MICROREACTOR APPLICATIONS, RESEARCH, VALIDATION, AND EVALUATION (MARVEL) REACTOR: STATUS, CONSTRUCTION, AND TESTING

J.H. Jackson
Idaho National Laboratory
Idaho Falls, Idaho, USA

M.W. Patterson
Idaho National Laboratory
Idaho Falls, Idaho, USA
Email: mw.patterson@inl.gov

A. Abou-Jaoude
Idaho National Laboratory
Idaho Falls, Idaho, USA

Abstract

This paper presents the current status of the Microreactor Applications, Research, Validation, and Evaluation (MARVEL) microreactor design, qualification testing, fabrication, and high-level construction schedule. An overview of the initial criticality, low-power physics testing, and startup testing is provided, along with the envisioned processes by which end users can engage the project for access to operational data or specific demonstrations. Designed by Idaho National Laboratory (INL) under the auspices of the U.S. Department of Energy (DOE)'s Microreactor Program for construction and operation at INL, MARVEL is a small, fully functional advanced reactor that utilizes UZrH fuel and generates a thermal output of 85 kW. It represents a unique opportunity for scaled demonstrations that may dramatically accelerate the design, licensing, and deployment of commercial microreactors for power production or process heat applications.

MARVEL is a small, liquid-metal thermal reactor that will be built at INL to demonstrate microreactor design and operating processes, microgrid integration, and process heat applications. In September 2023, MARVEL completed its 90% final design, and in early 2024 it finished undergoing an independent project assessment. Fabrication of long-lead components and fuel, the safety analysis review, and procurement for construction are now underway. Assembly and construction of MARVEL will begin in 2025, with fuel loading expected in mid-2027. Initial criticality will be performed in a dry condition in late 2027, followed by loading of NaK coolant and startup testing. Approximately 6 months afterward, release for unrestricted operations will enable subsequent testing of microreactor characteristics, microgrid integration, and select heat extraction applications.

1. INTRODUCTION

The U.S. Department of Energy (DOE) Microreactor Program supports research and development (R&D) of technologies related to the development, demonstration, and deployment of small, factory-fabricated, transportable, self-regulating nuclear reactors to provide power and heat for decentralized generation in the civilian, industrial, and defense energy sectors. Such applications currently face economic and energy security challenges addressable by this new class of innovative nuclear reactors. Led by Idaho National Laboratory (INL), the program conducts both fundamental and applied R&D to reduce the risks associated with new technology performance, manufacturing readiness, and microreactor deployment. The program aims to verify that microreactor concepts are licensable and deployable by commercial entities in a manner that meets specific use case requirements. The MARVEL microreactor project is funded and managed by the DOE Microreactor Program.

2. MARVEL DESIGN

MARVEL is a beryllium (Be)- and graphite-reflected, hydrogen-moderated, solid-fuel, loop-type reactor capable of generating up to 100 kilowatt-thermal (kWth) power. It will function at a nominal 85 kWth, with a designed operational lifetime of 2 effective full-power years, operating intermittently within a 2-calendar-year period. It will hold 36 fuel rods, each containing 30 wt.% uranium enriched to 19.75% U-235. MARVEL fuel elements will be identical to standard Training, Research, Isotopes, General Atomics (TRIGA) fuel elements, except 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. FIG 1 captures the high-level details of this design.

The primary coolant system (PCS) is a four-loop hydraulic circuit assembled to transport nuclear fission heat from the nuclear fuel to the intermediate heat exchanger (IHX), using the natural convection flow of the primary coolant. The PCS is a high-temperature, low-pressure boundary that houses the core internals, reactor primary coolant, and argon gas headspace. It also passively maintains a decay heat removal capability. The boundary is a metal weldment made from stainless steel (SS) 316H for high-temperature reactors and was designed per American Society of Mechanical Engineers (ASME) Section III, Division 5.

Approximately 120 kg of NaK liquid metal at room temperature serves as the primary coolant. The heated liquid-metal NaK rises above the top of the active core, through the upper grid plate and distribution plenum, and to the IHX, which extracts the heat and cools the NaK. The secondary coolant system is a natural circulation loop of eutectic gallium-indium-tin (eGa-In-Sn), with compositions of 66.5 Ga, 20.5 In, 13.0 Sn to 78 Ga, 15 In, 7 Sn.

MARVEL is currently envisioned to utilize commercial off-the-shelf Stirling engines from Qnergy. Each Stirling engine can produce 5–7 kW and comes equipped with supporting ancillary equipment for low-grade heat rejection. An alternate high-grade heat extraction system can be optionally installed to extract high-grade heat for process heat applications testing, or for potentially interfacing with other electrical power conversion systems.

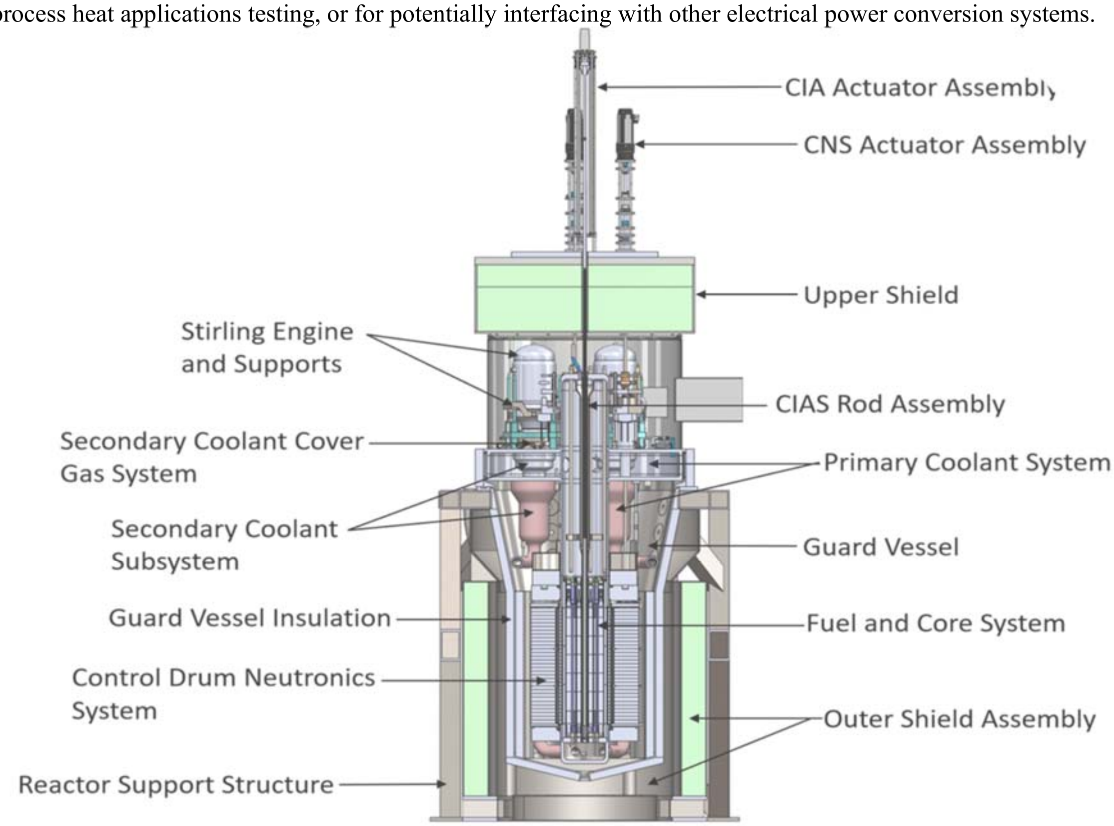

FIG 1. MARVEL design layout [1].

3. MARVEL QUALIFICATION TESTING

A driving philosophy behind the MARVEL design is to minimize the development time and cost by utilizing readily available (i.e., off-the-shelf) technologies, or by requiring as limited an implementation as possible. The main motivation behind the MARVEL microreactor is to provide potential technology end users with a shared platform and to pave the way for the commercial demonstrations that are expected to follow shortly thereafter. MARVEL is neither intended nor licensed to compete in commercial spaces where efficiency is of paramount importance. It is designed to leverage an existing fuel system, a previously utilized primary coolant, an existing power conversion system, and standard SS materials of construction. Furthermore, it is sited within INL's Transient Reactor Test Facility (TREAT) and will thus be authorized by DOE as an addendum to the existing TREAT safety basis [2].

3.1. Fuel

MARVEL utilizes a well-known fuel system employed in university research reactors [3], known as the TRIGA SS-304-clad U-$ZrH_{1.6}$ pin-type fuel system. Analysis of the MARVEL fuel system [4] concluded that, under the worst possible accident scenario (i.e., simultaneous occurrence of a loss-of-flow accident and a loss-of-coolant accident), the expected peak fuel temperature in a given element would still be approximately 180°C below the rated peak conservative allowable fuel temperature of 900°C. As the MARVEL fuel is able to maintain its geometry and afford stable, predictable behavior, it is considered bounded in the worst-case scenario, rendering additional qualification testing unnecessary, per NUREG-1537 [5]. Note that even though MARVEL is a DOE-authorized reactor, Nuclear Regulatory Commission guidelines were used to qualify the fuel.

3.2. Coolant and thermal hydraulics

The power conversion heat exchangers connect to the reactor vessel and interface with the NaK coolant via the IHX containing the eGa-In-Sn. These heat exchangers (or high-grade heat exchanger, depending on the configuration) extract heat from the primary coolant and lower the NaK temperature. The cooled NaK then flows downward through four downcomer pipes until it all meets up in the lower plenum. It then rises back up through the active core, thanks to natural circulation forces driven by the heated (or fueled) section of the active core.

During normal shutdown operations, residual heat is removed via power conversion heat exchangers. However, the low power density and large thermal mass also enable, via conduction, heat transfer from the fuel to the guard vessel (GV) boundary, where it is removed to the environment by means of convection, radiation, and conduction. The small amount of decay heat generated by fission products in the reactor core post-shutdown is thermally connected—via conduction—to large thermal masses provided by structures and shielding. This means fuel temperatures can remain below the operating limits by relying purely on passive conduction, convection, and radiation.

3.3. Reactivity control system

The reactor barrel acts as the up-flow coolant boundary. The side reflector is a BeO annulus that moderates and reflects neutrons back into the active core. The BeO annulus consists of two parts: the four rotatable control drums (CDs) and the stationary reflectors located between the CDs. The MARVEL reactor contains elements used for reactivity control and shutdown. The first of these elements is the boron carbide (B_4C) covering a third of the surface area of the four CDs, whereas the remaining surface area is covered in BeO so they can function as neutron reflectors when not rotated in for shutdown. The second element is the central insurance absorber (CIA) rod positioned in the central location of the core. This rod is fully withdrawn during operation and is used during shutdown.

The MARVEL reactor also has a very high net-negative temperature feedback for prompt reactivity control, thanks to the inherent Doppler broadening of resonances. Manual/passive reactivity control and shutdown are achieved using four custom-designed, safety-related CDs and a defense-in-depth CIA that controls reactivity via motor drives in the control cabinet to properly position the CDs and rods within the reactor structure. Passive actuation functions are built into the design for loss of power and inadvertent energizations of the motors.

4. MARVEL FABRICATION AND CONSTRUCTION

Fabrication of the MARVEL reactor is underway. Long-lead procurement of the following structures, systems, and components (SSCs) has been approved, and they are being fabricated under various contracts:

— Material procurement and fabrication of SS 316H SSCs

- PCS
- GV
- structure frames and outer shields
- reactor support structure
- secondary support structure
  - Stirling engines and controls
  - high-assay low-enrichment uranium (HALEU) fuel feedstock and fuel element fabrication
  - Be metal reflectors and dowels
  - reactivity control system procurement and fabrication.

Fabrication of these components is carefully controlled under the overarching INL Quality Assurance Program. As a Category B reactor (10 CFR 830, Addendum Chapter 15), it corresponds to fabrication and construction code ASME NQA-1, "Quality Assurance Requirements for Nuclear Facility Applications." A graded approach was adopted based on significance and risk, with notable tailoring as follows:

- ASME Boiler and Pressure Vessel Code (BPVC), Section III, Division 5, is a suitable code for application to both design and manufacture.
- Materials of construction for the GV and PCS will be procured under the provisions of Division 5, whereas materials for the support structure(s) will be purchased under NQA-1 requirements.

Materials were purchased from a qualified supplier, were validated via third-party testing, and are traceable to the originating mill. Commercial-grade dedications were performed on any safety-significant items not purchased from an approved NQA-1 supplier.

Though MARVEL vessels will not receive an N stamp, the following measures serve as high-level examples of how equivalency to those requirements will be provided:

- An INL Quality Engineer will be present at the manufacturer's facility throughout fabrication and testing of the GV, PCS, and support structure(s).
- Similar oversight will be applied to the manufacture and supply of the Be reflectors, Zr-IV debris shields, and Stirling engines.
- The GV shall be inspected and tested in accordance with ASME BPVC, Section III, Division 5.
- Weld inspection and acceptance will be performed per Article NCD-5300 of ASME BPVC III.1.NCD-2021.
- GV structural and leak tightness integrity will be verified via pneumatic pressure testing (per HCB6000) and helium leak testing (per ASME BPVC, Section V).
- To address NaK hazards, PCS inspection and testing will entail the requirements of Class A Vessels Containing Hazardous Substances (HBB5000).

Long-lead components will be stored and staged at INL as they are received. The balance of MARVEL's fabrication and construction will occur once the preliminary documented safety analysis (PDSA) has been approved by the authorizing entity (i.e., DOE Idaho Operations Office). With approval of the PDSA, a fabrication and construction contract will be competitively bid. The precise sequence and duration of the fabrication and construction will not be precisely known until the contract is awarded. However, during construction, the pit in TREAT's north bay, the control room, etc., will be prepared in parallel so as to support MARVEL startup.

MARVEL construction will be performed under strict foreign material exclusion (FME) controls. Components and systems will be received within the FME boundary, inspected, and, if necessary, cleaned so as to meet MARVEL's cleanliness requirements. Within the FME boundary, the components and systems will be connected to calibrated instruments, controls, and power sources. Their responses to commands from the control room will be demonstrated to verify that the components and systems have been constructed as designed and are ready to operate as a cohesive unit. Components and systems will be completed at various different times, meaning that, in practice, there is no fixed beginning for construction testing and no fixed release to the cold pre-operational testing that marks the next phase of the MARVEL project.

5. MARVEL STARTUP

The MARVEL Startup Plan [6] summarizes and applies the recommendations found in "Initial Test Programs for Water-Cooled Nuclear Power Plants, Regulatory Guide (RG) 1.68, Revision 2, August 1978, U.S. Nuclear Regulatory Commission, Office of Standards Development." RG 1.68 provides broad, general guidance for initial startups in light of the current U.S. light-water reactor fleet. It recommends and summarizes good practices but does not contain requirements. Revision 2 of RG 1.68 was chosen over the current revision, as it is simpler, more succinct, and provides more applicable guidance to the relatively simple MARVEL reactor and plant.

MARVEL's initial testing program consists of test procedures that specify the actions, data, and operational analyses whose results demonstrate that all the SSCs have been built as designed and are ready for operation. A progressive approach to testing will be employed, with increasing test complexity being applied to the testing of individual components, the components being integrated into systems, and the systems being ultimately operated as an integrated facility or plant. The reactor core and plant will be operated at incrementally increasing power levels. Equipment and systems will be tested to the greatest extent reasonably practical for the existing conditions, prior to proceeding on to more integrated and complex operation. Per this approach, the first step is to establish a startup organization to manage the startup and testing through the following phases:

(a) Construction completion and equipment operability testing
(b) Cold pre-operational testing and core loading
(c) Pre-critical testing
(d) Initial criticality and low-power physics testing
(e) NaK loading and low-power thermal testing
(f) At-power (or power ascension) testing.

Following acceptance of the test results and turnover to unrestricted operations, MARVEL will operate for a 2-year period, following a typical 3-day-per-week operating schedule. For the other 4 days, the reactor will be maintained in a hot standby condition, with an average coolant temperature of approximately 200°C. This temperature will be maintained by decay heat and supplemented by the CIA heaters. From this condition, the 3-day operating period is generalized as follows:

(a) Preparation for Startup: The Stirling engine cooling system pumps are started.
(b) Start of Operation: The CIA heaters gradually increase the average coolant temperature until the Stirling engines begin operating. The functionality of the power generation system and the proper operation of the Stirling engines and their heat rejection loops are verified.
(c) System Checks: The functionality of the critical monitoring, instrumentation, and control systems is verified.
(d) Transition to Power Generation: The CIA heaters are turned off, enabling the system to gradually cool until the Stirling engines can be shut off at their lower threshold temperature. The CD startup sequence is then initiated to gradually introduce nuclear fission heat, increasing from 0% to 100% power over the course of approximately 1 hour.
(e) Steady-State Operation: The reactor is maintained at a steady state for the duration of any applications tests, which are expected to last 12–24 hours over a normal weekend. However, the reactor design allows for longer operational runs so long as they do not interfere with TREAT's regular operating schedule.
(f) Shutdown Procedures: After completing the applications tests, the reactor is shut down by manually scramming or incrementally driving the CDs into their shutdown positions. The system then cools until the Stirling engines automatically shut off at the minimum threshold temperature.
(g) Maintenance of Hot Standby: Following shutdown, the CIA heaters are controlled to balance heat loss with decay heat and heater power, maintaining the system coolant in a hot standby state at an average temperature of approximately 200°C.

Specific applications test programs will be addressed in the MARVEL Final Documented Safety Analysis, or in revisions thereof, as needed. MARVEL access to test specific applications is discussed in the following section.

6. MARVEL ACCESS AND DEMONSTRATIONS

The MARVEL reactor is intended to serve as a testbed for demonstrating novel microreactor technologies and capabilities. A wide variety of tests and demonstrations that leverage this reactor can be envisaged. FIG 2 gives a non-exhaustive list of potential demonstrations that may be proposed by external stakeholders. To highlight a few: the project is expected to provide an invaluable repository of knowhow, lessons learned, and validation data, and can be used to test novel controls for microreactors (secure remote operations or semi-autonomous controls). It can also be used to demonstrate innovative electrical/ heat applications for nuclear.

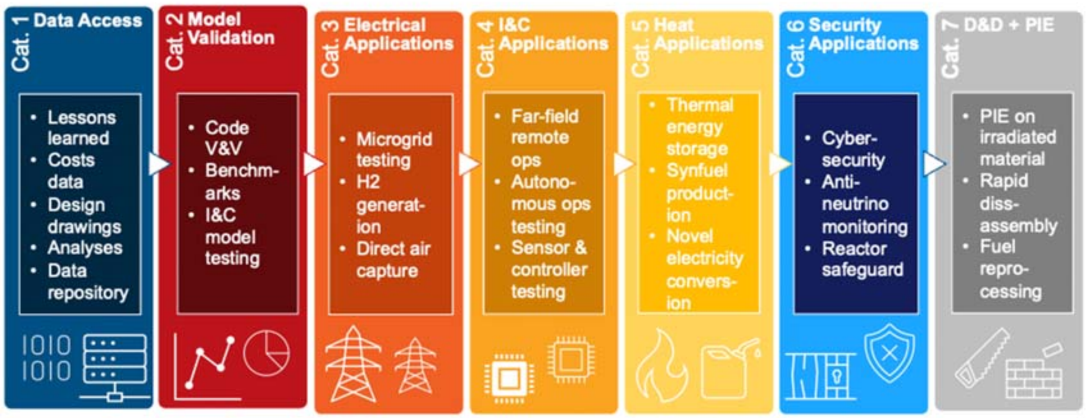

FIG 2. Conceptual overview of potential MARVEL applications (not intended to be exhaustive).

Additional information is given in the MARVEL Utilization Plan [7], which discusses potential funding opportunities that stakeholders can pursue to conduct some of the suggested tests, along with recommended timelines. It also discusses the anticipated MARVEL data management plan and possible configurations for combined heat and power applications.

7. SUMMARY

MARVEL is a small, fully functional advanced reactor that utilizes UZrH fuel and generates a thermal output of 85 kW. Its 90% final design was completed in September 2023. In the summer of 2024, a PDSA was submitted to DOE for review and approval so as to authorize INL to begin procurement and construction activities. Fabrication of long-lead components and systems, including the fuel, is now underway.

MARVEL assembly and construction will begin in 2025, with fuel loading being expected in late summer-2027. Initial criticality will be performed in a dry condition in late 2027, followed by NaK coolant loading and startup testing. Approximately 6 months afterward, release for unrestricted operations will enable subsequent testing of microreactor characteristics, microgrid integration, and select heat extraction applications.

The MARVEL Utilization Plan discusses potential funding opportunities for stakeholders to pursue, as well as suggested tests and recommended timelines. MARVEL's anticipated data management plan and possible configurations for combined heat and power applications to enable interaction between potential end users and the MARVEL team. MARVEL offers a unique opportunity for scaled demonstrations that can dramatically accelerate the design, licensing, and deployment of commercial microreactors for power production or process heat applications.

ACKNOWLEDGEMENTS

This manuscript was authored by Battelle Energy Alliance, LLC, under contract no. DEAC07-05ID14517 with the U.S. Department of Energy (DOE). This project is funded by the DOE Office of Nuclear Energy.

REFERENCES

[1] MARVEL Design Team, MARVEL 90% Final Design Report, INL/RPT-23-74280, Idaho National Laboratory, 2023.

[2] U.S. DOE, Environmental Assessment for the Resumption of Transient Testing of Nuclear Fuels and Materials: Final, DOE/EA-1954, U.S. Department of Energy, Idaho Operations Office, 2014.

[3] NRC, Safety Evaluation Report on High-Uranium Content, Low-Enriched Uranium-Zirconium Hydride Fuels for TRIGA Reactors, Docket No. 50-163, GA Technologies, Inc, Nuclear Regulatory Commission, 1987.

[4] EVANS. J.A., et.al., Uranium-Zirconium Hydride Nuclear Fuel Performance in the NaK-Cooled MARVEL Microreactor, J Nucl Mater, 2024.

[5] NUREG-1537, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors., U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, 1996.

[6] PHOENIX, W., Startup Plan for Initial Testing of the MARVEL Test Reactor, PLN-6816, Idaho National Laboratory, 2023.

[7] ABOU-JOURDE, A., PATTERSON, M.W., MARVEL Utilization Plan, INL/RPT-24-78261, Idaho National Laboratory, 2024.