield Total Capital and Investment Cost (TCIC) for a nuclear plant, which "is the cost of building the plant and bringing it into commercial operation" (EMWG, 2007, p. 29). A general description, with some examples as necessary, of each top-level account is listed below:

10: Site-related: land, permits, studies; **20**: Buildings, structures, and equipment;
31-34: Indirect construction costs; **35-39**: Construction management services;
40: Staff; **50**: Supplementary costs: shipping, taxes, decommissioning;
60: Escalation, fees, interest on loans; **70**: Annualized O&M costs;
80: Annualized fuel costs; **90**: Annualized financial costs (EMWG, 2007, pp. 30–1)

2.5.3 Levelized Cost of Electricity

The levelized cost of electricity (LCoE) metric can be used "to compare economic competitiveness across energy technologies... [specifically] costs of energy production over lifetime production horizons across technologies" (Black et al., 2023, p. 6). Notably, "this long-term comparison is especially important for nuclear power where capital costs are relatively higher than for other technologies" (Black et al., 2023, p. 6). Considering the cost categories in the GECOA provides a starting point for calculating LCoE. For a breakdown of how GECOA categories can affect LCOE, see Appendix A.4.1.

2.5.4 Optimistic Outlook

Black et al. conduct and review some BUA and conclude that MRs will be cost competitive with large NPPs. A BUA of NuScale's SMR design, compared with the existing PWR-12 (PWR-12) NPP showed that direct costs "were lower for the SMR design, both in absolute costs and on a per kilowatt basis, than for the PWR-12 design" (Black et al., 2023, p. 5). A BUA of Westinghouse's SMR, comparing with the Westinghouse AP1000 NPP, found that direct costs would be "relatively larger for small reactors than for large NPPs on a per kilowatt basis, but that indirect, contingency, and owner's costs would be significantly lower" (Black et al., 2023, p. 5). In general, Black et al. conclude that MRs are likely to be economically viable "because the much smaller size of new nuclear designs allows for solutions and efficiencies not available to large reactors" (Black et al., 2023, p. 6).

The lower construction costs and shorter construction periods of MRs are expected to reduce their financing cost (Black et al., 2023, p. 6). MRs are also expected to have "relatively long operational horizons," resulting in "similar downward pressure on LCoE estimates" (Black et al., 2023, p. 7). Black et al. and find that:

- the MR manufacturing market should expect a standard learning rate of about 15-20
- MR fuel and OM costs will decline "as the industry matures" (though the large-scale adoption of MRs might counter this effect)
- an INL "study found that over half of the contributions to the LCoE of this [Design A HP reactor from Los Alamos NL] microreactor design stem from direct capital costs" (Black et al., 2023, p. 8)

MRs also have positive externalities, both direct and indirect, which make them more cost competitive with other energy sources. A direct economic benefit is in regards to thermal output, which is almost always a multiple greater than its electric output. An MRs heat can be used to produce steam, which can then be directed to heating systems, for example, saving on heating costs, which can sometimes be more expensive than electric costs. Indirect economic benefits include energy resiliency, supplementation of renewables, and integration with microgrids (Black et al., 2023, p. 8).

2.5.5 Pessimistic Outlook

Proponents of the broad economic viability of MRs claim that TDAs, which usually result in higher MR cost projections, are not applicable to MRs because of their differences with large NPPs in terms of design and manufacturing. TDAs, it is argued, usually lead to estimates that are "significantly higher, on a per megawatt basis, than other low-carbon energy technologies" (Black et al., 2023, p. 4). Some economists, however, point out that these design and manufacturing differences explain precisely why MRs will never be broadly viable. MRs and other small reactors "are expected to be more expensive per unit of output because of something that economists have known for decades and termed economies of scale" (Ramana, 2021, p. 3). The "capital and operating costs" of larger reactors "do not scale linearly with generation capacity" (Ramana, 2021, p. 3). Thus, while large NPPs may have high capital costs, their LCoE is still lower given their several hundred, if not close to one thousand, megawatts (MWs) of power output. Even if some differences in design between MRs and large NPPs partially invalidate the "economy of scale" argument, "the general principle about economic losses due to smaller size will still hold" (Ramana, 2021, p. 3).

Additional costs for MRs, and resulting increases to LCoE, also result from the fact that they are first-of-a-kind (FOAK) products being developed in an unsuitable regulatory environment. There is “simply no appetite within the private sector to underwrite such large risky investments” (Ramana, 2021, p. 3). Because of this high FOAK cost, “the economic case for SMRs critically rests on fast learning” (Ramana, 2021, p. 3). The nuclear learning rate estimated by the University of Chicago, however, is only 3 to 10 percent, which is “low compared to most other energy technologies” (Ramana, 2021, p. 3).

Thus, MRs will have to be “manufactured by the thousands” to break even, and this is only economically feasible given a high demand (Ramana, 2021, p. 3). While MR proponents expect high demand from markets including disaster relief in developing countries, several important prerequisites for accessing these markets, such as onsite MR security and international MR transportation regulations, have yet to be fulfilled. Onsite security is, in particular, a non-trivial problem, especially in developing countries. In other words, there are only so many universities and Department of Defense (DOD) bases to provide an initial demand; proponents need to think realistically about total demand, and whether there will be enough incentive to produce MRs at the required scale (Ramana, 2021, p. 3).

Proponents of MRs not only acknowledge factory production as a necessity but in fact emphasize its potential to reduce costs and improve safety. A “lack of adequate demand,” however, “either in niche markets, grid connected markets, or developing countries, is a major constraint” on MR feasibility (Ramana, 2021, pp. 5–6). With no demand, factory-scale production cannot be economically justified. If lack of demand prevents factory-scale production, MRs have no chance of becoming broadly economically viable. If demand slowly increases, active MR developers may have to lose money until factory production initiates.

2.6 Previous MR Research at WPI

There have been three prior studies which have explored the prospect of deploying a Gen. IV MR – Westinghouse’s eVinci – at WPI. The first study explored the broad “feasibility of reintroducing nuclear power”, and the next two explored the “feasibility” of using NRs for “energy” and “research” at WPI, respectively.

All the studies affirm that a Gen. IV MR would place WPI at the forefront of nuclear research. An MR in the 5 MWe and 10 MWt range would drastically reduce WPI’s carbon emissions, were it used for electric and/or thermal power generation, while being theoretically safe. The only survey of student, staff, and faculty opinions indicated a positive reception towards the idea of having an MR on campus. As the federal regulatory landscape is not designed to accommodate MRs, however, consensus from previous studies is that the licensing process may not be standard, particularly in the case of using an MR for both power and research.

These studies considered the eVinci MR, by Westinghouse, as the MR that would be deployed. In addition to the aforementioned findings about MRs in general, eVinci would offer numerous opportunities for research, bring in research grants, and create learning opportunities for students. It would satisfy nearly all of WPI's electric and thermal power needs. Locations do exist near campus which would be suitable for a research and power generation facility, though the possibilities for integration with existing thermal infrastructure remain unclear.

Chapter 3

Methods

3.1 Overview

The goal of our study was to assess the technical, regulatory, economic, and political feasibility of deploying MARVEL, at WPI, for research and power. To these ends, we achieved the following objectives:

1. Conducted a preliminary assessment of MARVEL and its integration on campus.
2. Assessed the technical, regulatory, economic, and political aspects of deploying MARVEL at WPI.
3. Proposed recommendations for future research on crucial regulatory issues, approaches for a cost-to-benefit analysis, and public engagement.

Given that Gen. IV MRs are experimental technology, and have yet to be deployed, opportunities for quantitative research and data analysis are lacking. Thus, we have employed qualitative methods. We obtained information from literature, institutional white papers, and expert interviews. We also conducted a photo response survey of WPI students, building off the survey done by Coelho et al., to help "triangulate" students' understanding and perspective on MRs (Lune and Berg, 2017).

We conducted five expert interviews, with interviewees including Professor David Medich; Professor Emeritus David S. Adams, WPI's RSO; Mr. Norbert Hugger, a WPI PhD Researcher; a WPI Facilities representative; and an NRC representative. We chose to conduct semi-structured interviews to effectively gather specific information on key topics, while maintaining flexibility to follow-up on emergent areas (Lune and Berg, 2017). As preparation, we developed questions and sorted them first thematically, and then in a logical and chronological order. When necessary, we prepared definitions and clarifications on relevant material for the interviewee. In terms of data analysis, we made summary sheets, with key facts, after each interview.

3.2 Assessed technical feasibility of operating MARVEL in terms of research, safety, infrastructure, and sustainability.

MARVEL's technical feasibility relies on its potential for research, its ability to integrate with existing electric and thermal campus infrastructure, and potential engineering challenges. Potential engineering challenges included a lack of contextual information for interviewees, such as exact shielding requirements, funding sources, and deployment timeline. We analyzed MARVEL's compatibility with existing infrastructure, its potential for research, and potential engineering challenges. To characterize MARVEL's research potential, infrastructure compatibility, and associated challenges; we interviewed Professor Medich, Mr. Hugger, Professor Adams, and a WPI Facilities representative.

To understand safety protocols and emergency procedures relevant to MARVEL's operation at WPI, we conducted an interview with the Facilities representative. Engaging these experts allowed us to explore hypothetical integration scenarios and potential safety challenges associated with MARVEL. Through these discussions, we aimed to develop a comprehensive understanding of the safety considerations relevant to reactor operation at WPI, which will inform the development of tailored safety protocols and emergency procedures.

We gained insights into specific capabilities and constraints of the infrastructure, which informed our assessment of its suitability for accommodating MARVEL. These interviews also enabled us to identify potential gaps or areas requiring modification to ensure the reactor's safe and efficient integration.

Faculty, researchers, and staff at WPI possess the expertise to inform a sustainability assessment of MARVEL. We conducted interviews with Professor Medich, Mr. Hugger, and Professor Emeritus Adams. Their insights on reactor safety analyzes, waste stream management, fuel cycle dynamics, and experience with research reactors will prove invaluable. To understand compliance with nuclear regulations and long-term fuel sustainability, we interviewed an NRC representative. Meetings with relevant NRC personnel from the offices dealing with micro reactors covered regulatory requirements, licensing processes, safety evaluations, and projections on future fuel availability/viability.

3.3 Assessed regulatory feasibility of deploying MARVEL for research and power with a Class 104 (c) license.

Given WPI's goal of nuclear research, the Class 104 license – which, as mentioned in Section 2.4.1, is the only license for Research Reactors – is the clear licensing pathway. Indeed, previous studies identified the License as necessary (Burns et al., 2023a, p. 47).

Questions remained however, about the License's exact applicability, as well as how WPI could potentially use Class 103 license, Part 52, and Part 53. Indeed a previous study identified the need to "investigate the details of a Class 104 license's funding rules, confirm what types of research are allowed with a test reactor" (Burns et al., 2023a, p. 62). We explored how potential regulatory frameworks could apply to MARVEL and other, more powerful, MRs which could eventually be deployed at WPI. We read and familiarized ourselves with applicable legislation and regulation, and supplemented that with literature. We interviewed a representative from the NRC, and reached out to a faculty member at University of Illinois Urbana-Champaign (UIUC), who is also exploring the Class 104 licensing pathway for a research and power MR. One challenge was not getting a response from the UIUC faculty member; given that WPI shares a similar goal, it's possible that competitiveness played a role.

3.4 Analyze economic restrictions on research reactors and apply Code of Accounts model to MARVEL deployment.

Any decision to deploy an MR on campus, as a power source, will likely require an economic, or "cost/benefit", analysis of the reactor. Unfortunately, any economic analysis of experimental technologies such as ARs will share the same, if not greater, degrees of uncertainty. We outlined, qualitatively, whether WPI could expect to bear all, some, or none of the financial burden for each second-digit cost category in the GECOA model. We also considered whether the legislative economic restrictions on Research Reactors (RRs) might end up applying to MARVEL. We obtained information from literature and expert interviews. The main challenge was to avoid attempting a more detailed economic analysis than would be valid given our economic expertise and the current lack of information about MARVEL's deployment. We were unable to find a contact for Starcube, and did not receive answers to written questions from INL, and thus had no access to any existing preliminary economic models or analyzes of MARVEL.

3.5 Examine the political feasibility of deploying MARVEL

3.5.1 Conducted photo response survey of WPI community.

The opinions and perceptions of students, staff, faculty, and locals will help inform the deployment of MARVEL and garner community support. Indeed, a previous study recommended conducting "a follow up survey based on our findings" (Coelho et al., 2022, p. 65). We used a photo response method with anonymous written responses to explore attitudes towards having a micro reactor at WPI. We presented a poster with images of MARVEL as well as some potential benefits and concerns around deploying a Gen. IV reactor. The poster included a rating scale from 1-5: 1) Strongly Opposed, 2) Somewhat Opposed, 3) Neutral, 4) Somewhat in Favor, 5) Strongly in Favor. We engaged with interested people, asking them to provide an anonymous rating and written response on the scale.

We set up our photo response twice, first at the WPI Green Team's Climate Action Fair, and then at the WPI Office of Sustainability's Climate Action Plan Update. Our team was present to provide information and answer questions, and participants could engage at their convenience by writing responses on provided sticky notes.

A key limitation of this technique is the inability to isolate truly representative data from a non-rigorous voluntary photo response method. While allowing for candid responses, our participants may not statistically represent the broader WPI community. However, the qualitative data still provides insights into some of the viewpoints and narratives surrounding this topic from those who chose to participate.

3.5.2 Outlined elements and evaluated locations for a public mockup or virtual tour of MARVEL and its facility.

Public opposition to deploying MARVEL, and in particular public hearings mandated by the CFR and negative sentiment towards WPI, could present challenges to deployment. Public engagement and education about MARVEL, and Gen. IV reactors, have the potential to reduce unreasonable opposition and are a basic courtesy. Indeed, a previous study identified the need to eventually "develop and deploy an informative [public engagement] campaign" (Burns et al., 2023b, p. 84).

We can model engagement and education on the "Charrette" model used in urban planning. In the context of a construction project, a charrette is an "intensive, multi-disciplinary workshops aimed at developing design solutions or visions for a project or planning activity" (US EPA, 2014). It might consist of meetings that involve the project developer listening to, responding to, and possibly incorporating the perspectives of local residents and officials into project decisions (US EPA, 2014). A charrette usually makes the construction process more concrete and more tangible to locals and helps develop a better relationship between the developer and the community.

On this basis, a mockup – "a full-sized structural model built to scale" ("Definition of MOCK-UP", 2024) – of MARVEL, and its facility, could be built. The mockup would be a tangible representation of the potential facility, and could contain educational content, both expository and argumentative. We will design various elements that could be included in a mockup characterize their advantages and disadvantages, and discuss potential mockup locations.

3.6 Formulate actionable recommendations.

We employed a comprehensive approach to analyze the feasibility and considerations for operating MARVEL at WPI. To synthesize our findings, we systematically processed the information gathered from reactor design assessments, stakeholder interviews, literature reviews, and industry best practices. For the reactor design assessments, we evaluated MARVEL's technical specifications against WPI's infrastructure capabilities, identifying areas of compatibility and potential gaps that would need to be addressed. The stakeholder interviews provided valuable insights from subject matter experts on research potential, safety protocols, infrastructure requirements, and sustainability factors. We carefully examined the interview transcripts and notes, extracting key themes and specific considerations raised by the different stakeholders.

The literature reviews allowed us to contextualize our findings within the broader landscape of research reactor operations, nuclear regulations, and lessons learned from previous projects. We analyzed the literature to understand industry best practices, regulatory frameworks, and strategies that have proven successful in implementing nuclear facilities.

By triangulating the data from these diverse sources, we identified converging themes, potential challenges, and critical factors to consider for MARVEL's implementation at WPI. Our analysis integrated the technical aspects from the design assessments, the practical insights from stakeholder experiences, and the theoretical foundations from the literature. This comprehensive synthesis enabled us to develop a holistic understanding of the research, safety, infrastructure, and sustainability dimensions influencing MARVEL's technical feasibility at WPI.

Chapter 4

Results

4.1 MARVEL Reactor

4.1.1 Research Opportunities

MARVEL has significant potential to bring new research opportunities to WPI. Mr. Hugger noted WPI's previous reactor provided valuable experience with neutron scanning and training for nuclear operators and technicians, suggesting a new reactor could offer similar capabilities.

Both the Facilities rep. and Mr. Hugger highlighted the potential research benefits a new nuclear reactor could provide for WPI's physics and engineering programs. The Facilities rep. noted the previous reactor was valuable for neutron scanning and training nuclear technicians, while Mr. Hugger added that MARVEL's advanced fuel and autonomous controls could enable a wide range of new research opportunities.

4.1.2 Safety Measures

Nuclear safety protocols are crucial in the commissioning, operating, and decommissioning of a reactor. Security measures would include double-locked doors, fingerprint access controls, and surveillance cameras (Professor Adams, personal communication, 2024-04-04). Environmental and safety regulations necessitate conducting safety analyses to confirm the location's leak-proof status and adherence to acceptable standards (NRC rep., personal communication, 2024-04-12).

The reactor is designed to be safe, with proper shielding and an onboard computer to ensure the inactive default state during emergencies or power loss, a process managed autonomously by the computer system. This helps limit the maximum danger to potential radioactive particle leakage, providing a relatively safe research environment (Professor Adams, personal communication, 2024-04-04). Personnel training is essential, requiring a proficient Senior Reactor Operator on site during operation, along with adequate training and shielding for mitigating risks (Professor Adams, personal communication, 2024-04-04). The choice of liquid sodium coolant offers safety benefits by reducing potential hazards compared to water-cooled reactors. However, sodium's reactivity with water could pose fire risks, necessitating specialized containment and handling procedures (Mr. Hugger, personal communication, 2024-04-02).

4.1.3 Integration with WPI's Infrastructure

The interviews highlighted the logistical complexities involved in integrating a new nuclear facility within an established university campus (Professor Adams, personal communication, 2024-04-04, Facilities rep., personal communication, 2024-04-10). Constructing a dedicated, nuclear-grade building adheres to NRC guidelines for siting research reactors, though it departs from approaches at some institutions that have repurposed existing structures (Facilities rep., personal communication, 2024-04-10). This choice carries trade-offs, with new construction potentially offering greater design flexibility and inherent safety features but also higher upfront costs and extended timelines. The new facility would incorporate research laboratories designed with access to ports in the reactor shielding to utilize the reactor's neutron beams. The reactor would require several feet of concrete shielding. The Facilities rep. suggested involving Harrison St., a firm partnering with WPI to update energy infrastructure, highlighting collaborative decision-making and regulatory compliance needs.

Integrating the reactor's energy with campus utilities, particularly for heating applications, emerges as an engineering challenge (Facilities rep., personal communication, 2024-04-10). The reactor's waste heat could potentially supplement WPI's existing steam-based campus heating distribution network through a new hot water loop system (Facilities rep., personal communication, 2024-04-10). Findings from a 2020 study on using SMRs for district heating underscore the complexities involved, even when economic viability is demonstrated (Teräsvirta et al., 2020). Factors like variable electricity pricing, seasonal heating demands, and compatibility with existing distribution networks must be carefully evaluated.

Integrating the reactor's electrical output into WPI's campus grid would face regulatory hurdles, requiring a power and feasibility study and approval process with the local electricity provider, National Grid (Facilities rep., personal communication, 2024-04-10). One limitation on future integration of high-output nuclear power is WPI's lack of substantial on-site energy storage, which could constrain load-balancing and load-splitting opportunities (Facilities rep., personal communication, 2024-04-10). MARVEL's relatively small electrical output would also limit the benefits of connecting it to the local grid, as opposed to just its own facility (Facilities rep., personal communication, 2024-04-10).

The Facilities rep. raised practical considerations relating to the site preparation timeline, construction/renovation, and upgrading of campus infrastructure, such as steampipes. He estimated a three-year process for the design, regulatory approval, and construction of a new building for the reactor (Facilities rep., personal communication, 2024-04-10). The MARVEL reactor offers some potential environmental benefits, such as generating low-carbon electric and thermal energy, which could help offset WPI's reliance on fossil fuels (Facilities rep., personal communication, 2024-04-10). However, a comprehensive environmental impact analysis covering the reactor's lifecycle would be necessary to fully understand its sustainability profile.

4.1.4 Waste Management and Heating

Ensuring the long-term sustainability of reactor operations is a critical consideration. The reactor's fuel cycle and waste management processes require careful planning. According to Mr. Hugger, the reactor lacks built-in refueling capability, necessitating the entire unit to be removed and replaced or refurbished once the initial fuel is depleted. While this simplifies on-site waste management, responsible off-site disposal would require coordination with regulatory authorities and waste management experts (Mr. Hugger, personal communication, 2024-04-02).

From an environmental standpoint, the reactor's design incorporates some energy efficiency features. However, integrating its waste heat with WPI's existing infrastructure could necessitate extensive modifications to the heating distribution system (Facilities rep., personal communication, 2024-04-10). Such modifications would need to be evaluated for their economic feasibility and potential environmental impact.

Compliance with nuclear regulations is also a key aspect of sustainability. As highlighted by the NRC representative, extensive safety analyses are required to ensure adherence to acceptable standards for leak prevention and environmental protection (NRC rep., personal communication, 2024-04-12). Ongoing monitoring and adherence to regulatory requirements would be necessary throughout the reactor's operational lifetime.

Furthermore, the long-term viability of the reactor's fuel supply and potential for future fuel availability should be considered. The NRC representative provided insights into projections and assessments conducted by regulatory bodies regarding the sustainability of advanced nuclear fuel sources (NRC rep., personal communication, 2024-04-12).

4.1.5 Regulatory Applicability and Licensing Pathways

Idaho National Laboratories (INL), as the designer and developer of MARVEL, would manufacture the unit that WPI would deploy (Professor Medich, personal communication, 2024-04-05). INL may need a manufacturing license to manufacture MARVEL, depending on its status as a commercial or research reactor (NRC rep., personal communication, 2024-04-12). Regarding transportation of MARVEL from INL to WPI, the NRC rep. stated that, under current regulations, it would not be possible to load fuel into MARVEL, or any other NR, and transport it to its operating site. Current regulations, which, it bears repeating, were written for water reactors, consider an NR with loaded fuel to be operational. If fuel were loaded into MARVEL at INL, it would then be considered operational, and transporting it would be not be legally feasible (NRC rep., personal communication, 2024-04-12).

Regarding the upcoming 10 CFR Part 53, the NRC rep. noted that it might contain rules on how a reactor loaded with fuel could be transported from the factory to its site. He also mentioned that applicants would not have to wait for such a rule to be officially released, whether under Part 53 or even as unofficial NRC Guidance, for its content to be utilized. For example, applicants could file for a regulatory exemption to transport a loaded reactor and use this rule to inform the exemption. The NRC rep. also noted that Part 53, like Part 52, only applies to commercially licensed reactors. Were Part 53 to be published while WPI was in the pre-application or application phase under Part 50 or Part 52, it would be possible for WPI to switch licensing pathways and use Part 53, though this would require switching to the commercial license and possibly redoing some public hearings (NRC rep., personal communication, 2024-04-12).

Regarding 10 CFR Part 50, the NRC rep. disputed the claim by INL's Owusu et al., 2018 that "hearings could [theoretically] take as long 23 years to complete" (Owusu et al., 2018, p. 4). Hearings should be roughly the same length under both Parts 50 and 52, and should take about six to twelve months (NRC rep., personal communication, 2024-04-12). Regarding 10 CFR Part 52, the NRC rep. affirmed that while neutron-related research activities are forbidden, the Licensee could still conduct R&D activities that concerned the reactor's operation. With MARVEL, for example, these activities could include studies on autonomous control, the reactor's sensors, and power generation.

Regarding research reactors specifically, the NRC rep. could not forsee any specific problems with licensing MARVEL. MARVEL being a power reactor, by design, does not impact the ability to license it for research. He also noted that non-profit educational institutions licensing research reactors avoid some fees present when licensing commercial reactors. Additionally, the number of public hearings may be reduced from two to one.

Economic Restrictions

The AEA, as well as 10 CFR Part 50.22, place economic restrictions on "sales" derived from research reactors, as covered in Section 2.4.1. The exact definition of "sale", in terms of the buyer, seller, and commodity, however, is not made clear. In particular, it is unclear whether the Licensee's usage of its reactor's own power is an R&D activity that is "exempt" from the economic restrictions. Even if power usage is not "exempt," it remains unclear whether the Licensee's own power usage constitutes a "sale".

The NRC rep. affirmed that power generation could constitute a research and development activity permissible by the AEA, §31. He could not say, however, if a Licensee's use of their own reactor's energy would constitute a "sale", and he referred us to a colleague on the matter of power usage being "exempt" (NRC rep., personal communication, 2024-04-12).

The only other institution that appears to be licensing an MR for research and power is the UIUC, and their pre-application licensing pathway proposal provides insight on these economic restrictions. UIUC is working with Ultra-Safe Nuclear Corporation (USNC) to deploy their Micro-Modular Reactor (MMR) on campus. The "research" that UIUC hopes to conduct will explore "commercial viability and applicability [of MRs by]... interfacing [the MMR] with existing university-owned power generation and distribution infrastructure" (Brooks, 2022, p. 11). In other words, their "research" will directly pertain to power generation, usage, and infrastructure integration.

UIUC maintains the position that if the Licensee uses energy from its own reactor, then this does not constitute a sale (Brooks, 2022, p. 12). To be clear, they address this issue directly in their WP on using the Class 104 (c) licensing pathway:

> [UIUC will pursue] integration of the reactor system within existing campus power generation infrastructure and additional technologies for process heat applications...

> Energy generation with the reactor and subsequent use of the generated energy is not planned to be sold, rather it may be used on-campus (internal to the university organization, which is the “licensee”) for demonstration purposes and associated research and technology development. (Brooks, 2022, p. 13)

Official NRC feedback on this White Paper (WP) does not reject UIUC’s position on reactor-related sales. They qualify their feedback, however, as not suggestive of an endorsement of UIUC’s proposed licensing pathway. Furthermore, they recommend “additional pre-application interaction related to this topic” and note that if guidance on power generation with research reactors does not exist, then the “equivalent power reactor guidance documents” should be examined (Oberson, 2022, p. 4). The NRC reiterates that this type of feedback is neither “final” nor “comprehensive”, and the their “lack of comment [on an issue]... should not be interpreted as [the] NRC [being in] agreement” (Oberson, 2022, p. 3).

4.1.6 MARVEL’s Economics

There are two primary economic considerations for deploying an RR for both power and research. The first concerns regulatory restrictions, and whether they apply to R&D related to power generation, usage, and integration. The second concerns the general cost-to-benefit feasibility of the RR, and requires some form of comprehensive economic analysis, be it a TDA or BUA.

Code of Accounts Model

We performed a preliminary analysis of the applicability of each second-digit cost category in the Gen. IV International Forum Economic Modelling Working Group Code of Accounts model to MARVEL’s deployment. For each second-digit cost category, we identify whether WPI can expect to pay “all” the cost, “some” of the cost, or “none” of the cost (the resource is gratis, perhaps paid for by a grant). If we cannot estimate the applicability of a cost category – due to either lack of expertise, information, or both – we label the applicability as “unknown”. Our preliminary TDA is in Appendix A.4.2. Some design features of Gen. IV reactors eliminate some cost categories all together, such as #23, for turbine generator equipment. The applicability of some other cost categories is difficult to estimate, so they are given an “unknown” status. Some cost categories, such as “Other” or “Contingencies” are left out.

Regulatory Restrictions

As mentioned in 4.1.5, it is unclear whether the economic restrictions of the AEA and 10 CFR 50.22 apply to research into power generation, usage, and integration, as well as if the restrictions apply to the Licensee. If the restrictions did apply, WPI would need to determine the monetary quantities below to estimate whether the restrictions would kick in. Most of these quantities are reactor-specific, but some, such as "production of materials, products... [or] services" – which would presumably include research services, such as letting non-WPI researchers conduct experiments – might be independent of the reactor and could be calculated, in general, for any reactor system.

Monetary Quantities Relevant to Class 104 Economic Restrictions

1. The AOOC, O_a
2. Expected annualized cost of "production of materials, products, or energy for sale or commercial distribution, or to the sale of services", C_s (10 CFR 50.22)
3. Expected annualized revenue from "sales of nonenergy services, energy, or both" (henceforth, sales of nonenergy services, or energy, or both (NESEB)), R_s (AEA §104(c))
4. Expected annualized revenue from "sales of energy" specifically (AEA §104(c)), R_e

To ensure compliance with the AEA and 10 CFR 50.22, the following relations would have to be satisfied:

$$C_s \leq 0.5 O_a \qquad R_s \leq 0.75 O_a \qquad R_e \leq 0.5 O_a$$

The low power output of MARVEL raises particular questions. On one hand, MARVEL's low power output, which is proportional to R_s and R_e, might help it easily comply with the limits on revenue. On the other hand, MARVEL's low power output might also be proportional to a low O_a. This would make it more difficult to comply with the limits on revenue and cost of "services", C_s.

To actually estimate these quantities, both the cost of "services" as well as revenue, or "sales of nonenergy services, energy, or both", must be defined. As to the value of "sales", a crucial question to be answered is if the Licensee's use of its own reactor's energy constitutes a "sale" from a regulatory standpoint, but no actual transaction occurs, how can the "sale" be financially quantified?

Assuming the Licensee buys electricity "from itself" at the average, local price, we can calculate the expected annual "sales of energy" from MARVEL :

$$\text{capacity factor} \cdot \text{power} \cdot \text{annual time} \cdot \frac{\text{kWh}}{\text{unit power}} \cdot \frac{\text{dollar}}{\text{kWh}} = \text{annual energy sales revenue}$$

To estimate annual revenue, we consider only the electrical power output of MARVEL. We assume a capacity factor of 100% to avoid an underestimate. We assume a price per kWh of \$0.1, which is about half the national average, and about one third the Worcester average ("Electricity Cost in Worcester, MA", n.d.); we assume this reduction compared to national and local averages because it would be reasonable to expect that the local electricity supplier would purchase energy from WPI at a reduced rate (Facilities rep., personal communication, 2024-04-10). At this rate, the annualized revenue from sales of electricity is:

$$\frac{20000\text{J}}{\text{s}} \cdot \frac{31536000\text{s}}{\text{yr}} \cdot \frac{\text{kWh}}{3600000\text{J}} \cdot \frac{\$0.1}{\text{kWh}} = \frac{\$17520}{\text{yr}}$$

In other words, at a rate of \$0.1 per kWh, 1W of electric power corresponds to about \$1 of annual revenue.

4.2 Public Engagement

4.2.1 Strategies for Gauging the Community

Gauging and addressing community perspectives through robust public engagement analysis has been widely recognized as crucial for the successful deployment of energy projects, including nuclear facilities. A substantial body of literature has examined effective strategies and best practices. Many studies emphasize the importance of early and frequent two-way communication and dialogue between stakeholders and community members (Koningstein and Azadegan, 2021). Techniques like public surveys, focus groups, interviews, and establishing community advisory boards have been recommended to understand diverse viewpoints and concerns (Vaughn and Jacquez, 2020). Transparency about risks, benefits, and safety measures, is considered vital for building trust.

Identifying and working with respected local "champions" within communities can help mobilize social change and increase perceived legitimacy (Abdurrahim et al., 2022). Tailoring messaging and engagement approaches to specific stakeholder groups is also crucial for WPI, considering the diverse perspectives within Worcester and surrounding areas. Some stakeholders prioritize safety and environmental impact, while others may be more concerned about the economic and technological implications of nuclear projects like MARVEL.

Innovative methods for improving public understanding and dispelling misconceptions include interactive facility tours, simulations, and virtual reality. These approaches provide firsthand experiences as well as opportunities to visualize the inner workings of nuclear facilities, thereby demystifying complex processes and promoting informed discussions (Mallik and Aithal, 2024). Building on insights from studies exploring the use of virtual reality in education, immersive and interactive technological experiences can significantly bolster comprehension of complex scenarios and bridge theory with real-world applications.

By inviting community members to participate in simulations or virtual facility tours, WPI can foster a sense of transparency and trust, encouraging open dialogue and collaboration. While challenges like costs and technological access must be addressed, leveraging innovative visualization methods holds transformative potential for enhancing public engagement around advanced nuclear projects.

Understanding how the public perceives and conceptualizes risks is crucial, as these risk perceptions often diverge from expert technical assessments (Baron and Herzog, 2020). Hu, Zhu, and Wei provide valuable insights into the formation of public acceptance of nuclear energy (Hu et al., 2021). They develop a "Belief-Perception-Attitude" integrated conceptual model which identifies key predictors and mechanisms influencing public acceptance. Their findings highlight the direct relationship between public perception and nuclear power acceptance, as well as the indirect effects of concerns for environmental pollution and beliefs about energy shortages on acceptance levels.

4.2.2 Photo Response

The data from our photo response surveys are in Table 4.1, and a bar chart is in Figure 4.1.

Response	Number of Participants
Strongly Opposed	2
Somewhat Opposed	3
Neutral	5
Somewhat in Favor	17
Strongly in Favor	32

Table 4.1: Combined data from both photo response surveys.

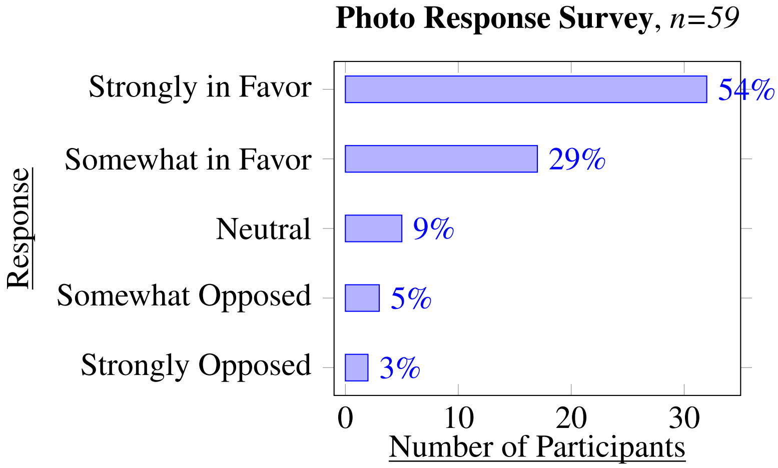


Figure 4.1: Bar chart of photo response surveys' data.

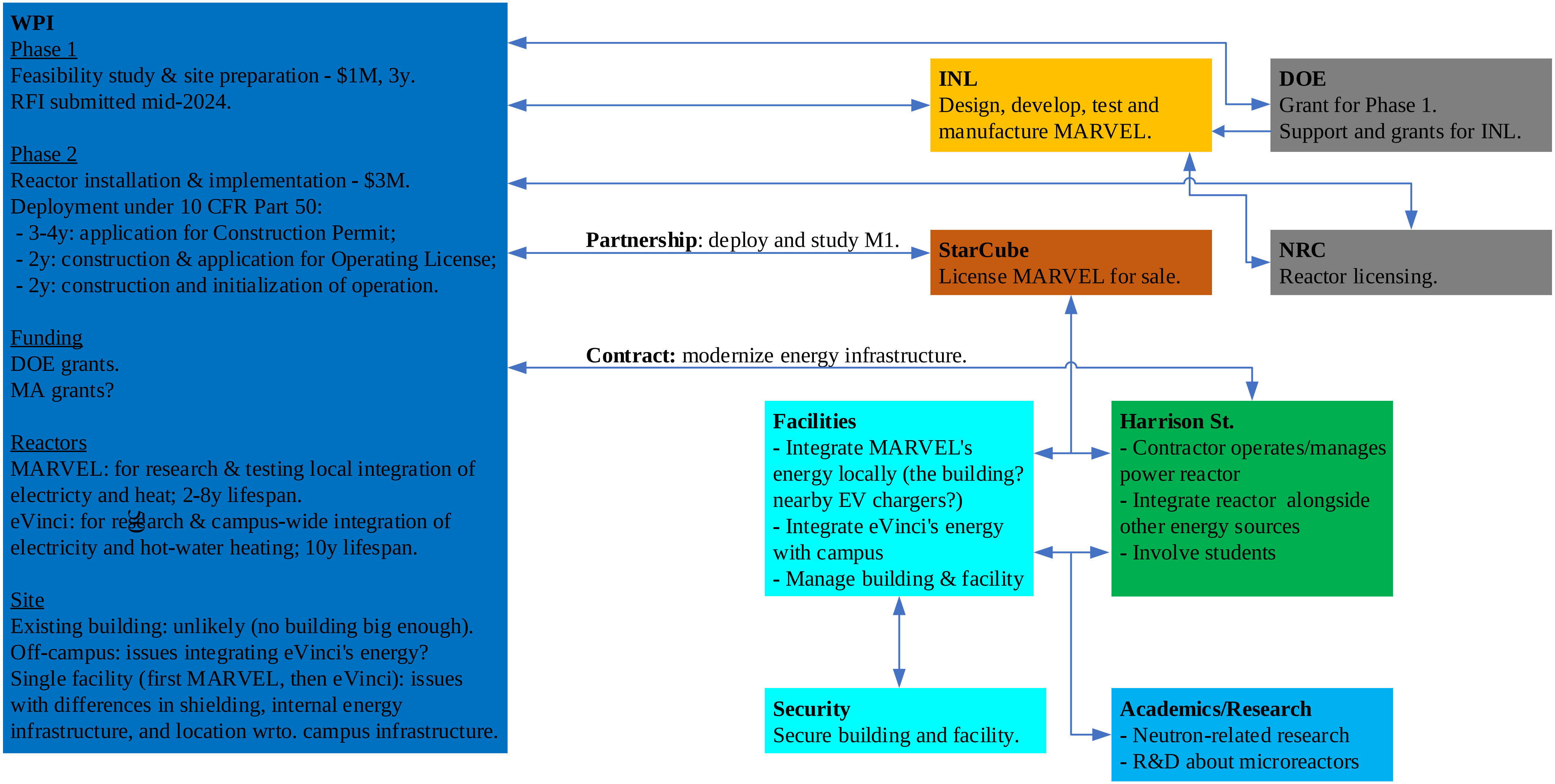
4.2.3 Facility Mockup and Virtual Tour

As mentioned in Section 3.5.2, a mockup of MARVEL's facility – "a full-sized structural model built to scale" ("Definition of MOCK-UP", 2024) – or a virtual tour could be useful for public engagement. A mockup facility would offer a somewhat realistic representation of the eventual reactor facility. The mockup would consist of informational and argumentative elements about MRs, MARVEL, and nuclear power, to list a few. These elements would have to be located indoors, in a building, but could also be contained in an enclosure to provide a more realistic impression.

In Appendix A.2, we briefly consider characteristics of an enclosure or building. We then consider elements, first outlining categories related to the elements' purpose, argumentative approach, and medium. We then identify specific element mediums and content. For a potential virtual tour, we outlined steps towards creating and implementing it in Appendix B.4.1.

4.3 Institutions and Entities Involved

The following diagram shows all institutions and entities involved in the deployment process.



WPI
Phase 1
Feasibility study & site preparation - $1M, 3y.
RFI submitted mid-2024.

Phase 2
Reactor installation & implementation - $3M.
Deployment under 10 CFR Part 50:
- 3-4y: application for Construction Permit;
- 2y: construction & application for Operating License;
- 2y: construction and initialization of operation.

Funding
DOE grants.
MA grants?

Reactors
MARVEL: for research & testing local integration of electricty and heat; 2-8y lifespan.
eVinci: for research & campus-wide integration of electricity and hot-water heating; 10y lifespan.

Site
Existing building: unlikely (no building big enough).
Off-campus: issues integrating eVinci's energy?
Single facility (first MARVEL, then eVinci): issues with differences in shielding, internal energy infrastructure, and location wrto. campus infrastructure.

INL
Design, develop, test and manufacture MARVEL.

DOE
Grant for Phase 1.
Support and grants for INL.

Partnership: deploy and study M1.

StarCube
License MARVEL for sale.

NRC
Reactor licensing.

Contract: modernize energy infrastructure.

Facilities
- Integrate MARVEL's energy locally (the building? nearby EV chargers?)
- Integrate eVinci's energy with campus
- Manage building & facility

Harrison St.
- Contractor operates/manages power reactor
- Integrate reactor alongside other energy sources
- Involve students

Security
Secure building and facility.

Academics/Research
- Neutron-related research
- R&D about microreactors

BLUES: WPI-related.
GREEN: government/regulatory.
ORANGE: INL.
RED: StarCube.
GREEN: Harrison St.
Arrows→: inputs and communication.

Institutions and Entities involved in deploying a microreactor at WPI.
NRC: Nuclear Regulatory Commission.
INL: Idaho National Laboratories.
DOE: Department of Energy.
StarCube: microreactor startup.
Harrison St.: energy consultants.

Chapter 5

Discussion

In this section, we explore the implications of our results for MARVEL's technical, regulatory, economic, and political feasibility. MARVEL's overall feasibility, however, must also be contextualized with the possibility of deploying two MRs. As necessary, we mention how deploying a second MR would add complexity to deploying MARVEL. This second MR would be more powerful, with an approximate 5MWe and 10MWt power output; it would be autonomous and have a similar Emergency Planning Zone (EPZ) to MARVEL. Given that previous studies have examined deploying the eVinci reactor, we will refer to eVinci as a second MR which could be deployed.

5.1 Research, Safety, Infrastructure, and Sustainability

MARVEL presents significant research opportunities for WPI's physics and engineering programs, providing hands-on training with neutron scanning and enabling new avenues with the reactor's advanced fuel and autonomous controls (Mr. Hugger, personal communication, 2024-04-02, Facilities rep., personal communication, 2024-04-10). However, stringent nuclear safety protocols are crucial throughout the lifecycle, including physical security, environmental analyses, inherent safety designs to contain hazards, and specialized personnel training (Mr. Hugger, personal communication, 2024-04-02, Professor Adams, personal communication, 2024-04-04, NRC rep., personal communication, 2024-04-12). Infrastructure integration poses challenges like potentially needing a dedicated nuclear-grade building, assessing utilities integration feasibility with heating/electric systems, and compliance with construction/regulatory requirements (Facilities rep., personal communication, 2024-04-10, NRC rep., personal communication, 2024-04-12). Long-term sustainability hinges on fuel cycle management, replacing depleted units, responsible waste disposal coordination, evaluating economic and environmental impacts of modifications, adhering to regulations for environmental protection, and assessing future fuel viability projections (Mr. Hugger, personal communication, 2024-04-02, Facilities rep., personal communication, 2024-04-10, NRC rep., personal communication, 2024-04-12).

5.2 Regulatory Applicability, Licensing Pathways, and Challenges

Each stage of MARVEL's deployment process will, at some point, depend on applicable regulations and the chosen licensing pathway. These stages – reactor licensing, reactor manufacturing, facility construction, local energy infrastructure, research infrastructure, reactor shielding, and reactor transport – have different timelines which happen to be non-linear and inter-dependent. Complexity is only added when considering the prospect of continuously deploying MARVELs upon their end-of-life as well as deploying a more powerful MR for power generation.

Regarding Class 104 licensing for research and power, the License's economic restrictions pose a challenge to being able to use meaningful amounts of low-carbon power. If power generation, usage, and integration constitute R&D activities exempt from the economic restrictions of the AEA and Class 103 license, then WPI should have no issue licensing MARVEL, but more importantly, a more powerful MR, for research and power usage. If, on the other hand, the power-related R&D activities mentioned previously are not "exempt", it remains to be seen whether the Licensee's usage and integration of its power constitutes a "sale" or type of "reactor service" restricted by the AEA and Class 103 license. If so, then economic restrictions would apply to MARVEL, and to any other Class 104-licensed MR; if not, then the economic restrictions would not apply. Regarding reactor manufacturing, INL may need to have applied for and received a manufacturing license from the NRC. To the best of our knowledge and that of the NRC representative, INL does not have a manufacturing license. If the application process is begun late, this could result in delays.

The facility for an MR would not fit in an existing building on campus, and a new building would likely need to be built. Erecting a building could take as long as three years, and possibly longer if advanced laboratory technology needs to be added (Facilities rep., personal communication, 2024-04-10). The building could be designed so that an MR could be installed at a later date, meaning that, in terms of construction, timing with reactor installation is not an issue (Facilities rep., personal communication, 2024-04-10). Given the lack of information know about eVinci, for example in terms of its size, it may be difficult to design a facility that could house first MARVEL and then eVinci (Burns et al., 2023a, p. 96). Because of MARVEL and eVinci's differences in requirements for shielding and power integration infrastructure, however, it is unlikely that the same facility could be used for both.

The prospect of needing two different reactor facilities raises additional questions. Can WPI finance two reactors? Can WPI finance two separate facilities? Is the community comfortable with living near not one, but two, NRs? Notably, the MARVEL facility could be torn down, perhaps even only partially, and then replaced with the facility for eVinci. The years-long regulatory timeline for deploying eVinci would allow for rebuilding the facility on the same site, and MARVEL's short, two-year lifespan won't push back any demolition start dates. It may also be possible to deploy a second MARVEL after the first.

The current illegality of pre-loaded nuclear reactor transport has the potential to be the most serious obstacle. Waiting for new NRC rules to be released, in some capacity, however, as part of the upcoming 10 Code of Federal Regulations Part 53, should not theoretically pose any problems. MARVEL is expected to be operational at INL in 2027, and assuming WPI then begins a three-year Construction Permit pre-application process, it would be three to five years before transportation information would seemingly be necessary (NRC rep., personal communication, 2024-04-12). It would be prudent to receive confirmation from the NRC that Part 53 will include rulemaking on transporting pre-loaded reactors at some point prior to beginning the CP application. Overall, in terms of deploying MARVEL, if rules for pre-loaded MR transportation are released in about five years, the current lack thereof does not pose an issue.

Reflecting the uncertainty that surrounds NR projects in their early stages, particularly MR deployments, the NRC rep. suggested we clearly state that the information in our report concerning NRC regulation of WPI's deployment of MARVEL does not constitute an official NRC position and is included for discussion only.

5.3 Economics

We cannot assess the likelihood of a net financial gain or loss for deploying MARVEL, even qualitatively. Certain costs and benefits, however, MARVEL are clear:

1. Prototypes, for most products, and particularly FOAK NRs, cost more, and sometimes much

more, than the NOAK product (Black et al., 2023; Ramana, 2021).
2. The Class 104 (c) license does not permit profit with respect to AOOC, enforcing a loss on AOOC of at least 25%.
3. MARVEL would generate about $60k annually in premium-rate electricity sales.
4. MARVEL would provide only insignificant amounts of low-carbon energy.
5. Funding, and general support, from the DOE will be central to deploying MARVEL.
6. Partners, such as StarCube and INL, may provide expensive components (such as MARVEL itself).
7. Only one of the five criteria WPI expects to use to evaluate MR feasibility concerns costs and benefits (Burns et al., 2023a).

The known downsides are clear: MARVEL is a prototype, its revenue stream is limited, and even if WPI harnessed its electricity and heat, both of their low quantities would likely be insignificant in terms of revenue and savings on energy spending and carbon emissions. The upsides are less well-defined: the scope of grant funding is unknown, as are the financial obligations of our partners.

Some costs and benefits are also not quantifiable, such as WPI's feasibility criteria on "Public Perception". Deploying the first Gen. IV MR, for research and power, would attract invaluable attention and acclaim, but could bring public backlash. Costs may also only outweigh benefits in the short term or on the local scale. If WPI is willing to pay a premium, to help deliver NOAK MRs to safe and industrialized countries, then small net losses may not matter.

The uncertainty about MARVEL's lifespan adds further complexity because the costs and benefits of the two-year and eight-year lifespans are zero-sum. A two-year lifespan means less of a commitment and allows for quick iteration and improvement for another MR. This shorter lifespan, however, means that amortized costs will be greater than for the longer lifespan. In terms of the required facility, a two-year lifespan does allow more flexibility around deploying a second MR in the same facility.

5.3.1 eVinci

The costs and benefits of a more powerful MR, such as eVinci, differ from those of MARVEL. Several differences result from its much larger power output. While its electricity and heat would cover more energy costs and reduce carbon emissions, the larger heat output, in particular, may provoke more concern from the community. While eVinci's deployment TCIC might be greater than MARVEL's, its Annualized O&M Cost (AOC) (COA Account 7), Annualized Fuel Cost

(ASC) (Account 80), and Annualized Financial Costs (AFC) (Account 90) will likely be similar to MARVEL.

Like MARVEL, eVinci is also designed to be autonomous, meaning Accounts 71 through 73 will be similar in magnitude to MARVEL. Accounts 74 and 75 should be zero, or very small, and though the applicability of Accounts 76 and 77 is dependent on the details of the reactor's design and is thus currently unknown, we expect they will be low for a Gen. IV reactor. The only account which might cause eVinci's AOOC to be much greater than MARVEL's is Account 78, covering taxes and insurance. Given that eVinci is a power reactor producing large amounts of electricity and heat, insuring it may be more expensive. eVinci will only need refueling every eight years (Coelho et al., 2022). Thus, Account 81 will be zero, or very small. The applicability of the remainder of Account 80 is unknown.

If eVinci's AOC were cheaper than WPI's current spending on electricity and heat, the resultant savings would also be a benefit. According to WPI's annual sustainability report, annual electricity costs are about $5M ("Electricity Cost in Worcester, MA", n.d.). Across eVinci's eight-year lifecycle, it would "save" up to $40M in spending on electricity. While only a preliminary estimate, it is hard to conceive of eVinci's Annualized Costs (AC) being more than $5M. Thus, it is reasonable to estimate that eVinci could provide millions of dollars, if not tens of millions, in savings based on current energy spending. This leaves room for the possibility that eVinci would break even in its first lifecycle.

While this analysis does not factor in eVinci's TCIC, which, it is conceivable, might be the same order of magnitude as the $40M in electricity savings, TCIC is a different type of cost. Were TCIC to be included in the comparison – in other words, were eVinci's LCoE considered, instead of its AC – then eVinci's levelized cost of electricty and heat should be compared to WPI's current levelized cost of electricty and heat. eVinci might bring other potential benefits, such as using it's high-temperature thermal power (about 800°C) for production of hydrogen. Regardless, were the aforementioned legislative and economic restrictions to apply, it would likely be difficult to power campus without violating the Class 104 license.

5.3.2 Code of Accounts Analysis Implications

The list of second-digit cost categories outlined in Section A.4.2 serves as a starting point for an eventual TDA. We reveal which costs are not applicable due to MARVEL's Gen. IV design, such as "Turbine Generator Equipment" (Account 23), the "Simulator" (Account 28), and "Refueling

Operations" (Account 81). While true applicability of Capitalized Owner's Cost and Annualized O&M Cost is unknown, MARVEL's comparatively small requirements for facility construction and its autonomous nature will likely keep those staff-related costs low. Given MARVEL's smaller size and reduced complexity as compared with Light Water Reactors (LWRs), costs for "Spare Parts" (Accounts 52, 75), "Decommissioning" (Account 58), "Operations Chemicals, and Lubricants" (Account 74), "Utilities, Supplies, and Consumables" (Account 76), and "Capital Plant Upgrades" (Account 77) are also likely to be low. Additional costs may arise from research-related equipment and infrastructure, such as laboratory equipment and integration of beam ports.

5.4 Public Engagement

5.4.1 Photo Response

The photo response survey revealed strong overall support for operating MARVEL at WPI, with 32 out of 59 respondents expressing positive attitudes. This aligns with findings from a previous IQP study by Baker et al., where their online survey found proportionally more "Strongly Support" responses compared to our "Strongly in Favor" responses when asked about using a nuclear microreactor on campus for research purposes or power generation.

The overwhelming support likely stems from perceived benefits such as clean energy, research opportunities, advanced safety features, and the general appeal of new technology, especially at an engineering school. However, the presence of some opposition (5 out of 59 respondents) and neutrality (5 out of 59 respondents) in our survey highlights the importance of addressing diverse perspectives, echoing the mixed views on nuclear energy found in broader public opinion research.

Ecological attitudes prioritizing renewable energy and organic food preferences are associated with more skeptical views of nuclear power (Badora et al., 2021). Overall, public opinion remains divided, with nuclear energy prompting a range of reactions based on individualistic values, risk perceptions, and prioritization of different costs and benefits (Demski et al., 2015).

While our survey effectively captured attitudes, the convenience sampling likely introduced demographic biases that do not accurately reflect the intellectual diversity and makeup of the campus community. Respondents' perspectives may have been influenced by factors such as preconceived notions about nuclear safety, financial incentives, or WPI's tech-focused environment and positive perceptions of new technology. There were also instances where respondents lacked understanding, particularly regarding the safety of advanced reactors like MARVEL, possibly due to associations with less safe LWRs.

The findings align with research highlighting the importance of two-way communication, transparency about risks/safety, and tailored engagement methods for diverse stakeholder groups (Koningstein and Azadegan, 2021). With strong backing, WPI should explore feasibility while prioritizing rigorous planning – safety evaluations, environmental studies, security protocols. Given the polarizing nature of nuclear technology, sensitive framing is needed to avoid societal divisions. These potential influences and knowledge gaps underscore the need for careful interpretation of the findings and highlight the importance of implementing comprehensive engagement strategies. Addressing diverse perspectives, providing education on advanced reactor technologies, and fostering transparent dialogue will be crucial for responsible decision-making and successful implementation, should WPI proceed with exploring MARVEL's feasibility.

5.4.2 Strategies to Encourage Community Acceptance

Overcoming potential societal barriers to public acceptance emerged as a critical challenge for the proposed nuclear reactor project at WPI. Our interviews with Professor Emeritus Adams and the NRC rep. highlighted concerns rooted in past nuclear incidents like accidents and environmental contamination. This finding aligns with Dimitrov, 2021 assertions on the pivotal role of public education initiatives in addressing nuclear risk perceptions.

Insights from the literature on stakeholder engagement for socially controversial projects provide a constructive lens for developing strategies to address these barriers. Walsh's work emphasizes the necessity of proactively aligning diverse stakeholder interests and fostering committed coalitions as critical success factors (Walsh, 2015). Applying these principles, WPI could develop a comprehensive list of key community groups, opinion leaders, and decision-makers within the university, city administration, and broader Worcester region. Tailored engagement approaches could be crafted to understand each stakeholder's unique perspectives, motivations, and points of potential resistance.

To foster public acceptance, collaborative decision-making processes have proven effective for controversial facilities (Clark and Friedman, 2020). Establishing a community advisory board representing stakeholder groups could promote transparency, dialogue, and trust-building efforts (Clark and Friedman, 2020). Such a platform would facilitate two-way communication, addressing concerns proactively while allowing community voices to help shape project decisions and mitigation strategies.

5.4.3 Political Landscape Evaluation

Worcester

The political climate in Worcester appears potentially favorable for the development of a research and energy microreactor on the WPI campus. The city has demonstrated a strong commitment to renewable energy and sustainability, as evidenced by its ambitious goals to transition to 100% renewable energy for municipal facilities by 2030, residential electricity by 2035, and all energy use by 2045 ("Green Worcester Plan | City of Worcester, MA", n.d.).

This indicates the city is receptive to hosting these types of advanced energy projects. The city's "Green Community" designation which aims to increase the city's carbon free energy sources, and its associated grants which have been utilized to develop clean energy production and incentivize other entities in the city to do the same. This suggests local government support for clean energy initiatives. Additionally, the city has amended zoning regulations allowing expedited permitting for renewable and alternative energy manufacturing facilities of less than a year ("Green Community - Worcester Energy", n.d.).

Individuals that could likely have opinions and affect the possibility of implementing an MR include:

- The Worcester City Council and Mayor's Office: as the local governing body, they would play a crucial role in approving any necessary permits required. Their support would be essential. However, no active city council members have much experience or background in science or energy. The members of the City Council would likely require in-depth educational opportunities regarding MARVEL.
  - Joseph Petty, Mayor (Democrat): Petty has been a strong advocate for Worcester's sustainability initiatives and the city's transition to renewable energy. While he has not commented on nuclear power, his focus on clean energy suggests he may be open to a micro reactor project if it is framed as an innovative research endeavor that supports the city's broader goals.
  - Kathleen Toomey, Councilor, Chair of City Council Energy and Environment Committee (Democrat): as chair of the aforementioned Committee, Toomey could be a critical stakeholder. She publicly supports the city's renewable energy targets and has generally favored clean energy solutions.

- Worcester Energy and Asset Management Division: as the agency responsible for energy initiatives, they would likely be supportive of a project that aligns with the City's renewable energy goals. However, their feelings toward nuclear energy are unclear; most of their posted material targets solar and wind energy.
- WPI leadership: as the host institution, WPIs support would be critical. As discussed in the interview with Professor Adams, one of the universities previous presidents was responsible for the decommissioning of the old reactor. Also mentioned in the conversation with Professor Adams was his experience speaking with board members who actively hold opposition to nuclear energy. At this time, it is unclear how the current president and the Board of Trustees feel on the matter.

Massachusetts

Our search for historical documents and data on local public opinion yielded information relevant to state- and national-level opinions, but nothing for Worcester specifically. Several results covered the 2019 decommissioning of the Pilgrim NPP, in Plymouth MA, and the controversial issue of how to get rid of the radioactive water in the plant.

Both MA Senators, Ms. Elizabeth Warren and Mr. Edward "Ed" Markey, seem generally opposed to nuclear power. A 2021 CNN article covering difefrent types of carbon-free energy quotes Senator Warren as saying, "'We're not going to build any nuclear power plants and we're going to start weaning ourselves off nuclear energy and replacing it with renewable fuels,'... during CNN's climate crisis presidential town hall in 2019" ("5 Alternative..."). Senators Warren and Markey have high approval with Democrats and progressives. Were they to oppose MARVEL, or the larger eVinci, WPI might be faced with a difficult public relations campaign, in particular because WPI may fall out of favor with local and state power brokers if they opposed Senator Warren's views.

We identified ten MA-based groups which could conceivably oppose the deployment of an MR at WPI. These range from activist to scientific, and vary in their levels of apparent activity. In order of approximate membership: Union of Concerned Scientists (UCS), Sierra Club, Massachusetts Peace Action (MAPA), Toxics Action Center, Citizens Awareness Network, Cape Downwinders, Pax Christi, Civil Society Institute, Nuclear Free Future Coalition of Western MA (NFFCWM), and Demilitarize Western MA. For more information regarding these organizations see Appendix A.2.

The range of collaborative, activist anti-nuclear groups in MA could pose a potentially serious obstacle to a public relations campaign. Given that WPI would be deploying one of the first Gen. IV MRs in the US, expecting the involvement of groups even outside of MA is reasonable.

Potential challenges from some community members or environmental groups include concerns over nuclear safety and waste management. However, MARVEL's small scale and research use may help mitigate these concerns. Potential sources of support could be the city government, the community dependent on proper educational opportunities, as well as the academic and research sector. These entities of the Greater Worcester area may see the project as an opportunity to position Worcester as a hub for advanced energy innovation. Securing support from these stakeholders and effectively communicating the project's benefits to the broader community would be crucial for success.

Overall, the political landscape in Worcester has the potential to be supportive for the development of a research and energy micro reactor at WPI, yet it is still rather unclear as it seems many Worcester based organizations have yet to consider it. Careful stakeholder engagement and management will be essential to navigate any potential opposition and ensure the project aligns with the city's clean energy priorities.

5.4.4 Evaluation of Potential Mockup Locations and Elements

Advantages and Disadvantages of Potential Locations

All potential mockup locations have disadvantages. Most importantly, the benefits and drawbacks of various mockup locations have a zero-sum component when considering the reactions of those geographically closest. Wherever the mockup is placed, it will make the prospect of living in the same zip code as a nuclear reactor more realistic to those living near the mockup. A more realistic perspective could increase irrational speculation about the reactor by the local residents. As implied, no matter where the mockup is located, there remains a possibility for increased concern by the respective locals. A realistic representation of the eventual facility, however, is not guaranteed to provoke a net negative reaction. By appearing less dangerous than people might conceive, it could help dismiss concerns and speculation, particularly in the case of MARVEL, which itself is smaller than a Toyota Camry, a common American vehicle.

The two non-arbitrary locations for a mockup are an on-campus location and an on-site location. An on-campus location would be on the main campus. An on-site location would be on, or within eyesight of, the expected reactor facility. Given the low likelihood of the facility being on campus, the on-campus and on-site locations are mutually exclusive.

The on-campus location would make the prospect of living near a reactor more apparent to students, staff, faculty, and others who live or work on the main campus. However, the campus' educational environment, and feeling of partial isolation from the surrounding world, might help reduce concerns. Another benefit is that the locals' concerns might be reduced by whatever psychological distance exists between them and the campus. The on-site location, in comparison, offers the most realistic representation of the final facility. As such, it maximizes potential for negative and positive reactions.

Overall, our estimate of local reactions to a mockup should be the primary factor in choosing its location. If we expect generally positive reactions, a mockup would dispel concerns and speculation and would make the public more resilient to misinformation on nuclear reactors and nuclear energy. If located in an area where we expect extremely negative reactions, however, the mockup might not even serve its intended purpose. At worst, it would galvanize protesters and serve as a "ground zero" for organized opposition.

Enclosure

A full mockup, comprising an enclosure and a comprehensive, detailed facility may not be necessary for a small reactor such as MARVEL. If local reactions are positive, an argumentative mockup would be less necessary, and WPI could conceivably just display a minimal, informational mockup – perhaps a half-size model of MARVEL and some brochures and fact sheets – somewhere on campus, yet still open to the public. The lack of enclosure, and otherwise informal mockup setup, might bring benefits to itself. A comprehensive, argumentative, and detailed mockup might come off as overly convincing, implying that the underlying technology perhaps isn't safe, or that WPI has something to hide. A smaller, pared down mockup, however, would avoid this appearance.

An enclosure located in an existing building, or venue, will be cheaper, simpler, and faster to deploy than a new structure. A new structure would offer complete control over the mockup, however, and could even be used by potential researchers to lay out their lab space. Given that MARVEL is only operational for about two years, giving researchers the time to lay out and plan their experiments would allow them to begin immediately.

Mockup Elements

As shown in Table 5.1, we combine media and content from Section A.2.2 to identify potential elements, describing their primary, and sometimes secondary, purpose(s), media, and general content. The element's purpose is either informational or argumentative; an argumentative purpose is identified by its argumentative approach, where a "logos" approach relies on logical, fact-based reasoning, an "ethos" approach relies on demonstrating our capability to deploy and operate an NR, and a "pathos" approach relies on an emotional or values-based argument. These potential elements provide a broad foundation for designing a mockup that addresses the safety, utility, and sustainability of MRs.

One specific piece of argumentative content for the *ethos* approach is the NRC's decommissioning-related reports. They serve as the strongest evidence that WPI has experience maintaining a clean and safe nuclear facility; indeed, the Leslie C. Wilbur Nuclear Reactor Facility (LCWNRF) was left "suitable for unrestricted release" after decommissioning. Argumentative content based on these reports, perhaps even quoting directly, should emphasize that WPI kept the facility clean over its more than half-century of use. Specifically, we have kept our facility clean over the years it contained nuclear fuel: 48 years of operation from 1959 to 2007, and four more years of storing the spent fuel in the facility, for a total of 52 years.

If a mockup cites energy data related to a more powerful MR, that could inaccurately convey certainty in the possibility of deploying a more powerful MR after MARVEL. Given the heightened backlash that the idea of a more powerful MR could produce, care should be taken when mentioning a more powerful MR. WPI's choice to "start small", it could be said, with MARVEL, demonstrates prudence regarding new technology. A more powerful reactor could also power nearly all of campus with carbon-free energy. On the other hand, people might end up opposing MARVEL only because they see it as the first step towards a more powerful reactor with which they are uncomfortable.

Primary	Secondary	Media	Content
Logos	Info.	Video	Overview of reactor research and energy usage, with future outlook (5)
Info.	*Logos*	Banner	Technical facts (1)
Pathos, Logos	Info.	Brochure	“How Could This Affect Me?” fact sheet (3)
Logos	Info.	Banner, Brochure	Nuclear vs. other energies (2)
Pathos	Info.	Images, Video	Futuristic renders about the possibilities of MRs (7)
Info.	*Logos*	Banner	Gen. IV MRs vs. LWRs (8)
Pathos	Info.	Banner	Summary of NRC’s decommissioning report (9)
Logos	Info.	Video, Other	Geiger counter and background radiation 10
Logos	Info.	Video	Uncertainties about MRs
Pathos	Info.	Model	Life-size and scale models of MARVEL
Pathos	Info.	Model	Life-size and scale models of shielding
Logos	Info.	Video	Explanation of shielding functionality
Pathos	Info.	Banner, Brochure	Overview of research opportunities (6)
Info.	*Pathos*	Model	Setup of research experiments
Info.	*Logos, Pathos*	Video	Simulated power output information (12)
Logos, Ethos	Info.	Other	Security features (13)
Ethos, Pathos	-	Banner, Brochure, Video	Endorsement messages (14)

Table 5.1: Potential mockup elements, identified by purpose, medium, and content.

Chapter 6

Recommendations

We outline a broad range of recommendations covering deployment details such as infrastructure, licensing, economic analyses, and public engagement as well as more high-level aspects of the project. Providing answers to any of these recommendations' motivating questions would further a feasibility assessment of deploying MARVEL, at WPI, for research and for power generation, usage, and integration. Some recommendations, however, may lead to a negative, or even impossible, feasibility assessment. For example, following Recommendation 6.1.2 may reveal that it would be illegal to transport a pre-loaded MARVEL to WPI. Thus, we suggest the following Recommendations be addressed first: 1) 6.1.1; 2) 6.1.2; 3) 6.1.3; 4) 6.3.1

6.1 MARVEL Deployment, Licensing, and Construction

6.1.1 Recommendation: find a Project Manager and search for a project management team.

This study has revealed the vast quantity of information on which rests an ultimate feasibility assessment of deploying MARVEL. Beyond future feasibility assessments, MARVEL's deployment process will have multiple, inter-dependent aspects with non-linear, varying, and inter-dependent timelines. To ensure efficient, parallel progress during feasibility studies and deployment we strongly recommend the appointment of a centralized, experienced, and full-time PM or PM team.

6.1.2 Recommendation: seek regulatory clarity from the NRC and INL.

The feasibility of deploying MARVEL and of using MRs to supply meaningful amounts of low-carbon energy to campus depends on resolving several regulatory issues and uncertainties. We outline six crucial regulatory questions, in Appendix B.2, and strongly recommend their resolution in future feasibility studies.

6.1.3 Recommendation: fully characterize potential dangers of MARVEL.

MARVEL must be physically safe for WPI to consider deploying it, not only for those in the Emergency Planning Zone, but for those living nearby. MRs are indeed theorized to be safe enough from meltdowns, by design, and while theoretical analysis and computational simulation of the stresses and temperatures in MARVEL's fuel during the Maximum Hypothetical Accident indicate a high margin of safety, MARVEL has yet to be deployed (Evans et al., 2023). As such, there is no experimental data to compare with the theoretical analysis, and to claim MARVEL's safety is disingenuous. MARVEL is expected to become operational in 2027, and we recommend seeking experimental data then ("MARVEL microreactor start-up now expected in 2027, as fuel fabrication begins", n.d.). In the meantime, we recommend seeking information from INL to fully characterize the potential physical dangers of MARVEL. See Appendix B.1 for questions for INL.

6.1.4 Recommendation: determine whether we could deploy a second MARVEL after the first reaches end-of-life.

WPI's ability to continuously deploy MARVEL reactors has multiple effects. In terms of economics, being able to deploy multiple MARVEL reactors – or other MRs with similar thermal power – would help amortize Total Capital and Investment Cost. In terms of deploying another, more powerful MR, it would require a new building if MARVEL's were in use. Additionally, maintaining an RR, like MARVEL, would leave open the option of deploying a more powerful MR under a commercial license.

6.2 Reactor Economics

6.2.1 Recommendation: conduct a preliminary Top-Down Analysis for MARVEL.

Our preliminary Top-Down Analysis (TDA) provides a starting point for those more knowledge and access to detailed information to conduct a complete TDA. Grant funding, partnership agreements, and details about the reactor site, facility, and laboratory could all help clarify the applicability of certain cost categories. Information from departments on campus could serve to indicate orders of magnitude for costs. We thus recommend continuing our TDA by first examining cost category applicability in greater detail and then seeking cost estimates. We outline specific considerations for such steps in Appendix B.3.1.

6.2.2 Recommendation: *if Atomic Energy Act and 10 CFR 50.22 economic restrictions apply to Research Reactors*, determine how to estimate MARVEL's compliance.

The calculation of the monetary quantities listed in 4.1.6 is both non-trivial and essential to licensing MARVEL as a Research Reactor. Neither the Atomic Energy Act nor the CFR list or reference methods for calculating these quantities. Thus, we recommend determining how to calculate those quantities, most importantly numbers 1, 2, and 3.

6.2.3 Recommendation: *if Atomic Energy Act and 10 CFR 50.22 economic restrictions apply to Research Reactors*, estimate revenue from sales of annualized nonenergy services, or energy, or both from MARVEL.

Exact calculations of sales of nonenergy services, or energy, or both and Annual Owning and Operating Cost are impossible without more, detailed information about MARVEL and how we will use it. Estimating these values, however, can approximately indicate whether our preferred usage of MARVEL would lead to violation of the Atomic Energy Act or 10 CFR 50.22. Calculating sales of NESEB from our ideal usage of MARVEL would incorporate services such as selling reactor access to external researchers. If sales of NESEB appear greater than, to the order of magnitude, an approximated, theoretical maximum of AOOC, we could reasonably expect our ideal usage of MARVEL to violate the law and regulations. Thus, in place of exact calculations, we recommend using estimates to determine how close we would be to violating the AEA and 10 CFR 50.22.

6.3 Public Engagement

6.3.1 Recommendation: Develop strategies for gauging community perspectives on having MARVEL on campus.

Community perspectives are an important factor in deploying MARVEL, making strategies for building public awareness, trust, and acceptance important precursors to public engagement. Understanding historical and current views of the local community and the political environment can help inform these strategies. Thus, we recommend conducting archival research to investigate any documented nuclear-related activities, public engagement efforts, or debates in the Worcester area to understand historical views of the local public toward nuclear technologies.

Some key recommendations based on archival research and literature review include:

1. Take steps to foster early and frequent two-way communication and dialogue between stakeholders and community members. This could involve techniques like public surveys, focus groups, interviews, and establishing community advisory boards (Vaughn and Jacquez, 2020).
2. Prioritise transparency by openly sharing information about risks, benefits, and safety measures related to the nuclear facility. Building trust through transparency is vital.
3. Identify and work with respected local “champions” within communities who can help mobilise social change and increase perceived legitimacy of the project (Abdurrahim et al., 2022).
4. Tailor messaging and engagement approaches to specific stakeholder groups, considering the diverse perspectives within Worcester and surrounding areas regarding priorities like safety, environmental impact, economic implications, and technological aspects.
5. Implement innovative methods to improve public understanding and dispel misconceptions, such as interactive facility tours, simulations, and virtual reality experiences that provide firsthand visualisation of the inner workings of nuclear facilities (Mallik and Aithal, 2024).
6. Invite community members to participate in simulations or virtual facility tours to foster transparency, trust, open dialogue, and collaboration, while addressing challenges like costs and technological access (Mallik and Aithal, 2024).

7. Understand how the public perceives and conceptualizes risks, as risk perceptions often diverge from expert technical assessments. Consider factors like concerns for environmental pollution and beliefs about energy shortages that can indirectly influence public acceptance (Baron and Herzog, 2020; Hu et al., 2021).

6.3.2 Recommendation: comprehensively assess the history of nuclear in Massachusetts.

As mentioned in Section 5.4.3, the wide array of local and state-level individuals and groups who would possibly, or likely, oppose MARVEL indicates considerable potential for extreme opposition. A preliminary assessment of these individual's and group's political clout would help qualify this "considerable potential" for opposition. If this preliminary assessment indicates that MA' Senators could sway public opinion, even in Worcester, then a formal assessment should be done to characterize the opinions of powerful individuals and groups. We recommend carrying out the aforementioned preliminary assessment, and following up, as necessary, with a formal assessment.

6.3.3 Recommendation: determine public perceptions regarding the Leslie C. Wilbur Nuclear Reactor Facility, the NRC, and nuclear power management by the Federal Government.

Public perception of nuclear power will provide important context for public engagement. WPI has a 50-year history with the Leslie C. Wilbur Nuclear Reactor Facility, and should determine its presence in public memory, and whether associating MARVEL with the LCWNRF will be useful. Public perceptions of the federal Government as favoring MARVEL's deployment could galvanize or dissuade their opposition. Similarly, perceptions that the Government will ensure the facility's safety, prioritize the community's opinion, or be against deployment may result in less serious opposition. The range of possible reactions from the public should inform WPI's public engagement, and thus we recommend determining these public perceptions.

6.3.4 Recommendation: evaluate the potential for a facility mockup and virtual tour in context of public opinions and expected reactions.

Designing and implementing a full mockup or virtual tour of the expected facility would be a non-trivial effort, though they could provide immense value for engagement, education, and argumentation. Thus, we recommend evaluating the benefits and drawbacks of both, particularly in the context of how we could expect the community to react based on their current opinions on NRs.

If a mockup is necessary, we also recommend identifying a location and designing its elements. A location is useful to have early on in the design process because some elements have location-specific characteristics, such as size or power requirements. We also recommend determining whether researchers would benefit from a mockup; if it included laboratory spaces, they could lay out and plan their experiments before MARVEL is deployed and start their research immediately.

Chapter 7

Conclusion

We assessed MARVEL to be technically feasible, with roadblocks to its legal, economic, and political feasibility. MARVEL is suitable for neutron-based research and testing of power integration with campus infrastructure, due to its high neutron flux and small form factor. MARVEL's regulatory feasibility hinges on the future legality of transporting operational reactors. Regulatory requirements for reactor revenue and manufacturing could pose hurdles, albeit surmountable.

Economically, a quantitative cost/benefit feasibility assessment relies on characterizing unspecified costs and positive externalities. Project leaders familiar with potential funding sources and WPI's value framework, for energy infrastructure, could conceivably produce a qualitative assessment by deeming certain costs insignificant and certain benefits invaluable. Politically, the MARVEL project could provoke both positive and negative reactions from students, staff, faculty, administrators, and the local community. Determining feasibility requires more polling data and a deeper cultural analysis of nuclear power in MA.

Deploying MARVEL will require simultaneous progress on moving the project forward and resolving roadblocks. Reactor sites and facility characteristics should be identified while shielding details are being worked out. The pre-application licensing process should be started while licensing issues are being worked out with the NRC. A TDA should be initiated and regularly updated as costs and benefits are quantified. All this while reaching out to public leaders and gauging community perceptions in such a manner that does not immediately provoke opposition.

We recommend a dedicated team address these priorities and make an official, comprehensive assessment of MARVEL's technical, regulatory, economic, and political feasibility. Even a negative assessment will result in detailed information on areas of improvement; a positive assessment, and a smooth deployment, could help pave the way for a future sustained by Gen. IV reactors.

Appendices

Appendix A

Auxiliary Results and Information

A.1 Political Landscape

1. Union of Concerned Scientists (UCS):
   Based in Cambridge, MA, the UCS is a national, non-profit organization which, according to their website, "puts rigorous, independent science into action, developing solutions and advocating for a healthy, safe, and just future". They boast "nearly 250 scientists, analysts, policy experts, organizers, and communicators" and "more than 100,000 members". Their webpage on nuclear power leads with the reasonable headline, "Low-carbon electricity, with serious economic and safety issues". Their 2021 report on ARs, however, presents a generally negatively assessment of the technical, regulatory, and economic feasibility of ARs, as compared with LWRs, in the context of "the urgency of the climate crisis" (Lyman, 2021, p. 2). While UCS doesnt seem to publish activist material against nuclear power, they would likely oppose the deployment of MARVEL, particularly on the grounds that it is a prototype whose safety has yet to be consistently experimentally proven. Their glowing characterization of renewables as "our best hope in the fight against climate change," however, is indicative of potential bias, and UCS might have a stake in opposing nuclear, and MARVEL, that is based on more than purely scientific and rational analysis.
2. Sierra Club:
   While the Sierra Club is traditionally opposed to nuclear energy in large scale usage as they feel the financial obligations and the issues around waste fuel do not make it a more viable option than solar or wind. However, they may accept a microreactor project as it would be serving the primary purpose of research with energy production being an additional benefit and would only be a small instance of nuclear. They could, however, heavily oppose it if they perceive it as a precursor to a larger reactor or an increased favorability for nuclear energy.
3. Massachusetts Peace Action (MAPA):
   Based in Cambridge, MA, the MAPA "is a nonpartisan, nonprofit organization working

to develop the sustained political power to foster a more just and peaceful United States (US) foreign policy" ("About – Massachusetts Peace Action", n.d.). They are affiliated with Peace Action, a similar, national organization with more than 100,000 members, and MAPAs Board of Directors alone has 22 members. While they do not claim opposition to nuclear power, they have collaborated with groups like Nuclear Free Future Coalition of Western MA (NFFCWM). Additionally, with working groups on "Climate Action and Nuclear Disarmament", "Nuclear Disarmament", "Peace and Climate", and "Raytheon Anti-War Campaign", it is entirely conceivable that they would be opposed to nuclear power from the anti-proliferation perspective.

4. Toxics Action Center:
   Based in Boston, MA, the Toxics Action Center "offer[s] training and other resources to help people to confront local environmental threats and the polluters behind them" ("About Us - Community Action Works", 2023). With $1.5M in revenue and $3.6M in assets in 2021, they claim to have "worked with over 1,000 community groups," "directly trained more than 20,000 individuals across New England," and "held over 1,700 leadership sessions in the last 5 years". While nuclear material is not listed as an "Environmental Problem" on their website, they "spearheaded successful campaigns to shut down the Vermont Yankee NPP" and list "Against Nuclear Waste" as one of their "success stories" ("Toxics Action Center", n.d.). As a well-funded, active group with experience training activists, their opposition would need to be taken seriously.
5. Citizens Awareness Network:
   Based in Shelburne Falls, MA, the Citizens Awareness Network "is a volunteer, grassroots organization, committed to the creation of vibrant communities with the replacement of nuclear reactors and fossil fuels in New England with sustainable solutions". With more than 4,000 members, they claim, in detail, to have "won lawsuits against the NRC... [intervened] in NRC hearings on cleanup of Yankee Rowe and CT Yankee... organized a citizen health study with the MA DPH... engaged in a series of waste tours... and organized action camps in Vermont... [with] over 1,000 people" ("Citizens Awareness Network", n.d.). As a dedicated, experienced organization explicitly against nuclear power, the Citizens Awareness Network could mount serious opposition to MARVEL.
6. Cape Downwinders:
   Based in Harwich, MA, Cape Downwinders works "raise awareness and educate our local communities about the ongoing public health and safety issues during decommissioning of the Pilgrim nuclear power station in Plymouth and the spent nuclear waste storage facility" ("Cape Downwinders Homepage", n.d.). Led by twelve core volunteers, they have been active since the 1980s, and regularly update their website with updates about potential radioactivity at the decommissioned Pilgrim plant. While their website banner warns about "ongoing dangers from nuclear power production, decommissioning, and nuclear waste," they do not necessarily appear to be against nuclear power – though perhaps they are, by proxy, due to the production nuclear waste. As a apparently committed group actively set

against Pilgrim, they constitute another potential opposition group.

7. Pax Christi:
   Based out of Wayland, MA, with about a dozen local chapters – including one at Holy Cross College – Pax Christi "strives to create a world that reflects the Peace of Christ by exploring, articulating, and witnessing to the call of Christian nonviolence". This MA division seems particularly focused against nuclear weapons, with their website banner headlining a recent online video forum called, "Building A World Without Nuclear Weapons: An Urgent Imperative", which they boast has more than 1,000 views. While they have no material seemingly against nuclear power, Pax Christi is yet another group that could conceivably be strongly opposed to deploying MARVEL.
8. Civil Society Institute:
   Based in Woburn, MA, the Civil Society Institute "think tank is an action oriented research and community organizing center" ("Civil Society Institute", n.d.). In 2008, they co-issued a joint letter, signed by "67 grassroots organizations in 28 states", to President-Elect Barack Obama, listing "10 needed steps for short-term economic stimulus/job creation and additional movement to a clean-energy economy" ("Grassroots to Hold Obama to Clean Energy Promises: 67 Groups in 28 States Urge President-Elect to Act Now; 10 Key Steps Include $45 Billion in Short-Term Investments, Overhaul of National Electricity Grid to Make It More 'Renewable Friendly,' and Moratorium on New Coal-Fired & Nuclear Power Plants", n.d.). Step 10 is to "enact a moratorium on building nuclear power plants and coal fired plants in order to transit to a clean, energy efficient economy while at the same time phase in renewable and energy efficiency technologies that eliminate fossil fuel usage and nuclear power by 2050" ("Grassroots to Hold Obama to Clean Energy Promises: 67 Groups in 28 States Urge President-Elect to Act Now; 10 Key Steps Include $45 Billion in Short-Term Investments, Overhaul of National Electricity Grid to Make It More 'Renewable Friendly,' and Moratorium on New Coal-Fired & Nuclear Power Plants", n.d.). The Civil Society Institute might not only oppose a new reactor, but would have the capability to help organize other opposing parties. Their website, however, appears old, and the most recent linked material is from 2021.
9. Nuclear Free Future Coalition of Western MA (NFFCWM):
   Based in Northampton, MA, the NFFCWM works to "bring about the abolition of nuclear weapons and nuclear power" ("Nuclear Free Future Coalition of Western Ma | New England Grassroots Environment Fund", n.d.). While only having three "core members", and 20 general members on their Facebook page – whose most recent post is from 2021 – they claim to lead a coalition including the "American Friends Service Committee, New England Peace Pagoda, Arise for Social Justice, Citizens Awareness Network, Grace Church Episcopal Peace Fellowship, Haydenville Congregational church Peace and Justice Steering Committee, Northampton Committee to Stop the War, Physicians for Social Responsibility, MA" ("Nuclear Free Future Coalition of Western Ma | New England Grassroots Environment Fund", n.d.). Overall, it is difficult to judge their potential for organized opposition.

10. Demilitarize Western MA (DWM):
    A small, “anti-war, anti-imperialist and abolitionist collective”, DWM’s only self-directed online presence consists of Instagram and Twitter profiles (“Demilitarize Western Mass (@demilitarizewma) / X”, 2023). An article from October 12, 2023, covers the arrest of six of their members, who protested a weapons manufacturer, L3Harris, in Northampton, MA, by “barricading the entrance” (“Six arrested L3Harris activists given an extended pre-trial period - Massachusetts Daily Collegian”, n.d.). A co-leader of NFFCWM was present at this protest, and was “’thrilled’ to see the youth present” (“Six arrested L3Harris activists given an extended pre-trial period - Massachusetts Daily Collegian”, n.d.). While DWM may focus more on the military-industrial complex, nuclear fission – and, by extension, nuclear energy – could conceivably draw their opposition.

A.2 Facility Mockup

A mockup facility will consist of a building, or enclosure, containing the mockup itself. The mockup will contain a variety of elements, both informational and argumentative, across a variety of media. We have listed and evaluated characteristics of the enclosure and potential mockup elements as a starting point and repository for future work on a full mockup design.

A.2.1 Enclosure Characteristics

An enclosure will need basic functionality to accommodate visitors, such as appropriate heating and cooling. It will also need some type of security. The enclosure could be located on- or off-campus. An on-campus enclosure would be more convenient to visit for WPI students, staff, faculty, and administrators. It would be more secluded from the public, whereas an off-campus enclosure would be more visible, and more realistic. The mockup would likely occupy a single story, so any enclosure would not necessarily need to be more than one story. If the mockup were on the eventual facility site, its time would be limited to the start of facility construction.

A.2.2 Mockup Elements

We identify a variety of elements, both as abstract elements and in terms of specific content. We first identify categories for elements. While not intended to be comprehensive, they can serve as a starting point for evaluating each element:

- An element's explicit purpose. Is it informational? Argumentative?
- An element's argumentative approach. What is the element arguing for? Does it employ a logo-, etho-, or patho-centric approach?
- An element's medium. How does the element communicate with viewers? Via writing, images, renderings, video, or physical models? Potential media include dynamic content such as video; static content such as brochures, posters, banners, and images; and physical models or representations.

We then identify certain media, along with some specific uses for that media, without trying to designate their content:

- Brochures for taking home.
- Screens with videos.
- Life-size model of MARVEL.
- Scale model of MARVEL.
- Life-size model of shielding.
- Scale model of shielding.
- Representation of radiation levels.
- Representation of shielding functionality.
- Representation/model of potential research experiments.
- Representation/model of power generation unit.
- Representation/model of control computers and systems.
- Representation/model of large NPPs.
- Security features (e.g. fingerprint sensors, keycard access, and cameras).
- Endorsements and support from collaborative parties.

Finally, we identify specific element content:

1. Technical facts that highlight MARVEL's safety, including its low thermal power, coolant stability, passive cooling, high performance and containment under the (unlikely) Maximum Hypothetical Accident (MHA) (Evans et al., 2023), and tiny EPZ (could be represented as the size of a "gas station").
2. Technical facts that outline nuclear power's benefits over coal, fossil fuel, and current renewables.
3. General argumentative fact sheet: "How Could This Affect Me?". Should contain a balance of points about the new technology in comparison with NPPs, its utility in energy and research, and its MHA and the resulting dangers (if any).
4. Argumentative fact sheet on nuclear waste: outline what nuclear waste is, potential problems with its existence, and potential solutions. Compare nuclear waste to waste generated by other energy sources, both high-carbon and low-carbon.
5. General overview of this project, with a future outlook: neutrons collection for research experiments; electricity flows to WPI's grid and possibly the local grid; heat is captured and directed to water/steam systems.

6. Overview of potential research opportunities with MRs: include boring topics, such as materials science, and eye-catching, such as cancer research.
7. Futuristic renders and scenarios of MR uses, particularly focused on low-carbon energy, microgrids, and energy resilience in the US.
8. Comparisons of Gen. IV MRs with traditional NPPs highlighting the improvements and safety of Gen. IV reactors.
9. Summary of NRC's decommissioning report describing cleanliness and safety of LCWNRF.
10. Geiger counter with screen comparing local background radiation over time with expected facility levels (outside shielding). This could include comparisons with or from other nearby research reactors. A Geiger counter could even be placed in a publicly visible location next to the actual facility, as proof of no radioactive leakage.
11. Address uncertainties in MR feasibility: proven, experimental safety data and market demand. Addressing misconceptions and misleading nature of the "what about spent fuel waste" argument.
12. Simulated power output information. This could display statistics such as "14 houses powered for one year", "100 kT of CO2 saved so far", or "local air quality improved by...". Statistics for a more powerful reactor could also be included.
13. Actual security features, such as fingerprint sensors, keycard access, cameras, and motion sensors can be displayed.
14. A message from our supporters at the highest administrative levels, as well as messages from involved faculty. This could include a sincere acknowledgment of the risks, perceived and actual, from President Wang as well as an affirmation of the reactor's safety by faculty who will work alongside it all day.

Leslie C. Wilbur Nuclear Reactor Facility Decommissioning Report

Regarding WPI's decommissioning of the LCWNRF, Professor Adams clearly expressed that the NRC "said it was one of the cleanest decommissions they'd ever seen": "there was no contamination in the swimming pool... walls", or surrounding building faces (Professor Adams, personal communication, 2024-04-04). The NRC's Notice of Licensee Termination indeed confirms the Adams' statement:

> The FSSP indicates that all individual radiological measurement determinations made throughout the facility for surface contamination (both total and removable) were found to be less than the criteria established in the DP. Similarly, sample results from concrete, metallic liners, soil, and sediments were found to be less than the volumetric radionuclide concentration criteria established in the DP. ("Notice of License Termination for the Worcester Polytechnic Institute Leslie C. Wilbur Nuclear Reactor Facility", 2014, p. 3)

The NRC's inspections during the decommissioning process showed a safe facility:

> The inspections consisted of observations by the inspectors, interviews with personnel, and a review of procedures and records and acquisition of split samples. No health and safety concerns were identified during these inspections... The report showed that results of all samples were found to be less than the volumetric radionuclide concentration criteria established in the DP. ("Notice of License Termination for the Worcester Polytechnic Institute Leslie C. Wilbur Nuclear Reactor Facility", 2014, p. 4)

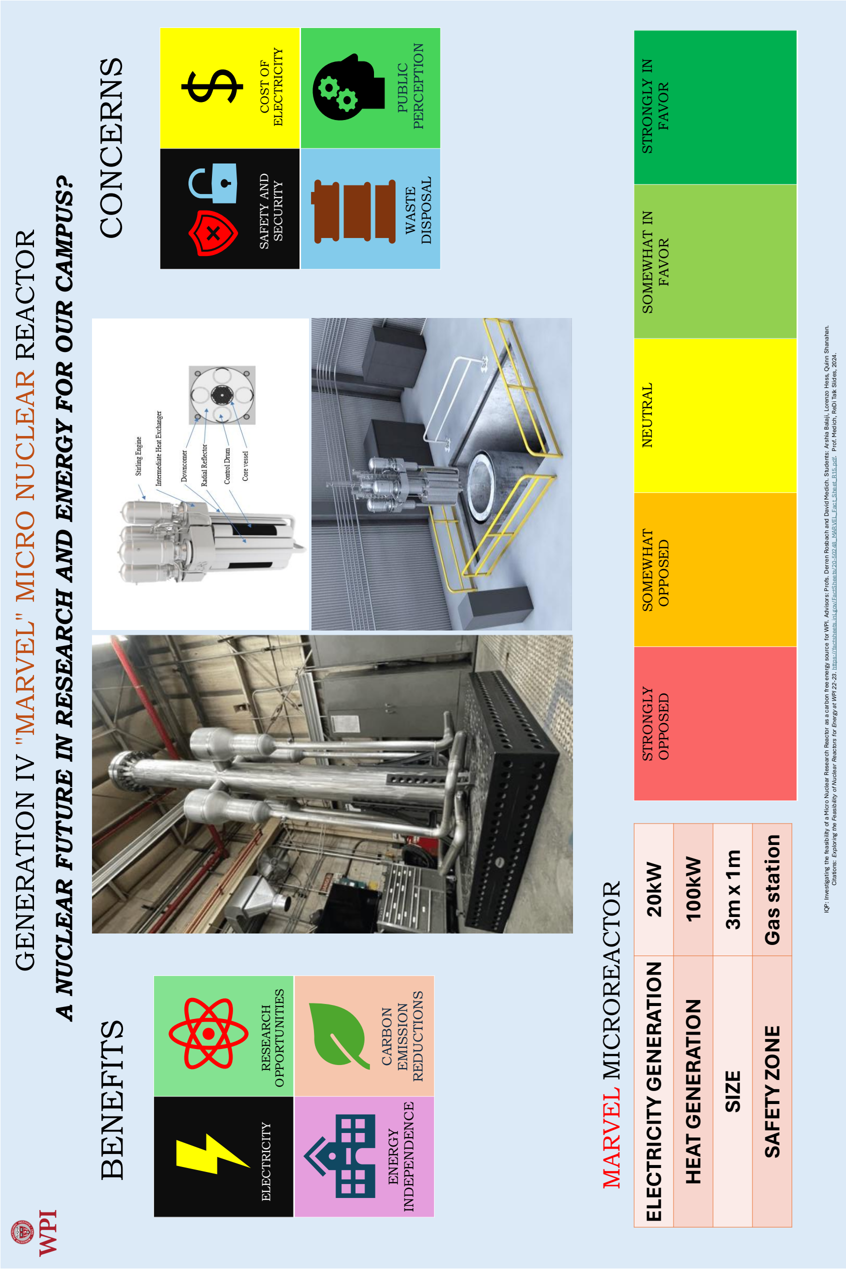
As to residual radiation and future use of the site, the NRC cleared WPI for return to normal use:

> All FSSR measurements were found to be less than the DP FSSP criteria, and NRC's analytical results from independent confirmatory surveys were consistent with the WPI FSSR results... NRC staff determined in its March 29, 2011, letter that... residual radioactivity... will not exceed 25 millirem (0.25 milliSievert) per year, and that doses would be reduced to levels as low as reasonably achievable... NRC evaluation of the WPI LCWNRF FSSR, DP, and associated documentation has determined that the facilities and site are suitable for unrestricted release... ("Notice of License Termination for the Worcester Polytechnic Institute Leslie C. Wilbur Nuclear Reactor Facility", 2014, p. 4)

Partial quotes from these excerpts, or perhaps even full quotes, could provide argumentative evidence for WPI's competence and experience with NRs.

A.3 Photo Response

Our photo response poster, printed at 24" x 36", is shown below:



WPI

GENERATION IV "MARVEL" MICRO NUCLEAR REACTOR

A NUCLEAR FUTURE IN RESEARCH AND ENERGY FOR OUR CAMPUS?

BENEFITS

- ELECTRICITY
- RESEARCH OPPORTUNITIES
- ENERGY INDEPENDENCE
- CARBON EMISSION REDUCTIONS

CONCERNS

- SAFETY AND SECURITY
- COST OF ELECTRICITY
- WASTE DISPOSAL
- PUBLIC PERCEPTION

MARVEL MICROREACTOR

ELECTRICITY GENERATION	**20kW**
HEAT GENERATION	**100kW**
SIZE	**3m x 1m**
SAFETY ZONE	**Gas station**

STRONGLY OPPOSED	SOMEWHAT OPPOSED	NEUTRAL	SOMEWHAT IN FAVOR	STRONGLY IN FAVOR

IQP: Investigating the feasibility of a Micro Nuclear Research Reactor as a carbon free energy source for WPI. Advisors: Profs. Derren Rosbach and David Medich. Students: Arshia Balaji, Lorenzo Hess, Quinn Shanahan.
Citations: *Exploring the Feasibility of Nuclear Reactors for Energy at WPI 22-23.* https://factsheets.inl.gov/FactSheets/20-50248_MARVEL_Fact_Sheet_R15.pdf. Prof. Medich, ReDi Talk Slides, 2024.

A.4 Economics

A.4.1 GECOA and LCoE

The LCoE for NPPs depends, in part, on initial costs. High overnight costs for NPPs are due, at least in part, to quality requirements for specialized materials, enhanced safety features, and backup control and other equipment. High financing costs, especially for large NPPs, result from large loans compounded by long construction periods. The capacity factor of an NPP also plays a large role in LCoE as it most directly correlates with revenue. The capacity factor (0-100%) measures how often an energy source is outputting maximum power (capacity factor of 100% means the source is producing maximum power all the time). Nuclear power has the highest capacity factor of any electrical energy technology, at a 93.5% average in the US (compare with 57% for natural gas, 48% for coal, 39% for hydropower, 35% for wind, and 25% for solar). Thus, the higher capital and financing costs for NPPs might be offset in the LCoE by the higher capacity factor.

The cost of nuclear fuel generally lowers the LCoE for NPPs because it is cheaper than coal and gas "on the basis of dollars per megawatt hour of electricity produced" (Black et al., 2023, p. 7). The cost of nuclear power is also "much less sensitive to [nuclear] fuel price volatility" than is the cost of power derived from fossil fuels because nuclear "fuel costs represent a much lower share of total generating costs than for fossil fuel[s]" (Black et al., 2023, p. 7).

For nuclear power, "fixed O&M costs" are usually higher than for fossil fuel-derived power because of "higher costs per kilowatt year for cooling systems, O&M personnel, and waste management" (Black et al., 2023, p. 7). Nuclear power, however, has "lower variable Operations and Maintenance (VO&M)" than fossil fuel power (Black et al., 2023, p. 7). The production period or operational horizon also affect LCoE. NPPs are often licensed for 40-60 years of operation, as compared to 20-25 years for wind and solar, 20 years for gas turbines, and 40 years for coal plants.

The validity of the LCoE metric is partially determined by the regulations and structure of the electricity market. In regulated markets, where "electricity prices are stable for extended periods, LCoE is a useful rubric to estimate the economic viability of new energy technologies" (Black et al., 2023, p. 7). In less stable or "competitive wholesale energy markets", however, "a key component of maximizing revenue from power sales is the ability to reduce power output... during periods of low electric prices", and, conversely, increase output during periods of high electric prices (Black et al., 2023, p. 7).

A.4.2 Preliminary TDA

What follows is the preliminary TDA described in Section 4.1.6

CPC

Account Number	Cost Type	WPI's Burden
11	Land and Land Rights	All
12	Site Permits	All
13	Plant Licensing	All
14	Plant Permits	All
15	Plant Studies	Some, possible grant backing.
16	Plant Reports	Some, possible grant backing.

CDC

Account Number	Cost Type	WPI's Burden
21	Structures and Improvements	All
22	Reactor Equipment	Unknown. INL or StarCube may share.
23	Turbine Generator Equipment	No applicability.
24	Electrical Equipment	Some
25	Heat Rejection System	Unknown applicability.
26	Miscellaneous Equipment	All.
27	Special Materials	Unknown applicability.
28	Simulator	No applicability.

CIC

Account Number	Cost Type	WPI’s Burden
31	Field Indirect	All
32	Construction Supervision	All
33	Commissioning and Start-up Costs	Some
34	Demonstration Test Run	All
35	Design Services Offsite	Some
36	Production and Construction Management (PM/CM) Services Offsite	Some
37	Design Services Onsite	Some
38	PM/CM Services Onsite	Some

Capitalized Owner’s Cost (COC)

Account Number	Cost Type	WPI’s Burden
41	Staff Recruitment and Training	Unknown applicability
42	Staff Housing	Unknown applicability
43	Staff Salary-Related	Unknown applicability

Capitalized Supplementary Costs (CSC)

Account Number	Cost Type	WPI’s Burden
51	Shipping and Transportation	Unknown applicability
52	Spare Parts	Unknown applicability
53	Taxes	Unknown applicability
54	Insurance	Unknown applicability
55	Initial fuel core load	Unknown applicability, possible grant backing
58	Decommissioning	Some

Capitalized Financial Costs (CFC)

Account Number	Cost Type	WPI’s Burden
61	Escalation	All
62	Fees	Unknown applicability
63	Interest During Construction	Some

AOC

Account Number	Cost Type	WPI’s Burden
71	O&M Staff	Some
72	Management Staff	Some
73	Salary-Related	Some
74	Operations Chemicals, and Lubricants	Unknown applicability
75	Spare parts	Unknown applicability
76	Utitilies, Supplies, and Consumables	All
77	Capital Plant Upgrades	Some
78	Taxes and Insurance	All

ASC

Account Number	Cost Type	WPI’s Burden
81	Refueling Operations	No applicability
84	Nuclear fuel	Unknown applicability
86	Fuel Reprocessing Charges	Unknown applicability
87	Special Nuclear Material (SNM)	Unknown applicability

AFC

Account Number	Cost Type	WPI’s Burden
91	Escalation	No applicability
92	Fees	Unknown applicability
93	Cost of Money	Unknown applicability

Appendix B

Future Research

B.1 MARVEL's Safety

The following questions will likely be best answered by INL, the manufacturer:

1. Is the MHA analyzed in the Fuel Performance Report (FPR) for MARVEL's fuel pins, specifically? Is there a different MHA for the entire reactor structure?
2. The most significant finding of the MHA analysis is that "the MARVEL fuel element maintains its geometric stability and structural integrity". Does this maintenance of "geometric stability and structural integrity" necessarily imply that nothing disastrous, or even dangerous, will happen during MHA conditions? How is this implication formed?
3. The FPR states that the "hoop stress generated in the cladding during [MHA]... is nearly an order of magnitude less than the predicted yield strength". What can be inferred, in terms of the entire reactor's safety, from the hoop stress's margin of safety of an order of magnitude?
4. The FPR states that the "fuel meat peak temperature limit of 925°C... is about 200°C higher than the peak fuel temperature predicted" at MHA. What can be inferred, in terms of the entire reactor's safety, from the peak temperature's margin of safety of 200°C?
5. Based on the fact that MARVEL's fuel "successfully meets its design and safety requirements under normal and most extreme accident conditions with a large safety margin", how would you characterize a statement given to the local community that "they would remain safe during MARVEL's MHA"? As accurate? Inaccurate? Honest? Disingenuous?
6. What other accident, and MHA, scenarios, could MARVEL have?
7. What accident potential does the sodium coolant pose, for example if it ended up mixing with surrounding air?
8. What accident scenarios that the public associates with traditional NPPs does MARVEL avoid or mitigate?

B.2 Regulatory Issues and Uncertainties

We recommend achieving clarity with the NRC and INL on crucial regulatory issues. These points of clarification require feedback from the NRC in some capacity that is more official than a student interview, and as such should be facilitated by an official PM or PM team. The feasibility of deploying MARVEL, regardless of its purpose, depends on answers to Questions 1 and 2. MARVEL's facility requirements and deployment timeline depend on answers to Questions 3 and 4. The feasibility of using an MR to supply meaningful amounts of low-carbon energy depends on answers to Questions 5 and 6. In the pre-application phase, methods for communication with the NRC would be outlined in an Regulatory Engagement Plan. While feasibility studies would occur before pre-application, WPI could still outline, and follow, methods for NRC communication based on existing Regulatory Engagement Plans or the Nuclear Energy Institute's guidelines for developing Regulatory Engagement Plans (NEI, 2018).

1. How will a pre-loaded MARVEL be transported from INL to WPI?
2. Could MARVEL be manufactured without fuel and have the fuel installed on-site, at WPI?
3. Does INL have a manufacturing license?
4. How long, exactly, within the two to eight year range is MARVEL's lifespan?
5. Is power generation, usage, and integration considered an R&D activity that is exempt from the economic restrictions of the AEA §104 and 10 CFR 50.22?
6. Is power usage and integration considered a "sale" under the AEA §104 and 10 CFR 50.22?

For reference, two regulatory certainties are that the Class 104 (c) license under the AEA is the only available license allowing neutron-based research and that Part 50 is the only regulatory pathway for RRs. As applicable during feasibility studies, we recommend assuming that MARVEL will be licensed with Part 50 under the Class 104 license.

Another potential issue, regarding eVinci, is eVinci's 15MWt thermal output. Research reactors are limited to 10MWt of thermal power, so eVinci would be classified as a Test reactor. Future research should examine the implications of eVinci being classified as a Test reactor as compared with a Research reactor.

B.3 Economics

B.3.1 Future Prelminary TDA Considerations

Someone with knowledge of grant funding to identify costs that might be covered by grants, and for someone knowledgeable about WPI's partnerships – particularly with StarCube and in terms of construction companies – to identify costs that would consist entirely of payments to those partners.

A complete TDA would require exact detail and specifications about the construction company as well as the reactor's site, facility, laboratory, and plans for operation. A team of students working with WPI's Department of Facilities, the Office of Finance and Operations, the academic department(s) managing the reactor, and the WPI Police, could reasonably create rough cost estimates, at least within order of magnitude, for each cost category. If quantitative data is lacking, they could attempt to rate the relative expense of certain cost categories, perhaps relative to their top-level account, to determine an approximate cost with a margin of error (e.g. [75], Spare Parts, would probably be low compared to [78], Taxes and Insurance).

Following through with this type of partial TDA could provide a preliminary estimate for the total cost of the project. To gauge the potential for reducing this total cost, the most expensive cost categories could be identified and revisited for reduction, perhaps through a more detailed calculation or revised estimate of grant coverage. Costs that may be specific to WPI's deployment which are not explicitly included in the COA model, such as research and laboratory equipment, should then be brainstormed and included. A future economic analysis should also estimate how much money WPI would save and generate in terms of electricity, heat, "carbon credits", selling to the local grid, selling research services, and additional, research-related grants.

B.3.2 Questions on Costs, Benefits, and COA Model

We recommend considering the following questions in feasibility analyses of any MR:

1. If WPI assigns a current employee to operate the reactor, how should that factor in? Will the employee be paid more or receive better benefits? Does another person need to be hired to do that employee's previous work?
2. How should we factor in the cost of installing another MARVEL once the first one runs out of fuel?
3. Has any economic analysis been done on MARVEL?

4. How does an MRs licensing status affect financing?
5. Will sales of energy or reactor services constitute a significant portion of MARVEL's expected economic benefits? In other words, will MARVEL's only option for profitability, or for its benefits to outweight its costs, end up triggering the economic restrictions of the Class 104 license?
6. How much money would WPI be willing to lose in exchange for a drastic reduction in carbon emissions?
7. How could MARVEL be studied to help inform the economic feasibility of deploying a more powerful MR at WPI?
8. How could an MR deployed at WPI be studied to help inform the economic feasibility of MRs in general?
9. How does WPI rank "Financial Incentives" relative to the other criteria for evaluating energy systems as part of its third phase of energy and infrastructure renovation plans?

The following questions arose as part of the preliminary TDA, and are enumerated by their respective Account Number. Future work on a TDA of MARVEL could consider:

41, 71 What types of and how many staff does MARVEL require?
42, 43, 71 Would WPI pay for staff at a reactor power plant? Would a subcontractor, like the one managing WPI's current power plant?
51 Who is transporting MARVEL to campus? How expensive is that transport related to all other necessary transport (e.g. for parts)?
53 What types of taxes are involved? Is WPI exempt as a non-profit educational institution? Does nuclear power or low-carbon energy receive any writeoffs or benefits? Local, state, and federal?
54 Who needs what insurance? Does WPI's status as the Licensee affect this? How does MARVEL's location affect insurance costs?
55, 84, 86 Are we buying MARVEL's fuel? Would a grant pay for it? Is the initial (and in fact only) fuel load somehow charged separately to the reactor by the manufacturer or vendor? Who takes care of the fuel once it is spent?
58 Who does WPI work with to decommission? Does the vendor pay to come take MARVEL away? How much of the decommissioning process is the vendor responsible for?

B.4 Public Engagement

We recommend considering the following questions in future feasibility studies:

1. Could publishing and emphasizing too much argumentative information about MARVEL make it seem like more of a hazard that it actually might be?

2. Could WPI, in collaboration with the Worcester government, commission a study on how local pollution, air quality, and general health levels would be affected were WPI to power nearly all of campus with an MR?

B.4.1 Virtual Tour of Facility

A virtual tour of the reactor facility has the potential to complement a facility mockup. Like a mockup, it would also provide opportunities for student involvement. Steps toward creating and implementing a virtual tour are as follows:

1. Select a platform to create the virtual model. Options include:
    - Interactive website with 3D models, videos, and informational sections for those accessing the tour via desktop or mobile devices.
    - Create a virtual reality experience for users with VR headsets, allowing them to immerse themselves in a realistic simulation of the GEN IV reactor facility.
    - Utilize 360-degree video tours for a more passive viewing experience, suitable for users without access to specialized VR equipment.
2. Developing content for this virtual tour model.
    - Create high-quality multimedia content that effectively communicates key information about the GEN IV reactor project
    - Produce informative videos explaining the reactor's design, operation, safety protocols, and potential benefits.
    - Develop interactive 3D models or simulations to illustrate complex concepts such as nuclear reactions, reactor components, and safety features.
    - Write concise yet comprehensive text descriptions to accompany visual elements and provide additional context.
    - Include testimonials or interviews with project leaders, researchers, and stakeholders to add credibility and humanise the experience.
3. Design User Experience to prioritise simplicity and ease of navigation to ensure a smooth user experience
    - Implement intuitive controls and navigation tools, such as clickable hotspots or menus, to allow users to explore different areas of the facility effortlessly.
    - Optimise loading times and minimise unnecessary distractions to keep users engaged and focused on the content.
    - Include clear instructions or tooltips to guide users through the tour and explain how to interact with various elements.

  - Test the virtual tour with representative users to identify any usability issues or areas for improvement before launch.

4. Integrate feedback mechanisms
    - Include embedded survey forms or feedback buttons throughout the virtual tour, prompting users to share their thoughts, questions, and suggestions.
    - Allow users to leave comments or ask questions directly within the virtual environment, fostering dialogue and interaction.
    - Utilize interactive polls or quizzes to gauge users' understanding of key concepts and gather insights into their preferences or opinions.

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