Status Report - MARVEL (United States of America)

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1. Overview

- ☐ **In Operation**
- ☐ **Under Construction**
- ☐ **Described in**

Link to PRIS	--

- ☑ **New Concept**

Number of Units	--
Year	--

Reference Plant

Name of Site	--
Link to PRIS	--
Net Power Output (MWe)	0.027
Gross Power Output (MWe)	--

1.1 Introduction

The Microreactor Applications Research Validation and Evaluation (MARVEL) Project entails the design, development, construction, and startup of an INL test microreactor, funded by the United States Department of Energy (DOE) via the Microreactor Program (MRP). The goal of the project is to establish an operational nuclear applications test bed that can generate combined heat and power to enable integration and R&D with end-user technologies, as well as allow microreactor technologists to test next-generation control systems. The microreactor is a thermal reactor utilizing Uranium Zirconium Hydride (UZrH) fuel with authorization to be provided by the Department of Energy Idaho Operations Office (DOE-ID) for National Environmental Policy Act (NEPA) compliance, safety review, and supplemental readiness assessments for startup and operation. To enable rapid deployment, the MARVEL reactor will reside in the Transient Reactor Test (TREAT) Facility and utilize the existing operating Category B reactor facility, operating crews, and recent re-start experience. The MARVEL team consists of Idaho National Laboratory (INL), Argonne National Laboratory, Los Alamos National Laboratory, Walsh Engineering, Munro & Associates, and Creative Engineers Inc. The primary purpose of investigating a near-term concept is to determine its feasibility and utility for future microreactor research and development, such as a test bed for integrating microreactors with electric and non-electric applications and demonstrating the technology to key end-users. It can also drive

infrastructure development and capabilities to support future microreactor demonstrations. The U.S. DOE Microreactor Program supports research and development (R&D) of technologies related to the development, demonstration, and deployment of very small, factory-fabricated, transportable reactors to provide power and heat for decentralized generation in civilian, industrial, and defense energy sectors. Such applications currently face economic and energy security challenges that can be addressed by this new class of innovative nuclear reactors. Led by INL, the program conducts fundamental and applied R&D to reduce the risks associated with new technology performance, manufacturing readiness, and deployment of microreactors. The program aims to verify that microreactor concepts can be licensed and deployed by commercial entities to meet specific use case requirements. Microreactors, often referred to as special-purpose reactors or very small modular reactors, are factory manufacturable, easily transportable, and designed to produce tens of megawatts of thermal (MWth) energy. This power limit allows microreactors to be classified as Hazard Category 2 per the Code of Federal Regulations (CFR) at 10 CFR 830 and DOE-STD-1027. These reactors are decentralized energy sources that can provide sustainable and affordable heat and power to remote communities and industrial users while having self-contained geometry that requires very low maintenance. Microreactors are intended to be self-regulating and do not rely on engineered systems to ensure safe shut down and removal of decay heat.

MARVEL is targeted at researchers, technology developers, and end-users for enabling the successful deployment and adoption of microreactors through research and education. Some examples of R&D activities are:

Test, demonstrate, and address issues related to installation, startup, and operation

- Simplify siting and environmental review process
- Startup methodology for microreactors
- Normal operating transients such as startup and load management
- Cyber and physical security hardening
- Integration with a net-zero, electrical microgrid
- Demonstration of high and low-grade heat extraction.

Enable Automated Operation Technologies

- Automate operator functions, while maintaining reactor safety
- Demonstrate radiation and temperature-hardened sensors and instrumentation to enable remote monitoring, advanced sensor reliability tests, and online calibration
- Live data can feed a digital twin of the reactor to “train” an artificial intelligence-based control system
- Demonstrate transmission of live data of both electrical and thermal power output during startup, operation, and shut down. This allows real-time feedback on system output, performance, and prediction of any unplanned maintenance needed in an operating microreactor.

Enable Application Integration

- The control systems manage the energy grid demand and reactor power and heat supply. This management requires a carefully designed control system that can predict the interplay of controls, thermal inertia, and reactivity feedback.
- Demonstrate integration approaches for a range of applications investigating both reactor power management and load management approaches.

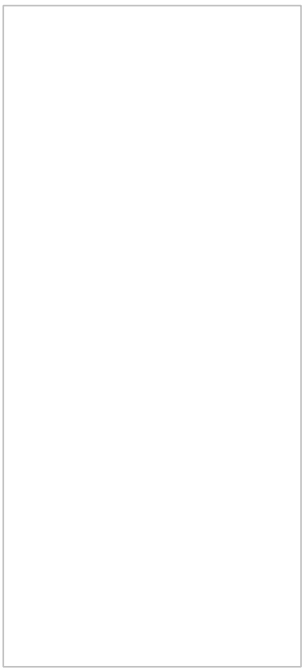


Figure 1. MARVEL design concept

1.2 Development Milestones

2024	A safety design strategy (SDS-119, Rev 1) has also been approved by DOE with a Preliminary Documented Safety Analysis (PDSA) submitted
2025	90% construction planned to conclude
2027	fuel load and initial criticality

1.3 Design organization or vendor company

1.4 Links to designer/vendor website

1.5 Design Description

The design philosophy is generally to select technologies that can lead to criticality within the shortest time possible. Time is the essential metric of project performance without sacrificing safety and quality. This drives the team to select technologies that are either (i) off-the-shelf, (ii) can be implemented, and/or (iii) can be developed to accelerate technology and manufacturing readiness levels. Innovation and creativity are embedded in the team culture and celebrated. This includes adopting multiple engineering tools and processes from non-nuclear technology industries, e.g. Scrum Agile Product development, and Design for

Manufacturability (DFM) modeling from the automotive industry.

1.6 Licensing Application Support Documents

1.7 Reactor Unit in PRIS

2. Category Fields

Table 1: ARIS Category Fields

ARIS Category	Value	Units of Examples
Current/Intended Purpose	Experimental	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Non-electric (Research and development)	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Inland	e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)		e.g. Single Unit, Dual Unit, Multiple Unit (# units)
Core Coolant	Sodium-Pottasium Eutectic	H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Reactor Core Size (1 core)	Thermal Power < 30 MWth	e.g. Thermal Power < 30 MWth, 30 MWth ≤ Thermal power < 1000 MWth, 1000 MWth ≤ Thermal power ≤ 3000 MWth, Thermal power > 3000 MWth
Reactor Type	Others	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	Microreactor	e.g. PWR, SMR
Neutron Moderator	Other	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout		e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type

Primary Circulation	Natural	e.g. Forced (# pumps), Natural
Thermodynamic Cycle		e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid		e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form		e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape		e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle		e.g. #, n/a
Fuel Material Type	Other	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Detailed Design	e.g. Conceptual, Detailed, Final (with secure suppliers)
Licensing Status		e.g. DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)
Neutron Spectrum	Thermal	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		
Design Life	40	Years
Lifetime Capacity Factor		%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages		# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources		# Staff in Operation / Maintenance Crew during Normal Operation

Reference Site Design		n Units/Modules
Capacity to Electric Grid		MWe (net to grid)
Non-electric Capacity		e.g. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption		MWe
Plant Footprint	8.9	m2 (rectangular building envelope)
Site Footprint		m2 (fenced area)
Emergency Planning Zone		km (radius)
Releases during Normal Operation		TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed		x – 100%, % per minute
Seismic Design (SSE)	IBC 2015 Risk Category IV Site Class C	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	0.39	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)	0.22	MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)		kg
Nominal Coolant Flow Rate (primary)		kg/s
Nominal Coolant Flow Rate (secondary)		kg/s
Core Inlet Coolant Temperature	450	ºC
Core Outlet Coolant Temperature	520	ºC
Available Tempeature as Process Heat Source		ºC
NSSS Largest Component	Reactor vessel	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length	2550	mm
- NSSS Largest Component Diameter	1220	mm

- NSSS Largest Component Thickness		mm
- NSSS Largest Component Weight	5.94	tonne
Reactor Vessel Material		e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design		e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory		kg
Pressurizer Design		e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume		m3 / m3 (total / liquid)
Containment Type		Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume		m3
Spent Fuel Pool Capacity and Total Volume		Years of full-power operation / m3
Non Electric Application	Research and education	-
Core Delta Temperature	70	ºC
Fuel/Core		
Single Core Thermal Power	0.1	MW(th)
Refuelling Cycle	>60	months or “continuous”
Fuel Material	Uranium Zirconium Hydride	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	19.75	%
Average Neutron Energy		eV
Fuel Cladding Material		e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”		Specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit		kg
Total Fissile Loading (initial)		kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation		Applicable to online refuelling and molten salt reactors

Fraction of fresh-fuel fissile material used up at discharge		%
Core Discharge Burnup		MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)		MWd/kgHM
Breeding/Conversion Ratio		Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing		e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Four ex-core, safety-related control drums, One defense-in-depth central shutdown rod	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber		e.g. Gd2O3
Core Volume (active)		m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary		n/(cm²*s)
Max. Fast Neutron Flux		n/(cm²*s)
Core Control Rod Absorber		-
Core Soluble Neutron Absorber		-
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	Active/Passive	- / - / -
- core injection	Active/Passive	- / - / -
- decay heat removal	Passive	- /- / -
- containment isolation and cooling	Active/Passive	- / - / -
- emergency AC supply (e.g. diesels)	Active/Passive	- / - / -
DC Power Capacity (e.g. batteries)		Hours
Events in which Immediate Operator Action is required		e.g. any internal/external initiating events, none

Limiting (shortest) Subsequent Operator Action Time		Hours (that are assumed when following EOPs)
Severe Accident Core Provisions		e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)		x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions		e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)		x/reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)		Months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort		Person-years (PY) [DP&P]
Construction and Commissioning Effort		PY [C&C]
Material and Equipment Overnight Capital Cost		Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C]/%[M&E]	
- Site Development before first concrete		(e.g. 25/10) (30/40) (20/25) (20/10) (5/15) (----------) (to add up to 100/100)
- Nuclear Island (NSSS)		
- Conventional Island (Turbine and Cooling)		
- Balance of Plant (BOP)		
- Commissioning and First Fuel Loading		
Factory / On-Site split in [C&C] effort		%/% of total [C&C] effort in PY (e.g., 60/40)
Nuclear System		
System Steam Flow Rate		kg/s
System Steam Pressure		MPa
System Steam Temperature		ºC
System Feedwater Flow Rate		kg/s

System Feedwater Temperature		ºC
Reactor Core		
Active Core Height		m
Equivalent Core Diameter		m
Average Linear Heat Rate		kW/m
Average Fuel Power Density		kW/kgU
Average Core Power Density		MW/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

4.1 Site Requirements during Construction
4.2 Site Considerations during Operation
4.3 Grid Integration

5. Technical NSSS/Power Conversion System Designn

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Power Conversion

MARVEL is capable of and is originally conceptualized as utilizing commercial, off-the-shelf Stirling Engines from Qnergy. Each Stirling engine can produce 5-6 kilowatt and comes equipped with supporting ancillary equipment for low-grade heat rejection. Qnergy equipment will absorb available high-grade heat and then convert that heat into either using electric power or low-grade heat for rejection into site processes or finally into the ultimate ambient heat sink. An alternate high grade heat extraction system will be available for extracting high grade heat for process heat applications testing, or for testing alternate power conversion systems such as Rankine or Brayton cycle.

Reactor Core

The MARVEL reactor will contain fuel elements sourced from TRIGA International (TI): LEU, 30% uranium, by weight, 19.75 % enriched (TRIGA LEU 30/20). Beryllium and graphite reflected, ZrH moderated, solid fuel, tank type reactor. The MARVEL reactor core comprises 36 LEU fuel elements arranged in a triangular pitch lattice around a central voided location for the central insurance absorber

(CIA) rod assembly. Surrounding the core is a thick axial neutron reflector composed of beryllium oxide.

Fuel Characteristics

The major components of the MARVEL fuel system are (1) U-ZrH1.6 fuel slugs (annular), (2) Zirconium filler rods (to be inserted into fuel slug annulus), (3) Molybdenum spacer disk placed between lower graphite reflector and bottom of the fuel stack, (4) Stainless steel 304 cladding, (5) Top and bottom graphite axial reflectors, and (6) Top and bottom end plugs.

Reactivity Control

The MARVEL reactor also has a high net negative temperature feedback for prompt reactivity control inherently due to the Doppler broadening of absorption resonances and spectrum hardening from the ZrH moderator with increased temperature. Manual and Passive Reactivity Control and shutdown are achieved with four custom-designed, safety-related Control Drums (CDs) and a defense-in-depth CIA that control reactivity via motor drivers in the control cabinet to position the drums and rods within the reactor structure. Passive actuation functions are built into the design for loss of power and inadvertent energizations of the motors.

Reactor Pressure Vessel and Internals

The Primary Coolant System (PCS) is a 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 ASME Section III Division 5.

Reactor Coolant System

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 circulation flow of the primary coolant. The PCS also transfers decay heat to the ultimate heat sink. Approximately 150 kg of NaK, liquid metal at room temperature, serves as the primary coolant. The power conversion heat exchangers connect to the reactor vessel and interface with the NaK coolant via the IHX containing eutectic gallium-indium-tin or other suitable, low melting point liquid metal coolant. The Stirling engine coils or high-grade heat exchanger, depending on configuration, extract heat from the primary coolant and reduce the NaK temperature. The cooled and denser NaK then flows outward to the periphery of the core, then downward through four downcomer pipes outside the beryllium oxide side reflector and through in the lower plenum. The NaK then rises back up through the active core under natural circulation forces driven by the heated section of the active core.

Secondary System

Eutectic gallium-indium-tin (eGa-In-Sn) has currently been selected as the coolant for the IHX, serving as the secondary system. An argon gas sweep will be maintained on the IHX overhead gas space to remove any volatile activation products for ease of maintenance and repair. Alternative liquid metal coolants may be selected if the integrated Stirling engines are replaced with a high grade heat extraction system.

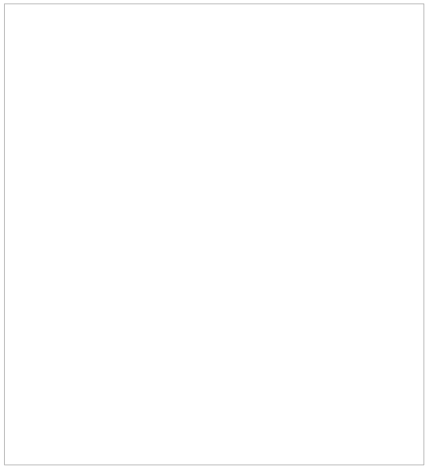


Figure 2

5.1 Primary Circuit
5.2 Reactor Core and Fuel
5.3 Fuel Handling
5.4 Reactor Protection
5.5 Secondary Side
5.6 Containment/Confinement
5.7 Electrical, I&C and Human Interface
5.8 Unique Technical Design Features (if any)

6. Technology Readiness

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Testing Conducted for Design Verification and Validation

The MARVEL team conducts rapid prototyping tests to mature its technologies. So far, more than ten separate effects tests have been conducted, including, but not limited to, the intermediate heat exchangers, control drums, instrumentation control, neutron detection, shutdown rod actuators, and Stirling engines.

Due to MARVEL's novel thermal hydraulic circuit, where a liquid metal natural circulation primary loop is in series with four parallel liquid metal natural circulation loops, an integral effects test (IET) of the system was considered necessary for verifying the transient dynamics of the system before reactor construction. Hence the team has successfully designed and fabricated a full-scale electrically heated prototype of the MARVEL reactor. This is conducted per ASME boiler and pressure vessel code (Section III and VIII) within nine months by employing an agile development process. The test hardware includes (i) a Full-scale mechanical IET test article; (ii) eight electrical control cabinets; (iii) a structural frame; (iv) four IET flow meters; (v) more than 200 thermocouples and pressure transducers; and (vi) four Stirling engines, engine control, and heat rejection units. The goals of this IET are to: (i) validate flow and heat transfer characteristics of MARVEL technology; (ii) benchmark modeling & simulation parameters; (iii) streamline manufacturing methods; (iv) de-risk supply chain; and (v) train operators.

Design and Licensing Status

DOE conducted an environmental assessment (EA) as part of the NEPA process, which analyzed the potential environmental impacts of constructing the MARVEL microreactor inside Idaho National Laboratory's (INL's) Transient Reactor Test Facility. At the conclusion of the EA process, DOE issued a final EA with a "finding of no significant impact" (FONSI) for the MARVEL Project (DOE/EA-2146). A safety design strategy (SDS-119, Rev 1) has also been approved by DOE with a Preliminary Documented Safety Analysis (PDSA) submitted in Q3 CY24. The MARVEL reactor is currently in Final Safety Review and preparation for full fabrication phase, with 90% construction planned to conclude in Q2, CY25, and fuel load and initial criticality in Q4, CY27.

6.1 Deployed Reactors
6.2 Reactors under Licensing Review
6.3 Reactors in the Design Stage

7. Safety Concepts

SUMMARY FOR BOOKLET

MARVEL employs rigorous safety standards and expectations for (i) reactivity control, (ii) passive shutdown, and (iii) decay heat removal by relying primarily on physics rather than engineered systems. The fuel has a high prompt negative temperature reactivity feedback due to the strong Doppler broadening of absorption resonances and neutron spectrum hardening from the ZrH moderator. In addition, passive shutdown features enable the use of potential energy to actuate negative reactivity in the core. Both primary and intermediate coolants are driven by natural circulation. Decay heat is removed from the fuel to the outer shell of the reactor primarily by conduction and radiative heat transfer and subsequently rejected to ambient air by convection. Finally, there are three robust fission product barriers- fuel cladding, primary coolant boundary, guard vessel to confine hazardous materials throughout system life in all operational, postulated design-basis, and beyond-design-basis events.

7.1 Safety Philosophy and Implementation
7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

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8.1 Fuel Cycle Options
8.2 Resource Use Optimization
8.3 Unique Fuel/Fuel Cycle Design Features

9. Safeguard & Physical Security

SUMMARY FOR BOOKLET

9.1 Safeguards
9.2 Security
9.3 Unique Safeguards and/or Security Features

10. Project Delivery & Economics

SUMMARY FOR BOOKLET

10.1 Project Preparation and Negotiation
10.2 Construction and Commissioning
10.3 Operation and Maintenance