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MARVEL Utilization Plan

June 2024

Microreactor Program

Abdalla Abou-Jaoude and M.W. Patterson
Idaho National Laboratory

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Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

This report provides a high-level overview of the utilization plan for the MARVEL microreactor. The main focus is on discussing testing and application-demonstration opportunities that leverage the reactor. With the reactor rapidly progressing towards demonstration, along with the short (2-year) operational window, it was deemed critical to establish a basis for how stakeholders can engage with the program and leverage the reactor as a testbed. This report discusses potential opportunities to use MARVEL, leveraging from data and design access to testing novel controls, and novel nuclear-electric and nuclear-heat applications. It provides guidance for interested stakeholders on potential funding opportunities that can be pursued to support tests during the operational lifetime of the reactor. The report discusses the recommended strategy for outreach and the organizational structure to review and select projects for participation. Interested stakeholders are encouraged to fill out a questionnaire on how they could leverage MAVEL at this link.

It is important to emphasize that this is intended to be a living document (updated annually or as needed) with revisions issued as the MARVEL demonstration timeline evolves. Similarly, the framework for engagement is subject to change as the project progresses.

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TABLES

ACRONYMS

AMMT	Advanced Materials and Manufacturing Technology program
ARD	Advanced Reactor Demonstrations
ART	Advanced Reactor Technologies
ASI	Advanced Sensors and Instrumentation program
CD	Control drum
CRADA	Cooperative Research and Development Agreement
EC	Engineering change
FEEED	Front-End Engineering and Experiment Design
FSP	Fission Surface Power
GAIN	Gateway for Accelerated Innovation in Nuclear
HALEU	High-assay, low-enrichment uranium
HTSE	High-temperature steam electrolysis
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LDRD	Laboratory Directed Research and Development
MACS	Microreactor Automated Control System
MARVEL	Microreactor Application Research Validation and EvaLuation
MRP	MicroReactor Program
MRWD	Material Recovery and Waste Form Demonstrations
NCRC	Nuclear Computational Resource Center
NEAMS	Nuclear Energy Advanced Modeling and Simulation program
NRC	Nuclear Regulatory Committee
NRDS	Nuclear Research Data System
NRIC	National Reactor Innovation Center
NTD	National Technical Director
OSTI	Office of Science and Technical Information
PCAT	Powerline Conductor Accelerated Testing
PIE	Post-irradiation examination
R&D	Research and development
SA&I	Systems Analysis and Integration program
SAR	Safety analysis report
SBIR	Small Business Innovation Research
SSC	Structures, systems, and components

TCF	Technology Commercialization Funds
TES	Thermal-energy systems
VIBRANT	Visual Benign Reactor As Analog for Nuclear Testing

MARVEL Utilization Plan

1. INTRODUCTION

The purpose of this plan is to provide a framework within which government programs, industrial developers, and academia can engage with the Microreactor Applications Research Validation and Evaluation (MARVEL) project and benefit from its development, startup, operation, and decommissioning. This plan identifies potential MARVEL end users and the mechanisms by which they can engage with the reactor project. It provides a general list of the capabilities that can be tested, an associated high-level schedule for end user tests, possible sources of funds for tests, and the organizations that will review, approve, and coordinate testing. It summarizes the processes by which tests, experiments, and end users will be prioritized. The timing of this plan's publication is intended to provide potential end users with an adequate period to design tests and experiments, prepare proposals, and secure funding prior to MARVEL's start up.

1.1. Motivation for MARVEL

The primary mission of the Department of Energy, Office of Nuclear Energy (DOE-NE) is to advance nuclear power to meet the United States' energy, environmental, and national-security needs by enhancing the long-term viability and competitiveness of the existing U.S. reactor fleet, developing an advanced-reactor pipeline, and implementing a national strategic fuel-cycle and supply-chain infrastructure. DOE-NE supports a variety of advanced-reactor designs, including microreactor concepts, which are defined as factory-fabricated, transportable, and self-adjusting nuclear reactors with power typically below 50 MW_{th} [U.S. Department of Energy Idaho Operations Office 2021].

Many microreactor concepts under development in the United States anticipate commercial deployment within the next decade. The DOE-NE Advanced Reactor Technologies (ART) Program develops new and advanced-reactor technologies to improve nuclear-energy competitiveness and support meeting the nation's energy, environmental, and national-security needs. Part of DOE-NE's role is to develop unique experimental infrastructure that enables testing and demonstration to reduce the risk in new technology. As part of ART, the Microreactor Program (MRP) focuses on applying these technologies and capabilities to microreactors to advance their deployment. Idaho National Laboratory (INL) leads DOE-NE efforts for research, development, and demonstration projects to help the nation maintain and expand the use of nuclear energy, offering unique facilities and capabilities that include modeling and simulation validation, nuclear-materials and fuels development and testing, instrumentation and sensors implementation, and systems testing. INL also performs research on integrated energy systems (IESs) that includes coupling nuclear- and renewable-energy resources.

In support of the DOE-NE, ART, and MRP missions, the MRP designed and is building MARVEL, an 85kW_{th} scaled, prototypic microreactor intended for installation and operation in the north storage pit at the INL's Transient Reactor Test (TREAT) Facility. The MARVEL demonstration is not intended for permanent use. Following reactor start-up and physics testing, the testing phase of the demonstration—during which microgrid, thermal storage, and process application can be demonstrated and tested—is currently planned to last up to two years. The intent of the project is to demonstrate technology and technological processes; all products (including electricity) during this period will be for research purposes only. Following operations, MARVEL will be decommissioned, providing additional opportunity for data collection, testing, and demonstration focused on end of life, including, for example, understanding the back end of the fuel cycle or the effects of irradiation on materials [Johnson, Patterson, and Wagner2022].

1.2. Background on MARVEL Demonstration

MARVEL is a beryllium- and graphite-reflected, hydrogen-moderated, solid-fuel, loop-type reactor, capable of generating up to 100 kW_{th} power. It will operate at a nominal 85 kW_{th}, with a design life of 2 effective full-power years, operating intermittently within a 2-calendar-year (CY) period. It will hold 36 fuel rods containing 30 wt-% uranium, enriched to 19.75% U-235. MARVEL fuel elements will be identical to standard Training Research Isotope General Atomics (TRIGA) fuel elements, with the exception that each fuel rod will contain five fuel meats instead of three. The core will be surrounded by a thick, axial neutron reflector, composed of metallic Be.

The primary coolant system (PCS) is a four-loop hydraulic circuit, transporting heat from the nuclear fuel to the four intermediate heat exchangers (IHX) by natural circulation of the primary coolant, eutectic NaK liquid metal). The primary coolant will be 120 kg of NaK liquid metal which, when heated by the fuel, rises above the top of the core, through an upper grid plate and distribution plenum to the IHXs. The IHXs extract the heat to four identical secondary loops containing eutectic (e) GaInSn. The cooled NaK then flows downward through four downcomer pipes where it mixes in the lower plenum. From the lower plenum, the NaK rises again through the active core by buoyancy forces created by the fuel heating the NaK, completing the primary circuit.

The PCS is the high-temperature, low-pressure boundary that houses the core internals, reactor primary coolant, and argon-gas headspace. In addition, the PCS passively maintains decay-heat removal capability. The boundary is a metal weldment made from 316H stainless steel for high-temperature reactors, designed per American Society of Mechanical Engineers (ASME) Section III Division 5.

Four secondary loops transport liquid metal, eGaInSn, by natural circulation. They transfer heat to four off-the-shelf Stirling engines, each of which produces 5–7 kW_e at 85–100 kW_{th} from the core. Alternatively, a different IHX may be installed in the future to test process-heat applications, but only early design alternatives have been evaluated. Design of a different IHX may need to couple specific process-heat applications or other power-conversion systems to the MARVEL core.

Reactivity control and shutdown are provided by a combination of active and passive components. Four control drums (CDs), which rotate outside the core barrel, and a central insurance absorber (CIA), which inserts down the center of the core, provide active reactivity control. The CDs are made of BeO, which acts as a neutron reflector. One third of the CD surface is covered by a B_4C plate that absorbs neutrons. Rotating the drum either increases reactivity by increased neutron reflection or decreases reactivity through neutron absorption. Sufficient rotation of the B_4C towards the core will shut down the reactor. The second active component is the CIA rod that can be inserted in the central pin location in the core. The CIA is fully withdrawn during operation and inserted during shutdown. Passive reactivity-control components include stationary reflectors located between the CDs and the hydrogen and graphite components within the fuel.

Instrumentation and controls are connected to the CD and CIA motor drives for positioning within the reactor structure. Passive actuation functions are built into the design for loss of power and inadvertent energizations of the motors. Instrumentation to ensure reliable plant control and early recognition of abnormal conditions is also provided. A cutaway view of the MARVEL microreactor with all major systems is shown in Figure 1.

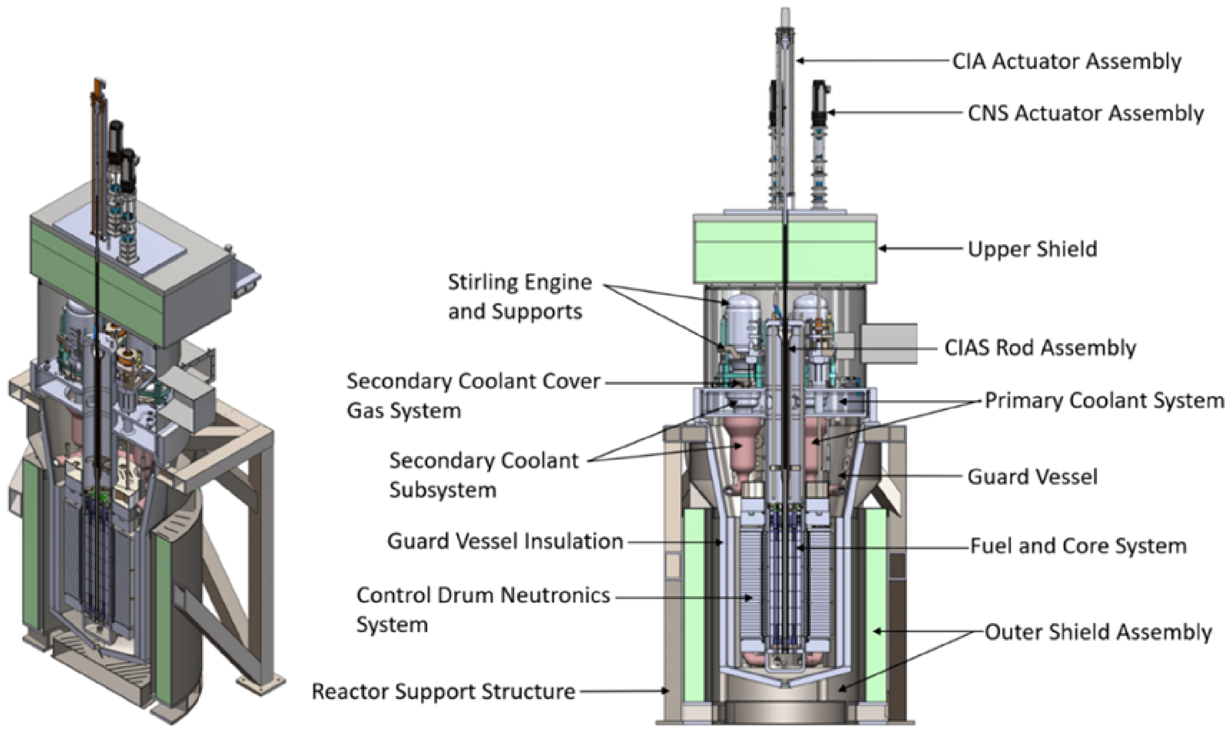

Figure 1. MARVEL microreactor cutaway view [MARVEL Design Team 2023].

The primary- and reactivity-control systems will fit within TREAT's north storage pit and occupy a space smaller than 8 ft long, 12 ft wide, and 10 ft high (less than 960 ft^3, roughly equivalent in size to a small bedroom). Additional equipment needed for testing, such as heat-rejection equipment and microgrid components, will be installed outside MFC-720 in portable trailers or in other temporary arrangements. Installation of support equipment, such as MARVEL control cabinets inside MFC-720, will be temporary. Permanent TREAT modifications are included in the institutional general plant project (IGPP) TREAT microreactor-experiment cell (T-REXC) and excluded from the MARVEL project.

The MARVEL reactor will be remotely operated from the MFC-724 control room. Most of its components will be fabricated off-site and installed in the TREAT north storage pit. It will not be permanently affixed, and at the end of its useful life, it will be defueled and removed. The equipment and materials are currently planned to be disposed of as waste or dispositioned for long-term interim storage as used nuclear fuel [MARVEL Design Team 2023].

1.2.1. MARVEL Status

MARVEL completed 90% Final Design, as defined in DOE-Standard (STD)-1189, "Integration of Safety into the Design Process," in September 2023. Completion of 90% Final Design indicates that the project design can support procurement, construction, testing, and operations [Office of Nuclear Safety (AU-30) 2016]. The design is organized into systems and subsystems, as shown below, where each system is given an engineering change (EC) number in the TREAT engineering files. These may be helpful as a reference when requesting data.

- Nuclear Core & Fuel System (EC 1759)
  - Neutronics
  - Fuel-performance report
  - Fuel-fabrication and shipping

- Reactivity-control system (EC 1756)
  - CDs and CIA actuators
  - CD system analysis
  - CD and seal
  - CIA housing
- MARVEL reactor structure (EC 1755)
  - Thermal hydraulics
  - ASME analyses
  - ASME Service Level D
  - Seismic analyses
  - NaK loading system
- Instrumentation and control (I&C) (EC 1758)
  - PCS detectors
  - Reactivity control I&C
  - Stirling=engine controls
  - Safety-related functions
  - Control software
- Power-generation system (EC 1757)
  - IHX and secondary fluid
  - Stirling cooling loop
  - Stirling engine.

The north storage pit at TREAT will be configured as part of a separate project, T-REXC, intended to establish a multipurpose, technology-agnostic critical experiment-testing capability. Reconfiguration of TREAT for this purpose includes establishing appropriate radiation shielding, providing appropriate (electrical, heating, ventilation, and air conditioning [HVAC], and I&C) support systems to the pit, and the installation of generic reactor components (neutron source, neutron reflectors, etc.). This equipment will be applicable to most critical experiments and small-scale microreactor demonstrations located in the TREAT pit, of which MARVEL will be the first. The structures, systems, and components (SSCs) for T-REXC include:

- North storage pit shield structures (to prevent neutron activation of the concrete)
- Pit lid, with integrated top shielding
- I&C infrastructure (to capture and display T-REXC facility data and demonstrator data)
- Electrical power infrastructure, including electrical-supply panel near the pit, standby power generator, etc.
- Control-room infrastructure, including signal and data transfer between MFC-720 and MFC-724
- Ventilation, including high-efficiency particulate air filter and exhaust monitoring
- Fire detection, including of sodium and sodium-potassium alloy (NaK) fires
- Fire-mitigation systems, in accordance with the TREAT fire-hazards analysis
- Neutron source for start up
- Radial static-neutron reflectors
- Reactivity-control materials in the form of BeO CDs for neutron-population control

- A system to preclude water intrusion into the pit
- Radiation monitoring.

MARVEL and T-REXC 90% final designs are being incorporated in the TREAT safety analysis report (SAR) as an addendum. DOE-ID approval after submission in July 2024 authorizes the start of procurement and construction. Several components and subsystems were authorized for long-lead or early procurement.

- Material procurement for 316H SS SSCs
- High-assay, low-enrichment uranium (HALEU) fuel feedstock
- Fabrication of 316H SS SSCs
  - Primary-coolant boundary
  - Guard vessel
  - Structure frames and outer shields
  - Reactor support structure
  - Secondary support structure
- Stirling engines and controls
- MARVEL fuel system
- Beryllium metal reflectors and dowels
- Procurement and fabrication of the reactivity-control system
- BeO components that may be used after MARVEL is decommissioned (T-REXC project)
  - CD reflector
  - CD reflector shield-bracket container
  - Outer reflector
  - Outer reflector shield-bracket container
  - Outer reflector thermocouple.

The procurements were initiated and are in various states of progress. HALEU feedstock was shipped from the Y12 complex in Oak Ridge, Tennessee, to TRIGA International in June 2023, and fuel fabrication is in progress. Delivery of the fuel to INL is expected in 2025. Approval of the preliminary documented SAR signifies that the reactor can be operated safely and authorizes the project to proceed with the rest of procurement, fabrication, and construction. The final documented safety analysis will be issued as an addendum to TREAT's final SAR. Its issue after incorporation of minor changes during construction is anticipated in late 2026-timeframe. This enables MARVEL to proceed with fuel loading after approval by the DOE startup authority.

1.2.2. MARVEL Project by Phase

MARVEL is organized into three phases, as shown in Figure 2, and is currently part-way through the first phase. Consideration of where proposed testing falls regarding progression through the phases will be considered in evaluating proposals. Descriptions of each phase follow the figure.

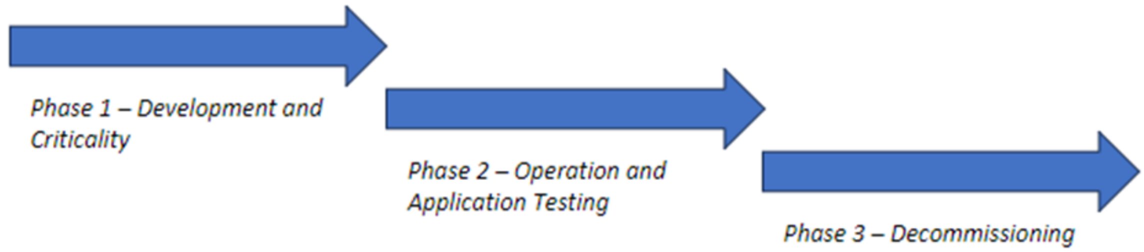

Figure 2. Entire MARVEL project by phase.

Phase 1 Development and Criticality includes design and construction, incorporating all phases of design, environmental permitting, development of the safety basis, procurement, fabrication, and construction. It also includes staffing, training, procedure development, and readiness. Phase I concludes after fuel is loaded, and the reactor achieves initial criticality, completes physics and acceptance testing, and is released to TREAT for unrestricted operations.

Phase 2 Operation and Application Testing includes testing of the power-production system and demonstration of industrial applications. At a minimum, power production will be demonstrated. It is anticipated that industrial end users will design and fabricate the equipment and processes they wish to demonstrate during this phase, which is expected to last 2 calendar years. Development and issue of a program plan for this 2-year period is planned for later in FY 2024.

Phase 3 Decommissioning after two years of testing. Following the final shutdown, a cool-down period is anticipated to allow decay of some fission products, which will reduce radiation fields. The reactor's NaK primary coolant will be drained, treated, and disposed of, as will be the eGaInSn secondary coolant. Residual NaK will be treated, and the reactor will be defueled. The planning basis for long-term interim storage of used fuel is Building number CPP-603 at the Idaho Nuclear Technology and Engineering Center (INTEC) and disposal of the equipment and materials is the Idaho Comprehensive Environmental Response, Compensation, and Liability Act Disposal Facility (ICDF) at INTEC. An evaluation by the Idaho Environmental Coalition in FY 2022 indicates that MARVEL's waste falls within the ICDF waste-acceptance criteria [Idaho Environmental Coalition 2022]. An update of the decommissioning plan for MARVEL is planned for late FY 2024.

2. MARVEL USABILITY

As previously stated, the MARVEL reactor is currently intended to operate on a 2-year timeline. This short window of testing will inevitably require future potential stakeholders to conduct preparatory steps well in advance of the start of reactor operations. Figure 3 shows an illustrative timeline of when each phase of the project is currently anticipated to occur. Phase 1 is currently expected to conclude by the end of CY 2027 or early CY 2028 Phase 2 would start shortly thereafter and conclude 2 years later (likely CY 2030). At that point, Phase 3 would begin, and it is not currently restricted in duration, which depends on examination or use of MARVEL components for research and development (R&D) purposes by other programs. It is important to note that the timeline may be subject to change based on possible schedule delays in the execution and operation of MARVEL or changes in DOE guidance—specifically, as it relates to the 2-year window. The timelines projected here should be interpreted as best estimates at this stage in the project. They are provided to help future users plan in earnest for the short window of MARVEL operations.

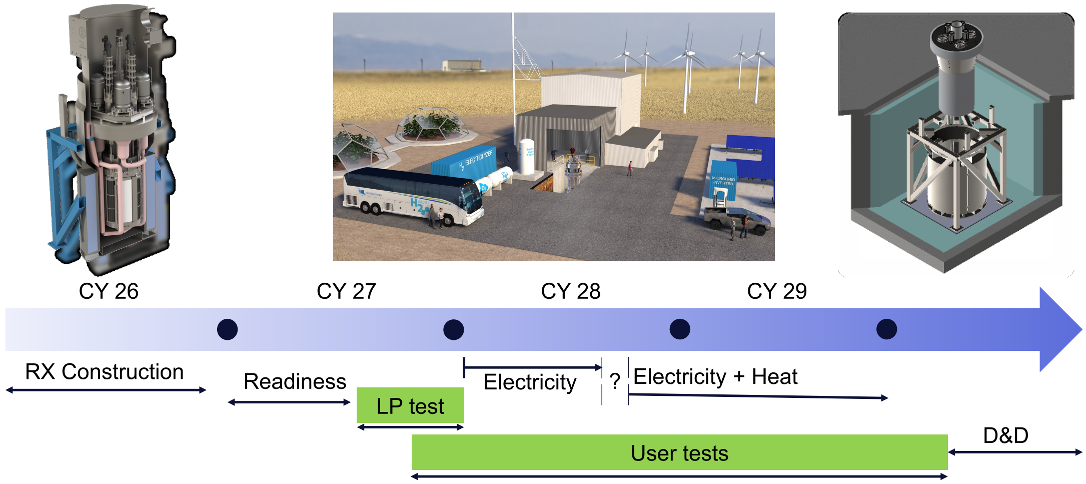

Figure 3. Tentative MARVEL timeline.

This section will provide an overview of foreseeable use cases leveraging MARVEL. The reactor is intended to become a microreactor test bed, providing data, know-how, training, and lessons learned to users, as well as a platform to demonstrate new technology that will help enable commercial microreactors. It is important to note that all proposed activities listed in this section are outside of the current scope of the MRP. Other funding mechanisms will be needed to pursue most of these activities. Potential avenues for funding opportunities are discussed in Section 3. A summary of the types of interfaces with the MARVEL reactor at each of the project phases is provided below.

- Phase 1: Technology development (reactivity control, PCS, etc.), data access, lessons learned, validation and benchmarking
- Phase 2: New technology testing, operational transients, new application demonstrations
- Phase 3: Decommissioning demonstrations, and post-irradiation examination (PIE).

While the MRP program is not expected to directly fund any new research proposal, research plans are expected to be reviewed by the MARVEL leadership team. This consists of the national technical director (NTD), the program manager, the MARVEL technical lead, the MARVEL experiment interface and TREAT management. It is also important to note that MARVEL testing will be integrated with TREAT operations. TREAT operates Monday through Thursday, and it is anticipated that MARVEL will operate Friday through Sunday, 24 hours per day. Proposals for use of MARVEL should take this schedule into consideration.

2.1. Engagement Categories

A wide range of potential engagement opportunities with the MARVEL reactor can be envisaged. This section is not intended to provide a comprehensive list, but rather to highlight several possible examples grouped within seven categories to help frame potential R&D projects leveraging MARVEL. Figure 4 provides an illustrative example of the wide variety of potential use cases that leverage the MARVEL reactor. The seven categories are not intended to occur in series; many may occur in parallel. They are grouped in this order to highlight the ones that can start earlier than others. For instance, users can already use data from the MARVEL reactor for R&D purposes whereas PIE activities will need to wait until Phase 2 is complete.

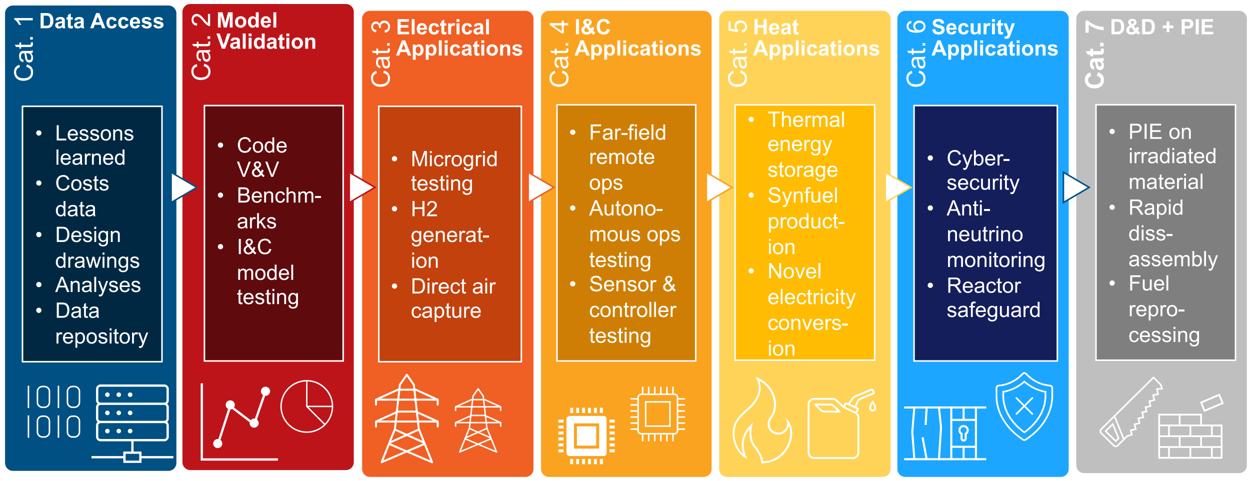

Figure 4. Conceptual overview of potential MARVEL applications. The list is not intended to be exhaustive.

Table 1 provides a more-detailed breakdown of potential tasks and suggested timelines for planning and execution. Some indication of possible timelines for execution along with recommendation for when to starting planning activities is provided. Suggested funding avenues for the different scopes are also provided. These will be discussed in greater detail in Section 3. The intent here is to provide a broad overview of possible scopes of work leveraging MARVEL.

Table 1. Overview of the various envisaged categories for MARVEL interface and applications.

	Description	Example Topics	Planning Timeline	Execution Timeline	Potential Funding Avenues
Cat. 1	This scope predominantly encompasses passive access to data from the MARVEL reactor. However, in some cases, specific requests can be made (e.g., testing a given transient). Users can request specific information to leverage for R&D purposes or technology maturation.	Subject to export control reviews, the MARVEL program can make available to users: Engineering drawings and calculations Cost data Sensor data Manufacturing and supply-chain experience Lessons learned	Phase 1: CY 2024 onward	Phase 1–3: CYs 2024–2030	DOE programs, CINR, LDRD, GAIN (voucher or legacy document access), CRADA, SPP, etc.
Cat. 2	Scopes here primarily relate to leveraging data from MARVEL to benchmark and validate models developed by the DOE and industry.	International reactor physics benchmark exercise. Validation of Multiphysics NEAMS codes	Phase 1: CY24 onward	Phase 1: startup V&V (27-28) Phase 2: Operation V&V (28-30) Phase 3: PIE V&V (>30)	DOE Programs, CINR, LDRD, GAIN, CRADA, SPP, etc.
Cat. 3	Leverage the electrical power output from the	Demonstration and testing of nuclear-	Phase 1: CY24–27	Phase 2: CY 2027–2029	DOE Programs,

	Description	Example Topics	Planning Timeline	Execution Timeline	Potential Funding Avenues
	MARVEL power conversion system to demonstrate novel nuclear-power applications.	powered microgrid with renewable power sources Nuclear-powered data center reliability demonstration			IRP, LDRD, IPL, CRADA, etc.
Cat. 4	Demonstrate novel paradigms for instrumentations and controls for microreactor operations.	Novel sensor-monitoring of advanced reactors. Testing of remote and autonomous controls for microreactors	Phase 1: CY24–27	Phase 2: CY 2027–2030	DOE Programs, IRP, LDRD, IPL, GAIN, CRADA, etc.
Cat. 5	Leverage MARVEL heat directly to demonstrate novel nuclear applications. This scope would involve some level of investment to change the currently planned state of MARVEL operations.	Providing heat for biomass and synfuel production Thermal-energy storage demonstration with nuclear High Temperature Steam Electrolysis (HTSE) for H_2 production. Testing of novel energy conversion systems (e.g., S-CO_2 Brayton)	Phase 1: CY24–27	Phase 2: CY 2028–2030	DOE Programs, IRP, LDRD, IPL, CRADA, etc.
Cat. 6	Test and demonstrate novel security & safeguards paradigms for advanced nuclear technology.	Cybersecurity assessment for remote data transfer from MARVEL reactor Demonstrating novel safeguards approaches for microreactors	Phase 1: CY24 onward	Phase 1: fuel loading monitoring CY 2027 Phase 2: Operation security & safeguards CY27–30 Phase 3: Decommis-sioning. safeguards beyond CY30	DOE Programs, IRP, LDRD, GAIN, SPP, CRADA, etc.
Cat. 7	At the end of the MARVEL operational lifetime, it will be decommissioned, and material could be made available for PIE.	Develop novel decontamination and decommissioning techniques for microreactors Fuel and structural material PIE	Phase 1: early planning CY 2024 Phase 2: preparation CY27–30	Phase 3: Decommis-sioning and PIE beyond CY 2030	DOE Programs, NSUF, LDRD, GAIN, SPP, CRADA,

	Description	Example Topics	Planning Timeline	Execution Timeline	Potential Funding Avenues
		Reprocessing of HALEU fuel from MARVEL			etc.

CINR, Consolidated Innovative Nuclear Research
CRADA, cooperative research and development agreement
GAIN, Gateway for Accelerated Innovation in Nuclear
IPL, Integrated Priority List
IRP, Installation Restoration Program
LDRD, Laboratory-Directed Research and Development
NEAMS, Nuclear Energy Advanced Modeling and Simulation
NSUF, Nuclear Scientific User Facilities
SPP, strategic partnership project

2.2. Data Management and Access

A key outcome of the MARVEL project is to trailblaze the path towards commercial microreactor deployment. Thus, an important goal is to provide access to data and lessons learned from different phases of the project to help facilitate the development and maturation of microreactors as a whole. The MRP should strive towards documenting and capturing as many insights as possible and on a wide variety of topics (e.g., project management, design activities, mistakes, cost data, simulations, operation data). This will be key to ensure follow-on projects can truly gain the benefit from the MARVEL experience and build on it. Hence, a data-management and access plan is needed to streamline interactions with stakeholders. This section proposed a three-tiered approach to data management and access.

2.2.1. Near-Term Data Access

Currently, the MARVEL project works to provide data on a one-time request basis. Stakeholders with specific needs are encouraged to directly reach out to points of contact (POCs) within the project to request specific access to relevant information. Once necessary reviews are conducted through the laboratory review process, and the information is cleared by MRP leadership, the information is provided to external stakeholders.

The MRP itself works to produce documents detailing lessons learned and cost information accrued so far and to distill it into public-facing documents. These are expected to be beneficial to users. In general, the MARVEL project produces myriad drawings and engineering-calculation documents that are stored internally. These can be made available to stakeholders following review. For an overview of the various design and engineering documents produced, interested parties are directed to the 90% Final Design Report [MARVEL Design Team 2023], and the upcoming preliminary documented SAR.

Beyond internal programmatic efforts, the primary external users of MARVEL data so far have been sister DOE programs. For instance, the MRP sponsors an ongoing scope in collaboration with the systems analysis and integration (SA&I) campaign on harnessing cost data from estimates for MARVEL to extrapolate cost and economic drivers for commercial microreactors. The Advanced sensors and instrumentation (ASI) program has an ongoing collaboration with MRP to test novel control paradigms on a non-nuclear replica of MARVEL. NEAMS received design-specification information that is used to build a multiphysics model of the reactor in parallel to internal MRP-sponsored modeling activities.

Industry users have also reached out to the MARVEL project requesting such specific data as design or supply-chain information. This is highlighted in several letters of support in Appendix A of this report. For instance, readily available information in the form of reports can be shared with external entities directly, following review. However, in several cases, the data require some processing to distill useful insight for an external stakeholder (e.g., producing a comprehensive design package on the MARVEL control system). In such cases, a dedicated agreement and contract for producing and sharing the required information is needed, along with corresponding funding.

Going forward, the MRP can be expected to continue interacting one on one with stakeholders to support their needs and share MARVEL information. The program will also strive to release more reports externally on the DOE Office of Science and Technical Information (OSTI) platform (https://www.osti.gov/). The MRP will continue internally funding lessons-learned reports that share important insights from the MARVEL projects openly to all interested users. However, beyond this existing setup, there is a need for more streamlined and systematic access to data produced by the project.

2.2.2. Medium-Term Data Access

In the medium term, a collaboration with NSUF will be established in order to leverage their novel database platform: the Nuclear Research Data System (NRDS, https://nrds.inl.gov/). NSUF's database currently hosts a wide range of PIE data generated by the NSUF Program, including raw measurement data. It also touts some advanced searching and processing capabilities (e.g., large-language models) that can be useful for users to find specific information. Figure 5 shows a screenshot of the current interface for the NRDS database.

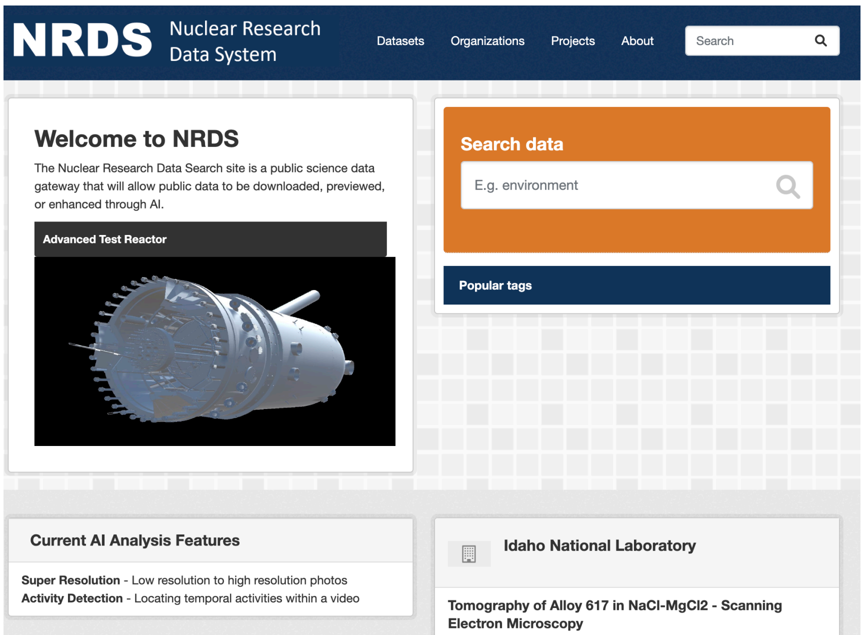

Figure 5. Screenshot of the NSUF's NRDS website interface (taken April 7, 2024).

A pilot project will be initiated with the closed access interface of the NRDS first. This will consist of setting up a MARVEL-specific workspace on the platform and hosting some initial data sets from the project (e.g., certain design drawings that have received prior review). Controlled access to the workspace will be provided to external entities upon request. Access requests would need to be reviewed and approved by an INL classification officer as well as the MRP leadership. The internal platform could even host export-controlled documentation with a more stringent user-review process in place to protect access. This is similarly to how the INL Nuclear Computational Resource Center (NCRC, https://inl.gov/ncrc/) provides controlled access to specific codes, even those that are export controlled. The center itself could potentially be leveraged to provide user access. Hosting this information in a structured framework like the NRDS platform would ultimately enable a more streamlined, controlled, and traceable approach for interacting with stakeholders.

Once the pilot project is established, certain datasets within the MARVEL-specific database could be released more openly on the NRDS website. This would only occur after adequate reviews. It would facilitate harnessing MARVEL-generated information by the microreactor community at large, including universities. This would also lay the foundation for a longer-term plan for data access.

2.2.3. Long-Term Data Access

The long-term objective that the program would strive for is a systematic review of all documentation and data produced to bin in one of the following three categories:

- **Documents cleared for external release**: these types of reports will be hosted both on OSTI and with a corresponding link on the open NRDS platform.
- **Other data cleared for external release**: this is composed of raw data—e.g., excel spreadsheets, cost reports, CAD, models, simulation input/outputs—generated by the MARVEL project. This would all be hosted on the open NRDS platform.
- **Non-external controlled data**: this could be composed of documents and datasets that are deemed sensitive, or export controlled. These can still be made available through the closed NRDS platform with user access reviewed on a case-by-case basis, similar to the process used by the NCRC (perhaps even leveraging the same access-request process).

The overall proposed data-management process is illustrated in Figure 6. The long-term proposed process would involve processing all MARVEL-generated reports, drawings, simulations, operational data, D&D information, etc., through the INL review process (referred to as Laboratory Review System [LRS]) to provide a determination on the required control (if any) to be placed on the data. Once guidance from the review process is obtained, the data moves to MRP leadership determination. At this stage, a dataset cleared for external released is expected to be released to OSTI and NRDS. If the information is deemed to contain sensitive information, the MRP leadership will determine whether to host it on the NRDS closed-access platform—e.g., in the case of design drawings that may be useful to industry—or not to provide any external access whatsoever, as in the case of business-sensitive information like component quotes. The MRP is expected to also coordinate with other campaigns such as GAIN and NRIC with active data management initiatives to highlight openly accessible MARVEL data.

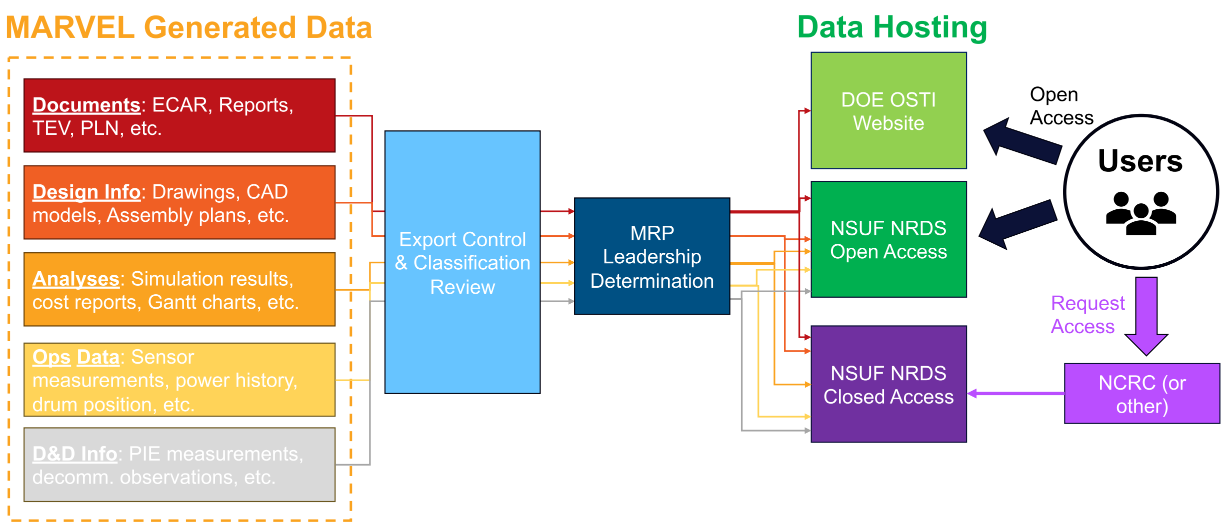

Figure 6. Schematic of the MARVEL data-management process.

This broader scope will be subject to DOE approval and funding constraints. The NSUF Program has agreed to provide access to the platform and computational hardware (for large-scale data storage). The MRP, on the other hand, will need to develop a scope of work to conduct systematic review of files and to upload the data in a structured format into the NRDS platform. Review of large datasets is not without challenges and can be a time-consuming process. Some degree of automation, along with a dedicated team to help shepherd files through the various systems, will be needed. Ultimately, however, a viable usable long-term data-management plan is expected to be provided in the project-execution plan that is currently being updated. Access to data is likely to prove invaluable for stakeholders and will likely substantially outlive the MARVEL project itself, providing value past its completion.

2.3. Hardware and Operation Modifications

Special consideration will be needed for applications that want to leverage the MARVEL testbed via hardware or operational modifications. This could be in the form of plugging a new application to MARVEL or altering the operations of the reactor (e.g., via novel control algorithms) to demonstrate a new capability. This section will discuss the various considerations associated with these types of modifications, primarily as they apply to Categories 3–6. It is important to reemphasize here that the MRP is not anticipated to provide funding of such modifications but will play a role in ensuring the MARVEL testbed is available to end users.

2.3.1. Potential Use Cases and Prioritizations

A wide variety of potential applications to demonstrate with the MARVEL reactor can be anticipated. Ultimately any proposed modification will need to pass four requirements:

1. Be deemed not to impact the safety basis of the TREAT/MARVEL reactor
2. Have secured adequate funding for completion of their scope
3. Be deemed not to impact logistical operations at the TREAT facility
4. Be deemed of technical interest by the MRP leadership.

Requirements 1 and 4 will be discussed in detail in the next subsection. In theory, any proposed application that passes these four requirements will be considered for the MARVEL testbed. However, in light of the currently planned 2-year operational window for the reactor, some degree of prioritization will be inevitable. Table 2 attempts to highlight the current priorities for MARVEL use, as perceived at this stage by the MRP program. This is subject to change and is mainly intended to encourage future users to target high-impact applications for MARVEL. Ultimately, the availability will be subject to some first-come-first-served approach; hence, early engagement with MARVEL points of contacts—namely, the authors of this report—is key. Interested users are encouraged to complete the pre-engagement questionnaire at the earliest opportunity possible to assist MRP staff in understanding potential use cases as well as to assist the prospective user in navigating the system in preparation for their experiment: https://qfreeaccountssjc1.az1.qualtrics.com/jfe/form/SV_72InKjSEz54Q2j4.

Table 2. Proposed prioritization of MARVEL applications. Cross-category ranking not included. These suggestions should not be interpreted as mutually exclusive.

Category	Higher Impact Demonstration	Other Impactful Demonstration
Cat. 1: Data Access	N/A (no hardware changes)	N/A (no hardware changes)
Cat. 2: Model Validation	Transients of interests for code validation	—
Cat. 3: Electrical Applications	Demonstrating nuclear-powered microgrid	Nuclear-powered datacenter
Cat. 4: I&C Applications	Providing testing for automated controls	Novel sensor testing
Cat. 5: Heat Applications	Demonstrating novel nuclear heat application	Testing novel electricity-conversion system
Cat. 6: Security Applications	Cybersecurity testing	Novel safeguards approaches
Cat. 7: D&D + PIE	Characterization and reprocessing of fuel	Novel disassembly methods

2.3.2. TREAT Interface and Review

MARVEL construction, startup, and testing will be performed in TREAT buildings MFC-720, MFC-724, and surrounding grounds. MARVEL is effectively a tenant in the TREAT facilities, and its occupancy will be governed by a tenant-use agreement, currently in development. Following completion of PLN-6816, “Startup Plan for Initial Testing of the MARVEL Test Reactor,” the operation of MARVEL will be turned over to TREAT plant management [Phoenix 2023].

Generally, the MRP will retain responsibility for technical development/oversight, management of funding mechanisms, data collection/management, and project management. The MRP will ensure that end-user proposals meet the terms of the tenant-use agreement. The TREAT organization will ensure facility work, associated hazard controls, physical-facility capabilities, and operational-safety limits and controls are not impacted or compromised by MARVEL-related operations. Potential modifications highlighted in the previous sections will likely be subjected to the execution of the unreviewed safety question process. Work can only commence on hardware modifications to the MARVEL facility or changes to its baseline operations after they are approved. Regardless of the mechanism by which an end-user submits a proposal, established TREAT processes will be used for facility modification, safety-basis implementation, maintenance, training, and conduct of operations.

Limits and controls for radiological limits, chemical inventory, and fire hazards will be observed or specifically established for unique conditions. Laboratory-wide work processes will be observed, and execution of work supporting any demonstration, including operation of the MARVEL reactor, will be in accordance with the TREAT annual operations schedule, plan of the week, and plan of the day. Qualified TREAT operations and/or maintenance personnel will operate all reactor controls.

2.4. MARVEL Post-Operations

Phase 3 of the MARVEL project will consist of decommissioning of reactor. This stage can still be useful to stakeholders, as highlighted by Category 7 scopes in previous sections. Therefore, an overview of planned activities and considerations as they relate to decommissioning of the reactor is provided here.

2.4.1. Decommissioning—Current Plans

A decommissioning study for MARVEL that presented five options for decommissioning MARVEL was developed in late FY 2022. That plan will be updated in late FY 2024, but the MARVEL 90% Final Design Report presents MARVEL’s current decommissioning approach, to be implemented in MARVEL Phase 3. A high-level summary follows.

- When radiation levels are sufficiently low (dependent on power history), the NaK primary coolant will be removed by pumping or evacuated by vacuum. Residual NaK will be reacted with a moisture-laden inert gas. Removed Na and K will be converted to their respective carbonate forms, followed by solidification and disposal at an off-site mixed-waste Subtitle D or C disposal facility. NaK removal is required prior to defueling the reactor.
- The Stirling engines and IHX can be removed without significant physical or health and safety concerns (changing the secondary coolant to GaInSn eutectic eliminated polonium-210 concerns from activation of lead-bismuth). Draining eGaInSn and removing the Stirling engines and IHX can be completed without significant physical or health and safety concerns. The vessel head can then be removed, and the reactor can then be defueled.
- The 36 MARVEL fuel elements (and one unirradiated spare) would be transferred using any of several suitable casks controlled under a cask-specific criticality analysis and out-of-commerce transport plan. The most likely location for long-term interim storage at INL is the CPP-603 dry storage facilities at INTEC. The project assumes that MARVEL fuel will be permanently stored at a national geologic repository when identified and constructed.

- After the core is defueled, the nuclear instruments will be disconnected and dispositioned or stored for reuse. Power to in-pit systems will be disconnected, and reactivity control systems will be removed and dispositioned. The activated BeO will be retained and managed under TREAT's Beryllium Management Program for use in subsequent demonstrations.
- The reactor vessel will be removed and grouted, if needed, for disposal at the ICDF where MARVEL is expected to meet the waste-acceptance criteria. A transfer vessel or a bottom-loading cask are assumed to be necessary for transport. The reactor-pit shielding is assumed to remain in place for use in subsequent demonstrations.

All radioactive waste, other than the reactor fuel, generated in Phase 3 will be Nuclear Regulatory Committee (NRC) Class A low-level radioactive waste or mixed low-level waste and has current disposition paths in DOE or commercial facilities. Details and updates are expected through Phase 2 to reflect the operating history, individual demonstrations, and the details of a decommissioning contract.

2.4.2. Potential Post-Irradiation R&D

While MARVEL has planned for disposition of the fuel and other reactor systems in Section 2.4.1, as a matter of due diligence, the decommissioning phase has considerable potential for valuable R&D. Additionally, the irradiated material—namely, the fuel—can provide useful scientific data and likely constitute a good source to demonstrate reprocessing capabilities.

2.4.2.1. Post-Irradiation Examination

TRIGA fuel has not been irradiated at MARVEL temperatures and PIE provides a unique opportunity. PIE scope may be as simple as measurements of swell and distortion or could involve a complex evaluation and measurement of microstructural change in the cladding and fuel. Evaluation of hydrogen migration may be of interest. Additionally, PIE of MARVEL structural components, high-temperature components, and/or reflector (Be and BeO) may be of interest. Of note, BeO reflector material is intended for reuse in subsequent demonstrations and may need to be replaced if destructive examination is proposed.

2.4.2.2. Reprocessing of HALEU Fuel Elements

MARVEL will have an operational life of 2 CYs after initial startup testing and turnover to unrestricted operations. It is expected to operate for 3 days per week at $85kW_{th}$. This light use will generate enough fission products to allow easy detection, but relatively low radiation fields compared to other used fuels. This may be beneficial in developing detection or reprocessing techniques. Further, there should be approximately 45 kg of uranium enriched to roughly 19.5% (rough estimate for minimal burnup), or slightly more than 9 kg of U-235. Demonstration of pyro-processing techniques with the metallic MARVEL fuel may make that uranium available and enable pyro-processing of other TRIGA feedstock.

2.4.2.3. Demonstration of D&D Techniques

MARVEL's short operational life will provide opportunities to demonstrate novel new D&D activities, processes, and/or techniques. The reactor is expected to be in good condition when the demonstration phase is over, and the design, drawings, and as-built conditions will be recent and accessible. Information from past decommissioning efforts of liquid-metal reactors is reasonably sparse, and MARVEL affords an opportunity to investigate and potentially standardize waste-processing and D&D techniques for this type of reactor.

3. OVERVIEW OF ENGAGEMENT AND FUNDING OPPORTUNITIES

As previously stated, the MRP-funded scope with MARVEL is limited to the reactor deployment and basic operation; it is not intended to cover novel applications and use cases. Two broad routes are available to users:

- Pay-for-use, which essentially involves leveraging pre-allocated funding (e.g., private industry, existing DOE program funding) to develop a MARVEL application
- Grant application, which would involve applying for funding through third parties (e.g., LDRD, GAIN) to finance a proposed MARVEL application.

The first option is self-explanatory: entities with existing budgets that they control can decide to leverage them to support MARVEL experiments. Direct engagements with MRP and the TREAT facility will be needed in those instances as highlighted in previous sections. The second route will be to apply for funding opportunities to sponsor part or all of the work. Table 3 lists several potential avenues for this funding. They will each be discussed in further detail in this section within the context of a given applicant type: national labs, industry, or universities. The MRP is already engaging with these different entities about a potential MARVEL-specific call for proposals. Additional information on these will be made available in due course.

Table 3. Overview of potential funding opportunities to leverage MARVEL.

Funding Opportunity	Applicability	Potential Topical Areas	Recommended Submission Date
GAIN voucher	Industry	Existing information Startup operations Simple hardware tests	current 2026 Q2–2027 Q4 After 2027 Q1
CINR-NEUP	University	Data access and analysis	2024 onward
CINR-NSUF	University National Lab	Hardware testing PIE	2026 call onward 2028 call
Seed LDRD	National Lab	Data access and analysis	2024 Q4 onward
Annual LDRD	National Lab	Hardware testing	2025 call onward
IPL	National Lab	Heat-extraction system	2026–2027 calls
iFOA	Industry	Hardware testing	2026 onward
Small Business Innovation Research (SBIR)/Technology Commercialization Funds (TCF)	Industry	Data access and analysis Simple hardware tests	2025 onward 2026 onward

3.1. External-Engagement Strategy

Following publication of this report, a dedicated engagement plan will be executed to solicit feedback and kickstart the planning stage for MARVEL operations. This is envisaged to be conducted in four stages, summarized below.

Step 1 begins with the release of this report on osti.gov, along with two updated MARVEL factsheets and a MARVEL engagement form. This form will consist of an online questionnaire that all parties interested in engaging with MARVEL will be directed to. Answers to the form will be contained within a centralized repository will help facilitate compilation of relevant stakeholders and will enable the MRP to start planning activities to support future tests leveraging the microreactor demonstration. The form will solicit information regarding: (a) background information on the submitter, (b) information on the type of test or capability leveraging MARVEL, (c) the availability of funds to conduct said test or information on which funding award is being sought. The form will contain basic information to help better inform submitters on the type of information requested (previous similar attempts have led to submission of irrelevant information due to misunderstanding of how MARVEL could be leveraged) along with a link to this report and two factsheets. Additional information on these factsheets is provided below. Once all of these documents are live, a dedicated social-media campaign will be launched to promote engagement with the MARVEL team on operational tests and direct interested parties to the online form. This will be followed by dedicated industry outreach to relevant companies to raise awareness within specific industries and encourage engagement to leverage MARVEL.

- Factsheet 1 will consist of updating the current MARVEL overview factsheet with more up-to-date design and operational information, along with a rough-estimate timeline for operational phases.
- Factsheet 2 will consist of a summary of this report with key insights on how to engage with and leverage the MARVEL demonstration to test novel capabilities.

Step 2 will consist of dedicated in-person outreach at industry events, the first of which will be the American Nuclear Society Annual Meeting in June 2024. A dedicated panel on the MARVEL reactor has already been organized: https://www.ans.org/meetings/ac2024/session/view-2584/. The session will include a presentation reserved to discuss the MARVEL utilization plan and how to engage with the program on potential future tests. This will be followed by a MARVEL presentation at the International Conference on Small Modular Reactors and their Application. The event will take place during October of 2024 and be hosted by the International Atomic Energy Agency. This will provide an opportunity for international engagement regarding the MARVEL project and gauge interest outside the US. Last, a dedicated panel on how to leverage MARVEL is being organized for the American Nuclear Society Winter Meeting in November 2024. There, the main focus will be on highlighting possible applications for the MARVEL testbed and on giving guidance on how best to engage with the program to start planning potential demonstrations of new technologies.

Step 3 will be kickstarted by a dedicated webinar (similar to the NRIC Tech Talks) on the MARVEL utilization plan. The 2-hour event will be open to the general public and advertised on social media prior to the date. The purpose will be an in-depth dive (as opposed to the 15-minute presentation in Step 2) on potential opportunities to leverage MARVEL, how to engage with the program, and how to apply for funding opportunities to support proposed tests. The event is likely to take place in early 2025. It will then be followed by one-on-one engagement with promising stakeholders. At this stage, it is expected that several stakeholders will have completed the form from Step 1. These different suggestions will be reviewed and prioritized by the MRP. In-depth discussions with the most-promising proposal submitters would then be scheduled to begin the necessary preparations.

Step 4 will be subject to DOE approval and congressional appropriation. Building on the high-level of interest gathered from the NRIC Front-End Engineering and Experiment Design for Testing Advanced Microreactors (FEEED) studies (https://www.energy.gov/ne/articles/doe-awards-39-million-advanced-reactor-experiment-designs), a similar approach will be followed for MARVEL testing and applications demonstration. The exact funding mechanism and award size is still to be determined (and will likely be substantially more modest than the NRIC FEEED studies). The focus will be primarily on hardware-based tests; other funding mechanisms would be better suited for engagements such as data access. The purpose is to formalize a review process for tests with external entities and demonstrate a commitment from the MRP to support leveraging MARVEL as a testbed for novel capabilities and applications. These proposed MARVEL utilization FEED studies would then initiate formal planning activities to advance towards hardware demonstration. In light of the short operational window of MARVEL, early engagement on hardware demonstration will be critical for success. However, it can be envisaged that companies would be hesitant to dedicate resources and funding to such activities prior to MARVEL operations. The MARVEL FEEED studies would aim to resolve this impasse by dedicating funds to support early planning activities and formalize the different engagements planning to leverage MARVEL.

3.2. National Laboratories

The MRP has been directly engaging with national lab representatives from several DOE-sponsored programs about potential opportunities to leverage the MARVEL reactor. These are all summarized in Table 4. These should not be interpreted as endorsement of any scope. Ultimate decision regarding these proposed activities would be subject to appropriations and agreement by respective leads from each campaign. Nevertheless, several confirmed commitments to leverage MARVEL were secured already at this stage and are indicated below. Programs engaged on the Office of Nuclear Energy (DOE-NE) side include IESs, NEAMS, Advanced Materials and Manufacturing Technologies (AMMT), Advanced Reactor Safeguards and Security (ARSS), ASI, SA&I, as well as Material Recovery and Waste Form Demonstrations (MRWFD). Beyond DOE-NE, programs within the Office of Electricity (DOE-OE), the Office of Energy Efficiency and Renewable Energy (DOE-EERE), and National Aeronautics and Space Administration (NASA) have been engaged as well.

Table 4. Potential areas of collaboration with various DOE programs. This list is not comprehensive and is expected to be updated as engagements with other US programs continues.

Program	Near-Term	Long-Term	Status
INL NetZero Initiative DOE-OE Microgrids R&D Program	Demonstrating nuclear microgrid using MARVEL.	Balancing microgrid load from renewables plus nuclear source.	Discussions ongoing and potential interest. No firm commitment.
DOE-EERE	HTSE with electricity from MARVEL and external steam.	HTSE with electricity and steam from MARVEL.	Discussions ongoing and potential interest. No firm commitment.
DOE-NE IES	Feasibility study on leveraging MARVEL heat for biomass torrefaction.	Implementing torrefaction hardware leveraging heat directly from MARVEL.	Commitment to near-term scope. No firm commitment for long-term.
DOE-NE NEAMS	Setting up multiphysics model of MARVEL using NEAMS tools. And code-to-code benchmarking exercises.	Startup and operational validation of NEAMS codes. Fuel modeling leveraging PIE data.	Funded ongoing near-term activity. Long-term goal commitment.
DOE-NE AMMT	Develop and deploy three dimensional (3D)-printed-metal liners to be used in the MARVEL heat exchangers.	Expand upon the 3D-liners to develop simple heat exchangers for MARVEL heat extraction.	Funded ongoing near-term activity. Interest expressed for long-term goal.
DOE-NE ASI	Deploy additional digital twin capabilities in the Microreactor Automated Control System (MACS) to mirror MARVEL	Deploy additional sensors in MARVEL for detecting core-tilting effects. Test novel control algorithms based on development with MACS.	Funded ongoing collaboration and intent to fund near-term goal. Committed to long-term goal.
DOE-NE SA&I	Leverage MARVEL cost data to project microreactor costs.	Follow evolution of MARVEL construction through construction to assess biases in nuclear cost estimation.	Funded ongoing near-term activity. Long-term goal commitment.

Program	Near-Term	Long-Term	Status
DOE-NE ARSS	Evaluating impact of overlaying cybersecurity requirements with existing MARVEL requirements	Assess cybersecurity of MARVEL once operations begin.	Funded ongoing near-term activity. Interest expressed for long-term goal.
DOE-NE MRWFD	Feasibility study for HALEU recovery from MARVEL fuel.	Execute pyroprocessing of MARVEL spent fuel at end of operations.	Commitment to scoping studies in upcoming FY.
DOE/NRC Collaboration for Criticality Safety Support for Commercial-Scale HALEU for Fuel Cycles and Transportation	Planning for Organization for Economic Co-operation and Development (OECD) zero-power criticality international benchmark for HALEU-reactors.	—	Funded ongoing near-term activity.
DOE & NASA Fission Surface Power (FSP)	Leverage CD designs from MARVEL for FSP demonstration.	Replicate the CD design for MARVEL in an FSP physical demonstration.	Interest in leveraging MARVEL data.

Several of the programs already have active ongoing engagements with the MARVEL project. Their current activities and planned future activities are described in detail below. The list is not exhaustive, but several programs are highlighted here due to the strong synergies and benefits to the two entities from collaboration.

- **NEAMS**: The NEAMS fuel-performance tool, Bison, is already being leveraged by the MARVEL program. Additionally, the NEAMS program has set up a thermal-hydraulic effort to model the Primary Coolant Apparatus Test (PCAT) facility and a reactor-physics effort to model the MARVEL core. Ultimately, the expectation is that these efforts will be merged into a single comprehensive mutiphysics framework that encompasses neutronics, hydraulics, and fuel performance. In the longer term, two tracks are envisaged for collaboration between the two programs summarized. The timeline for each track is summarized in Table 5.

Table 5. The two tracks of long-term collaboration between NEAMS and MARVEL.

	Reactor Modeling	Material Modeling
FY 2025	Code-to-code benchmark	Coupling fuel performance modeling with reactor physics modeling Leveraging characterization data
FY 2026	Comprehensive, coupled multiphysics model of MARVEL	
FY 2027	Startup validation	—
FY 2028	Full power and transient validation	Model material impact during operations
Beyond	Analysis of hardware modifications	PIE validation

- **AMMT**: the AMMT program has already conducted feasibility tests to 3D-print a steel-based liner for the MARVEL heat exchanger. GaInSn is expected to be highly corrosive; thus, a replaceable liner that matches the MARVEL geometry as much as possible is expected to be invaluable for the program. Several smaller-scale pieces have been manufactured by the program (see Figure 7). Going forward, the AMMT and MRP will explore the potential to 3D-print and install a to-scale liner in the reactor. In the longer term, the AMMT and MRP are considering 3D-printing a similar, but more complex structure that would serve as the heat exchanger for a MARVEL heat-extraction system.

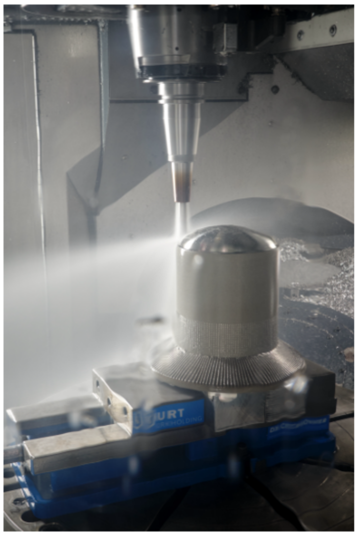

Figure 7. Ongoing effort by the AMMT program to 3D-print a liner for MARVEL. At left, final machining of the additively manufactured component, and at right, a finished reduced-scale piece. Credit: ORNL.

- **ASI**: The ASI program actively collaborates with the MRP on developing physical and digital-twin surrogates of the MARVEL reactor. The end-product is deployed using MACS, shown in Figure 8. The system interacts with a system called 'VIBRANT' (Visual Benign Reactor As Analog for Nuclear Testing) to replicate the effect of neutrons in a reactor using light as a surrogate. It can be used for control systems (hardware and software) and methods testing before attempting to implement those capabilities to the MARVEL reactor itself. The ASI campaign is also working closely with the MRP on the implementation of additional software capabilities to measure the impact of core tilting from CD rotations and react to it. This is expected to be critical for commercial microreactors.

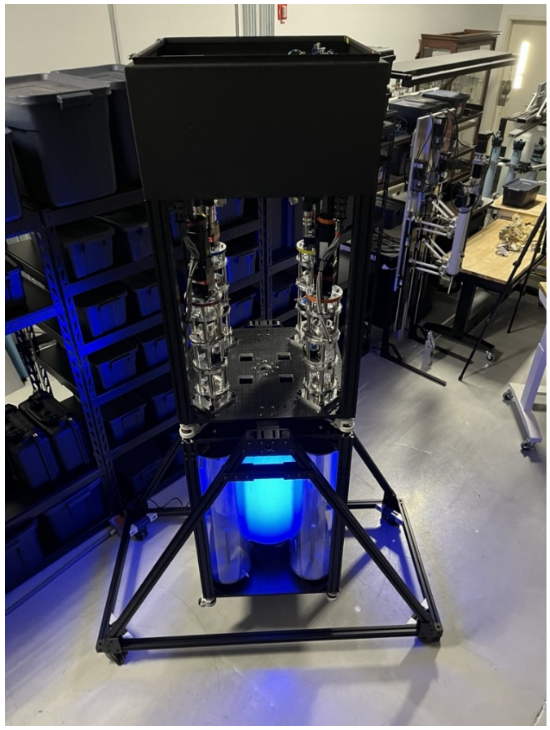

Figure 8. MACS, used as a non-nuclear replica of MARVEL for controls testing [Farber 2023].

- **SA&I**: This campaign has a longstanding collaboration with the MRP on MARVEL. The two programs leverage MARVEL cost and design data to develop a framework that can be used to estimate potential commercial-microreactor costs. Understanding whether microreactors can compete beyond niche markets will be key to this effort. To this end, SA&I and MRP sponsored a joint study that evaluated the potential for cost reduction from mass-producing microreactors in a factory setting. MARVEL was used as a use case due to the availability of detailed engineering and assembly information. The resulting plant schematic is shown in Figure 9. Ongoing work also includes incorporating MARVEL cost data into the SA&I cost framework to evaluate alternative configurations that are more representative of commercial microreactor designs.

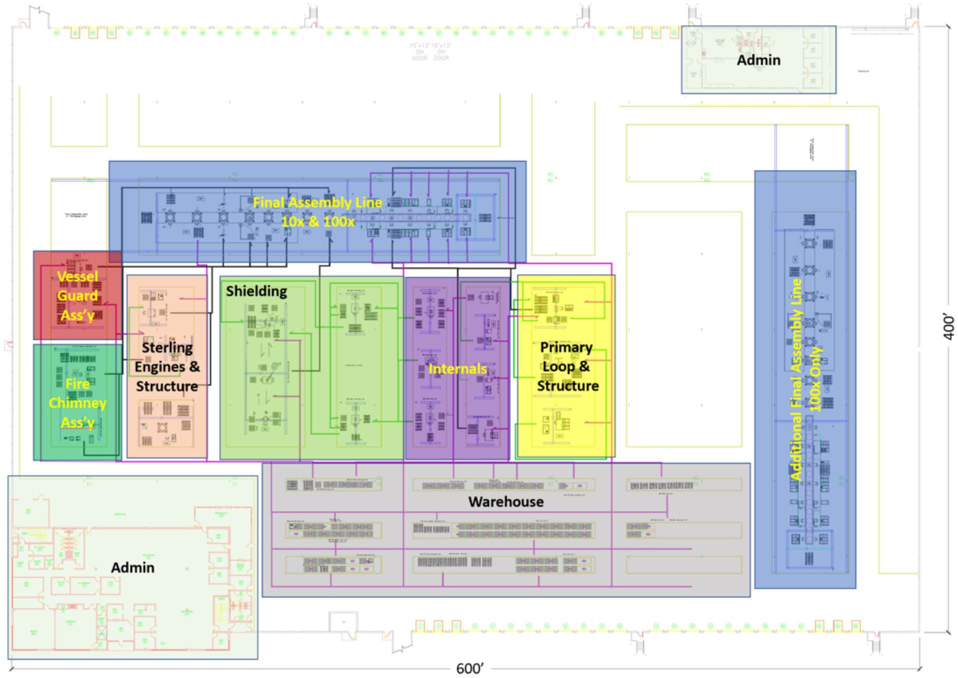

Figure 9. Overview of the microreactor factory layout with 100 unit/year throughput. MARVEL was leveraged as a use case [Abou-Jaoude 2023].

In addition to programmatic funding, national labs can seek funding to leverage MARVEL via indirect mechanisms, namely LDRD proposals. Engagements are ongoing with the INL LDRD office regarding a dedicated MARVEL-specific call for proposals. In general, national-lab stakeholders are encouraged to leverage the funding mechanism for MARVEL-related activities. In general, seed-LDRD scopes are more suitable for R&D topics that harness MARVEL-generated data. Hence, proposals targeting these applications can be submitted in earnest. The annual LDRD call will be more adequate for funding (operational or hardware-based) modifications to MARVEL. In light of the short window of operation of the reactor, applicants are encouraged to submit proposals for a 2025 or 2026 call in order to start design activities and associated reviews in 2026-2027 timeline. This would allow implementation to occur in between 2027–2029. Last, internal infrastructure-development funds can also be leveraged to potentially upgrade MARVEL capabilities.

3.3. Funding Opportunities for Private Entities

The MARVEL project is keen on engaging with private entities to help fully leverage the potential of the reactor. Broadly, engagements can be expected to either center around (1) reactor vendors leveraging MARVEL data and knowhow, (2) industry developers attempting to showcase novel controls and reactor interfaces, and (3) industrial end users wanting to test how their systems interact with a nuclear energy source. Example applications for the first include leveraging the proven CD design from MARVEL. In the second area potential areas of collaboration could include demonstrating a new human-machine interface system. In the third, an example use case would be powering a data center using MARVEL-generated electricity or testing a supercritical CO_2 Brayton cycle coupled to a nuclear heat source.

Several mechanisms exist for conducting these types of activities with the MARVEL project. The first falls under the pay-for-use umbrella. This includes CRADAs and SPPs. These are directly signed between the national laboratory (in this case INL) and the private entity. Clauses include Intellectual Property protection, scope of work, expected timeline, etc. The funding is directly provided by the private entity in an analogous approach to subcontracting. If private funding is available, this is the most direct and streamlined approach to leveraging the MARVEL reactor. Scope can commence as early as contracts can be implemented; this is not dependent on funding-award cycles. They can also be flexible in nature and extended as needed (based on private funding availability). End users potentially interested in leveraging this mechanism are encouraged to reach out directly to INL.

A second mechanism available to end users is the GAIN voucher program. Vouchers enable private entities to directly access expertise and capabilities available across the DOE complex. Awards typically follow an 80:20 cost-share arrangement and are funded on a quarterly cycle. A three-step process for submission can be expected:

1. All MARVEL-related proposals will be screened by an INL point of contact as well as the proposal team to develop a statement of work prior to voucher submittal
2. Once submitted, the GAIN program is expected to interface with the MRP NTD regarding the technical viability of the proposed topic
3. The final review step consists of the typical voucher review prior to selection.

Following submission, reviews for Steps 2 and 3 typically take 6 weeks to complete. Depending on the private company, work can then be kickstarted at national labs between 3 and 6 months following selection. Funding is usually limited to less than $500k, and the scope duration is 12 months. In a sense, a GAIN voucher pays for laboratory resources that can be used to review or provide support for a novel application leveraging MARVEL. An example would be a firm wanting to connect and test a hydrogen electrolyzer to MARVEL and willing to ship equipment to the lab, with the GAIN voucher funding the necessary reviews and installations at INL. In light of the aforementioned timeline, users interested in a demonstration in the 2027 timeframe need to submit applications in early 2026. Additional information on the GAIN voucher program can be found at https://gain.inl.gov/SitePages/Nuclear%20Energy%20Vouchers.aspx.

Beyond the options highlighted above, several other funding opportunities exist that can be leveraged for MARVEL-specific scope. One potentially viable route is the Industry Funding Opportunity Announcement (iFOA). While the program has ended, a similar initiative to support nuclear-industry-driven R&D can be envisaged in the future. The original iFOA awards were typically 3-years in length and could include several entities as partners, including national labs. Additional information on the iFOAs can be at https://www.energy.gov/ne/industry-foa-awardees-8.

Several other funding mechanisms exist to support nuclear-related R&D, including TCF and SBIR. These are typically smaller in scope and phased in implementation. Applicants interested in these avenues are directed to the following links:

- TCF: https://www.energy.gov/technologytransitions/technology-commercialization-fund
- SBIR: https://www.energy.gov/science/sbir/small-business-innovation-research-and-small-business-technology-transfer.

3.4. Funding Opportunities for University Engagement

University stakeholders are also encouraged to leverage the MARVEL testbed within the confines that were previously detailed. Funding for such activities can be secured via CINR proposals. Four award types can be used to support MARVEL-based activities. These are highlighted in greater detail in Table 6. Overall, it is important to recognize the value of MARVEL as a one-of-a-kind opportunity to train the next generation of nuclear engineers and expand knowhow in the field. In light of the expected timelines for advanced nuclear reactor deployments, it is critical to maximize opportunities to train and build a future workforce. Beyond the opportunities for funding R&D work at universities, the MARVEL project is engaging with CINR (namely NSUF) on best practices for providing user access to data as highlighted in Section 2.2.

Table 6. CINR funding mechanisms and their applicability to potential MARVEL scopes.

	Details	Example MARVEL Use-case	Frequency and Timeline
NEUP	Scopes are funding opportunities to support nuclear specific R&D at universities. They can be broad in scopes and typically consist of novel studies and analyses.	Incorporate lessons learned from MARVEL startup activities for broader guidance on advanced reactor startup procedures.	Annual. Apply in 2024 for data access, and 2026 for operations research.
Integrated Research Projects (IRP)	Three-year university-led projects that are broader in scope and funding. They are expected to be multidisciplinary and multi-institutional awards that attempt to address specific research gaps identified by DOE-NE.	Install and test a novel heat application to the MARVEL reactor. Multidisciplinary collaboration distilling lessons learned and knowhow from MARVEL construction and operation.	Annual. Apply in 2026 to fully encompass MARVEL operations window.
NSUF	Provides access to unique nuclear capabilities to external stakeholders. This includes reactors, hot cells, beamlines, and analysis instrumentation. MARVEL is in the process of being listed as a partner facility.	Sensor testing in MARVEL. Post irradiation examination of MARVEL fuel and structural material.	Annual. Apply in 2026 for scopes within MARVEL operation window, and in 2028 for potential PIE scopes.
Rapid Turnaround Experiments (RTEs)	Offer an avenue to perform irradiation-effects studies of limited scope on nuclear fuels and materials of interest using NSUF facilities. Reviews are on a more regular basis with results announced within a 4-month timeframe.	Analysis of samples removed from MARVEL exposed to irradiation (e.g., liners).	Quarterly. Apply in Q1 2027 for scopes to be performed in Q4 of 2028.

4. ORGANIZATIONAL STRUCTURE FOR MARVEL APPLICATION

4.1. Proposed Interface Structure

To coordinate this varied proposed engagement, an organized structure is needed to funnel reviews, connect stakeholders with internal POCs, and prioritize scope as needed. At minimum, representatives of the MRP program and DOE federal management are expected to be engaged or participating committee members reviewing MARVEL-specific R&D proposals (e.g., LDRD, GAIN, or NSUF). In general, the approval hierarchy for proposed R&D leveraging of MARVEL is intended to follow the four steps below. Note that this will not necessarily occur in a linear fashion; some concurrent reviews may be needed on a case-by-case basis. Each of these steps may result in a go/no-go decision in serial fashion (e.g., a no-go decision at Level 1 would remove the need for a Level 2 review).

1. **MARVEL interface**: national lab POCs screen proposed R&D scope at this stage for research merit and potential overlap with other scopes of work. If the research is deemed to be of value, additional reviews may be initiated.

2. **TREAT safety and operations**: as the facility hosting the reactor, the TREAT organization is in charge or reviewing the safety basis of any proposed scope of work as part of the previously outlined process. Secondly, the MARVEL operation schedule is led by TREAT, with the organization determining potential scheduling concerns (both within competing MARVEL scopes and potential disruptions to TREAT operations).
3. **MRP National Technical Director**: If prioritization clashes emerge, the NTD will be the deciding entity of which effort displaces others and needs for schedule shifting.
4. **DOE-Headquarters Federal Manager and DOE-ID Representative**: Provide final approval for proposed scope of work.

This hierarchical framework is expected to be exercised predominantly for scope that includes changes to operations (e.g., hardware installation). More-passive scope (e.g., leveraging MARVEL data) is not expected to require safety approvals, but will likely have MRP and DOE leadership engaging with the funding entity about the relative merit of the proposed scope.

4.2. Timeline Logistics

Once a research project is approved, it must be scheduled if it impacts MARVEL operations. The plan is for the MARVEL utilization scheduler to merge with TREAT's. This will ensure adequate windows for use of MARVEL for specific demonstrations without impacting TREAT operations. Currently MARVEL is expected to be operated on 24-hour rotation and a 3-day duration (Friday, Saturday, and Sunday). When turned off, the reactor is expected to remain in hot-standby condition, meaning that it can be turned back on in a few hours. Depending on interactions with TREAT irradiation campaigns, longer week-long runs of the MARVEL reactor can be envisioned, but they will require special approval and substantial preplanning activities.

Second, the MARVEL reactor is currently scheduled for 2 years of operation (2028–2030). This provides a rather short window to conduct experiments in the reactor. Thus, early engagement with the MRP is key. Ideally, planning activities should be initiated in 2026, with design and preparations completed in 2027 in order to install new capabilities to the reactor in the 2028–2029 timeframe and to collect data in the 2028–2030 timeframe.

4.3. Long-Term Vision for MARVEL Heat Applications

The current MARVEL scope and preliminary safety assessment review envisage the reactor to directly generate electricity. However, the safety basis was developed to enable more-flexible operations. Power-conversion systems are not credited with safety functions; hence, they can be replaced by heat exchangers in theory to provide heat directly to users. This is expected to be invaluable for nuclear demonstration because interests beyond grid applications of the technology are being pursued. The scope is particularly relevant to the two advanced-reactor demonstrations projects that target novel heat application (X-energy providing steam to a chemical plant) or heat storage (Natrium using thermal-storage systems to ramp electrical power output). MARVEL could then become an enabling platform generating data on these novel applications and providing the basis for integrating nuclear energy within a broad range of applications.

Two possible options to reach this end goal are being explored by the MRP. The first is illustrated in Figure 10. It consists of keeping part of the electrical-power conversion system in place but replacing the others with IHXs. This provides the basis for a high-grade heat-extraction system that can then be connected to specific applications. In light of MARVEL's operational flexibility and large safety margins, the intent is to classify this heat-extraction system as a non-safety system. This would allow a more-streamlined approval process to validate novel applications that can be connected to the reactor. The secondary heat exchanger would ideally be built outside of the TREAT wall to facilitate R&D activities.

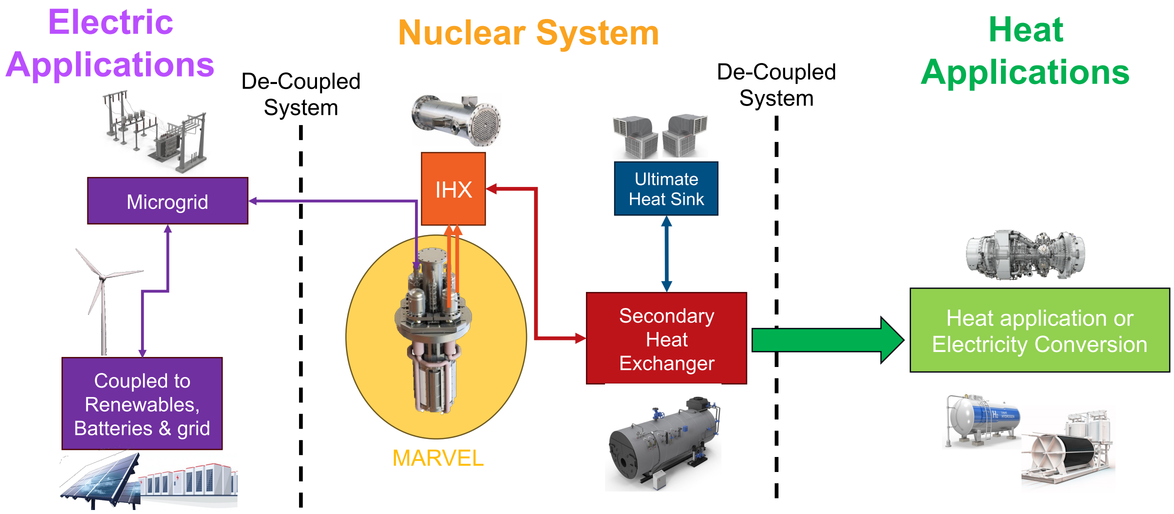

Figure 10. Option 1: Proposed vision for combined heat and power application of MARVEL using thermal-energy-storage systems.

Another approach, illustrated in Figure 11, builds upon thermal-energy systems (TESs). Here, all Stirling engines are removed, and the heat is fed directly into a salt-based TES. A stock-and-flow arrangement would enable complete decoupling of heat applications from the nuclear island. This would enable a broader variety of heat applications simultaneously. It would also simplify the coupling of a novel application and the potential review processes needed (applications cannot have any impact on the reactor in such a configuration). This arrangement would also provide greater flexibility in operation, potentially going as far as enabling 24/7 continuous operations in a case in which the heat demand is more than 40% of total MARVEL heat output. This first-of-a-kind demonstration, coupling a nuclear reactor to a TES, would provide an invaluable opportunity to generate data and enable more large-scale future testing of the technology.

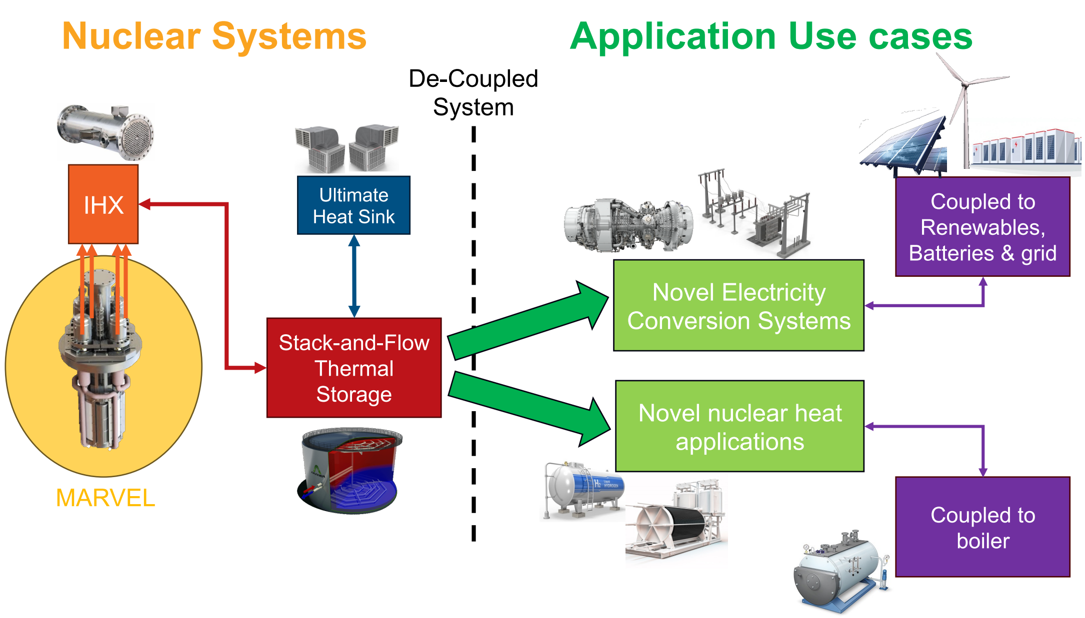

Figure 11. Option 2: Proposed vision for combined heat and power application of MARVEL using a TES.

Ultimately the option pursued (if any) will be subject to guidance from DOE and the availability of funding. The main purpose of highlighting these potential options is to provide an overview of a possible incarnation of a heat-extraction systems for MARVEL to facilitate long-term planning in light of the short operational window of the reactor.

5. SUMMARY

This report provides a broad overview of opportunities to interface and leverage the MARVEL reactor during operations. A wide range of opportunities can be envisioned to benefit the broader nuclear community. This includes:

- Data access, which can be in the form of lessons learned, cost data, design drawings, engineering reports, etc.
- Model validation can use operational data generated from MARVEL and the PCAT facility and is expected to be invaluable for code-validation opportunities.
- Electrical applications using the 20 kWe of electricity that the MARVEL reactor will generate in its current configuration. This can be leveraged for applications such as nuclear microgrid demonstration, or nuclear-powered data-center testing.
- Novel I&C applications are expected to be deployed in the MARVEL reactor. This provides an invaluable opportunity to demonstrate novel control algorithms or remote operations.
- Heat applications that extract nuclear heat for novel applications, such as torrefaction or synthetic-fuel production, can be accomplished by removing Stirling engines from the MARVEL reactor.
- Security application, including cybersecurity testing for controls, as well as novel safeguards approaches.
- Post-irradiation examination, including examination of fuel and material performance at the end of life, along with demonstration of HALEU recovery from hydride fuel.

This report also details a plan for external engagement and outreach. It suggests a wide range of funding opportunities to leverage MARVEL. These are grouped in terms of applicability between national lab programs, industry awards, and university awards. Last, a discussion of organizational structure and logistical consideration for review and prioritization of proposals is provided. Overall, this report provides useful guidance to interested parties on how to leverage MARVEL as a testbed for novel applications.

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Appendix A

Letters of Support

Thus far, the MARVEL program has received five dedicated letters of support from reactor developers. Copies of these letters are shown below. More broadly, several entities might be interested in leveraging different technology aspects of the reactor. This includes:

- Fuel: Oklo, BWXT, GA, Aalo
- Reactivity Control: Radiant, BWXT, GA, Westinghouse, LM, Oklo, Antares
- Automated control system – Sensor placement and integration, cybersecurity toward minimal staff: several
- Natural circulation system – PCAT: several
- NEPA: Westinghouse eVinci, BWXT, Oklo, etc.
- Safety Basis: several
- Fuel Loading and Startup: BWXT, GA, Westinghouse, Oklo, Aalo, Natrium
- Sub-megawatt, ultra-portable MARVEL: Lockheed Martin, U.S. Department of Defense (Navy, Army, Air Force)
- Larger MARVEL: for University Campuses (NCSU, UW, MIT)

Additionally, initial discussions were held with 20 non-vendor entities interested in potentially leveraging MARVEL for integration. These include:

- Dell
- Tesla
- Electrify America
- Chargepoint
- ExxonMobil
- Oxeon
- Bloom
- Fuelcell Energy
- Envoy Public Labs
- Eastman/Kodak
- GSE
- Shell
- Chevron
- AVEC
- Idaho Power
- Southern Company

- Holtec
- Battery 500
- Proton Conduction H2
- LIFEPo4

OKLO

June 29, 2021

John Jackson
National Technical Director DOE-NE Microreactor Program
Idaho National Laboratory

Yasir Arafat
MARVEL Technical and Project Lead
Idaho National Laboratory

Dear John and Yasir,

Oklo Inc. (Oklo) appreciates the efforts made by the Department of Energy (DOE) and Idaho National Laboratory (INL) to develop and establish fabrication capabilities for UZrH fuel forms, also referred to here as hydride fuels. Oklo is interested in deploying hydride fuels in its reactors due to their unique characteristics. Unfortunately, domestic hydride fuel fabrication capabilities have vanished, and economically competitive international fabrication capabilities have struggled to get started. Therefore, Oklo supports activities related to developing and establishing hydride fuel fabrication capabilities to support MARVEL and other national microreactor program activities.

Oklo would be eager to work with INL and DOE to develop and establish this fabrication capability to support research, development, demonstration, and deployment of hydride fuels, including contributing to cost-shared work. One of the primary factors that has delayed and hindered Oklo's efforts in hydride fuel use has been the lack of domestic fabrication capabilities. If a fabrication capability existed at a national lab, Oklo would likely exercise it to support deploying a reactor fueled by hydride fuel in the middle 2020s.

Oklo is actively developing advanced reactor designs, including the Aurora, for which it submitted a combined license application (COLA), the first ever for an advanced reactor in 2020. The Aurora COLA was accepted for review by the Nuclear Regulatory Commission in June of 2020.

If you have any questions or need any additional information, please contact us at hello@oklo.com or (650) 550-0127.

Sincerely,

Jacob DeWitte
CEO and Co-Founder, Oklo Inc.

GENERAL ATOMICS
ELECTROMAGNETICS

August 18, 2021

Dr. Youssef Ballout
Division Director of Reactor Systems Design and Analysis
Idaho National Laboratory
Idaho Falls, ID 83402

Subject: Request for Space in TREAT Facility for Fission Surface Power Reactor Testing

Dear Dr. Ballout:

I am writing to you to express our interest in securing a space within the TREAT Bldg for testing of our reactor power system for the NASA/BEA Fission Surface Power (FSP) program. Our system has similarities to the MARVEL system in that it operates at high temperature to facilitate space heat rejection but has a number of space-specific features. The TREAT building and facility support systems are ideal because the building is already qualified as a reactor site, and may already have existing interfaces with needed equipment such as shielding, I&C cabinets, control panels, power generation systems, heat rejection units, etc.

The time frame per the NASA/BEA preliminary information is 4-5 years to demonstration. The program is competitive but we are confident of our position due to the very high TRL of our system and the commonalities in MARVEL.

We appreciate your attention to this request and look forward to working with INL on FSP and other programs.

Please feel free to contact me if you have any questions. Christina.Back@ga.com, 858-762-7552.

Best regards,

Dr. Christina Back
Vice President, Nuclear Technologies and Materials Division
General Atomics Electromagnetic Systems

A A L O   A T O M I C S

2025 Guadalupe Street, Suite 260
Austin, TX 78705-5642

January 10, 2024

To:
Dr. John Jackson
National Technical Director, DOE Microreactor Program
Idaho National Laboratory

Dear John,

Subject: Letter of Support for the MARVEL Test Reactor Program

I am writing on behalf of Aalo to express our strong support for the Microreactor Applications Research Validation and EvaLuation (MARVEL) test reactor program at the Idaho National Laboratory. As a private entity committed to advancing nuclear energy technologies, Aalo is keenly aware of the critical role the MARVEL test reactor plays in the broader context of nuclear reactor development and innovation, particularly concerning our Aalo-1 reactor project.

The Aalo-1 reactor, our flagship project, shares fundamental technology with the MARVEL test reactor, including similarities in fuel, coolant, and operating temperatures. This technological kinship makes the success of the MARVEL reactor essential to the advancement and eventual licensing of Aalo-1 with the United States Nuclear Regulatory Commission (US NRC) and improving operational performance.

Achieving criticality with MARVEL allows us an unparalleled opportunity to benchmark our computational codes and models against real-world data, an invaluable asset in the rigorous licensing process. Moreover, the operational data and post-irradiation experiments planned for the MARVEL reactor over its two-year operating period are paramount to Aalo. These findings will provide critical insights into fuel performance and failure modes, enabling us to refine and derisk our reactor design. This is not merely a matter of academic interest but a crucial step in ensuring the safety, efficiency, and regulatory compliance of the Aalo-1 reactor.

While we recognize that many companies within the nuclear energy sector may find value in the MARVEL program's application testing, Aalo's reliance on the reactor physics data and operational experience from MARVEL is beyond that. Our shared technology base means that MARVEL's success directly influences our capacity to mitigate risks and navigate the complex regulatory landscape necessary for bringing Aalo-1 online.

In addition, the value of MARVEL extends outside Aalo in a few ways. Firstly, the value of inspiring young nuclear engineers cannot be quantified. Secondly, a rapidly building terrestrial advanced reactor could lend credibility to the industry's ability to innovate fast, proving that the nuclear promise can be satisfied. Lastly, with various advanced reactor developers vying to advance their designs, the developers of MARVEL will be able to share invaluable lessons learned for moving beyond paper reactors, embodying precisely the practical experience that Rickover once spoke of.

In conclusion, Aalo's future endeavors, particularly the licensing and operational success of the Aalo-1 reactor, are inextricably linked to the outcomes of the MARVEL test reactor program. We commend the Department of Energy and the Idaho National Laboratory for their foresight in initiating this project and eagerly anticipate the contributions it will make to the industry and the field of nuclear energy.

Thank you for considering our letter of support. We are committed to staying engaged with the MARVEL program and contributing to its success in any way possible. Please do not hesitate to contact me directly should you require further information or wish to discuss potential collaborations.

Sincerely,

Yasir Arafat
Chief Technology Officer
Aalo Atomics
(412) 736-4886
yasir@aalo.com

Antares Nuclear Inc

MEMORANDUM FOR DEPARTMENT OF ENERGY

FROM: Jordan Bramble, CEO Antares Nuclear Inc

SUBJECT: Letter of Support for the MARVEL microreactor demonstration project

Antares is developing a 300 kWe heat pipe cooled microreactor with the intent to demonstrate its first of a kind at Idaho National Lab under the DOE 1189 Standard. The MARVEL project is an important pathfinder project that is developing the regulatory certainty and national lab workforce to support industry projects such as ours.

In addition to the pathfinder benefits, we at Antares find value in accessing the cost and schedule data associated with the project because it helps us best forecast the costs we will incur in our demonstrations.

We have specific interest in MARVEL's supply chain and procurement procedures as well as the potential to license the reactivity control systems designs.

We at Antares hope to see the MARVEL project support industry by reaching its full potential in demonstration on the most expeditious timeline possible.

Very Respectfully,

Jordan Bramble
CEO, Antares Nuclear Inc

Innovating Nuclear Power Generation
Mission: Develop an Innovative Fully Integrated Modular Nuclear Engine
www.nucdev.com

March 13, 202

John H. Jackson
National Technical Director for the Department of Energy
Office of Nuclear Energy's Microreactor Program
Idaho National Laboratory

SUBJECT: MARVEL—Brayton Cycle

Dear John:

Many thanks again to you and your team for the valuable and highly informative conference last week.

I am writing to reiterate NuGen's interest in a closed Brayton cycle PCU being tested with MARVEL at some point after its initial start-up with Stirling engines. Like a numbe of other microreactor vendors, NuGen will be using a Brayton cycle in its microreactor design.

Briefly stated, substituting a Brayton cycle PCU after initial start-up would allow the integration of the components of a Brayton cycle with an actual reactor and would allow testing to reactions in variations in load and atmospheric conditions. The Idaho winters could present particularly appropriate conditions since one market for microreactors is at remote villages and mining sites in Alaska and Northern Canada.

The test results could be valuable to vendors in the design and development of microreactors using the Brayton cycle. Also, as has been the case with installation of MARVEL's Stirling engines, lessons would be learned from installing the Brayton cycle PCU, as well as from MARVEL's operation with the Brayton cycle PCU. Ideally, MARVEL configured with a Brayton cycle PCU could be used for other testing, such as connection to the INL microgrid. Based on last week's presentations, a microgrid using a Brayton cycle could be a viable solution for the load following needed with microgrids, which have been recognized as of increased importance. Regardless, operating MARVEL with a Brayton PCU is likely to identify other opportunities for microreactors using a Brayton cycle. Of course, MARVEL operating with a Brayton cycle PCU would also meet one of the "foundational goals" of The Microreactor Program: to have an actual operating microreactor up and running, and one in this case operating with the energy conversion cycle to be used by many microreactor vendors.

Lastly, in the past couple of years, there has been a growing recognition of the important roles that microreactors can uniquely fill for national security and infrastructure purposes when off-grid reliable resilient power (heat and electricity) is absolutely critical. MARVEL's operation with a Brayton cycle PCU can help advance the design, development and ultimate operation of these microreactors.

Thank you for your consideration of the foregoing.

SK Rhyne

Steve Rhyne
CEO
NuGen LLC