INL/RPT-25-84647

Lessons Learned from MARVEL Initial Fabrication and Testing

Department of Energy—
Microreactor Program

APRIL 2025

Justin Johnson,
Carlo Parisi,
Benjamin Baker,
Raymond Clark,
Stuart Jensen, and
Abdalla Abou-Jaoude

Idaho National Laboratory

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Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

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Idaho National Laboratory
Nuclear Science and Technology Microreactor Program
Idaho Falls, Idaho 83415

http://www.inl.gov

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EXECUTIVE SUMMARY

The Microreactor Applications Research Validation and Evaluation (MARVEL) project is intended to be amongst the first U.S. advanced reactor demonstrations in four decades. By virtue of being sponsored directly by the U.S. Department of Energy, the reactor is intended to benefit the broader nuclear community by exercising design processes, safety reviews, and supply chains. This project is intent on publicly documenting key lessons learned along the way toward demonstration. Building on a 2024 report that focused on lessons learned from the design and project management phase, this 2025 edition focuses on findings from the MARVEL guard vessel fabrication and primary coolant apparatus test (PCAT) testing. A high-level summary of the key lessons for each is provided in Table ES-1.

Table ES-1. Summary of lessons learned documented in this report regarding the MARVEL guard vessel fabrication and engineering tests conducted.

Lesson	**Description**
Guard Vessel Fabrication	
Traveler and work instructions	Importance of mandating component-level tracking of inspections and processing ahead of time. Notably that travels that travelers possess sufficient fidelity to track fit-up and welding at the component level.
Weld distortion challenges	Need to apply traditional restraint techniques (e.g., temporary stiffeners) to avoid weld distortion issues and to originally specify requirements for weld distortion mitigation plans.
Weld joint design	Weld design should consider options to minimize asymmetric weld stresses For instance, using double-vee weld joints instead of single-side ones to equalize the heat input to the joint where appropriate.
Welding process	The gas metal arc welding process can be more suitable for some weld areas, namely internal fillet welds.

Lesson	Description
Code of construction	Critical for designer and fabricator to understand the full scope of work imposed by invoked requirements. In particular, the uniqueness of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section III, Division 5 requirements (e.g., that components are required to be 100% examined using the magnetic particle or liquid penetrant method).
Fit-up and layout	Layout lines can be invaluable in ensuring consistent measurements and expediting dimensional inspection.
Control of nonconforming items	Any identified nonconforming material must be identified and segregated (using the so-called “Red Tag”) prior to disposition, and it is critical to avoid reluctance to issue nonconformance reports.
Pneumatic leak testing procedures	Need for strict adherence to the Boiler and Pressure Vessel Code requirements, ensuring all work is conducted per documented instructions and procedures.
PCAT Engineering Demonstration Unit	
Value of engineering demonstration unit	A representative scale, electrically-heated EDU can be invaluable in identifying “unknown unknowns” in a non-nuclear environment.
Proceeding at risk with fabrication	The potential schedule benefits of concurrent design and fabrication may be undone by design changes that affect completed or in-process components resulting in substantial ‘back-and-forth’ that may negate the benefits of accelerated start of fabrication.
Ensuring demonstration adequately informs final design	The value of an EDU is maximized when the results of EDU testing can be used to inform the design of the reactor.
Heater fabrication challenges	Wire sleeving is prudent if they might be exposed to high temperatures during operation or fabrication. Heat generated from welding can damage core systems (namely the heater assemblies in the case of PCAT). Bowing distortions can result from the welding annealing of tube materials, which could ultimately lead to failure in the case of heater contacts in PCAT.

Lesson	Description
Over-conservatism in requirements	Ensure that constraints, tolerances, and requirements are appropriate, value-added, clear, and achievable for a given design and use. Notably, a review should be conducted at the end of the design phase to re-evaluate engineering constraints and requirements to relax where appropriate. It is common to run into issues during the fabrication phase and then revise these constraints after the fact. Good examples in the case of PCAT include leak test specifications that are more stringent than could be achievable or wiring checks that can be performed through observation rather than double verification. Additionally, unclear requirements can amount to confusion and rework. These requirements need to be adequately communicated to the suppliers.
Experiment setup challenges	Recognize that all design decisions have trade-offs (e.g., longer instrument leads provide installation flexibility and increase signal noise). In a specific instance, having longer wires than needed appeared to be useful at first, this ultimately lead to noise transmission issues. Sensor calibration challenges for nuclear quality assurance are nontrivial. It is important to ensure experiment calibrations are within their expiry date at each iteration. This is particularly challenging for long-lived experiments (hence the importance of making sure these sensors are accessible).
Experiment design considerations	Adequately defining testing duration and requirements prior to initiation. For instance, ensure that EDU design and test plans consider the need to inspect, calibrate, incorporate adequate chemistry control (e.g., oxygen levels) and/or replace sensors and instrumentation. A plan should be developed prior to testing with a methodology consistent with the data requirement needs. The plan should also account for the high likelihood that the testing campaign might substantially exceed the original intended timeline.
Change control and evaluation	Seemingly trivial changes can lead to large experimental and/or operational discrepancies. A careful review of follow-on impacts should be evaluated. In the case of PCAT, the assumption that water cooling can be substituted with glycol proved to be false and required a redesign on the cooling system to an 80/20 mix.
Off-the-shelf systems	Systems are no longer “off-the-shelf” when used in any manor for which they have not been designed, evaluated, and/or tested. One key finding from the MARVEL

Lesson	Description
	experience was that multiple Stirling engines mounted on top of a large structure is challenging to engineer.
Stirling engine mounting	Leveraging a liquid (rather than a gas as the systems are originally intended for) and changing the support structure can lead to several challenges, including helium tube rupture due to oxide formation, corrosion, potential rubbing wear, melting and thawing pressures, and increased vibration. In the case of the PCAT setup, the freeze-thaw stresses along with increased vibration are believed to be the primary failure mechanism. The freeze-thaw stresses can be addressed by draining the fluid during shutdown or by ensuring it is always maintained in a liquid state. Using the same vibration dampening equipment is not sufficient if the engines are not connected to a similar support system for mass dampening. A custom vibration dampening system and supporting analysis would be required as a result.

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ACRONYMS

ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CEI	Creative Engineers Incorporated
CGD	Commercial Grade Dedication
DOE	U.S. Department of Energy
EDU	Engineering demonstration unit
GMAW	Gas metal arc welding
HX	Heat exchanger
IHX	Intermediate heat exchanger
INL	Idaho National Laboratory
MARVEL	Microreactor Applications Research Validation and Evaluation
NCR	Nonconformance Report
NQA-1	Nuclear Quality Assurance
PCAT	Primary coolant apparatus test
RELAP5-3D	Reactor Excursion and Leak Analysis Program
TC	Thermocouple
TRIGA	Training, Research, Isotopes, General Atomics

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Lessons Learned from MARVEL Initial Fabrication and Testing

1. INTRODUCTION

This report is part of an annual series of lessons learned documents that compile lessons learned for the Microreactor Applications Research Validation and Evaluation (MARVEL) project from project planning through reactor design and fabrication, construction, operation, and ultimately decommissioning. It provides a narrative overview of the project's evolution. This particular document follows an initial lessons learned document that was released in 2024 and focused on lessons learned associated with project management and achievement of 90% Final Design (Paterson, 2024). That initial report provided a breakdown of cost and scope growth, as well as lessons learned, and included technical maturity as part of the project assessment. Additional assessments of MARVEL were also conducted throughout the project (Grecheck, Arenaz, Pérès, Pierpoint, and Raisch, 2024). Specific topics of interest in the current volume of lessons learned (this report) include MARVEL initial fabrication and non-nuclear validation testing using the primary coolant apparatus test (PCAT), which is effectively an engineering demonstration unit (EDU) for MARVEL.

A record of MARVEL's evolution and lessons learned through planning, design, and initial fabrication is expected to benefit other advanced reactors as they follow with their own planning and design. Lessons learned are being recorded continuously, even before the completion of MARVEL, so stakeholders do not have to wait for the information. Chronicling the project at an interim point minimizes the loss of "tribal knowledge" as technical experts from the early project phases move on to other assignments. This report spans initial MARVEL reactor fabrication and the validation of MARVEL core thermal hydraulics using the PCAT EDU.

1.1. Background and Motivation

Key to deploying nuclear energy is addressing financial and technical risks that industry is unable to solve alone. The U.S. Department of Energy (DOE) Office of Nuclear Energy is addressing technical challenges to improve the economic competitiveness and license-ability of microreactors. This includes developing experimental infrastructure to enable the testing and demonstrating of microreactor technologies and enabling microreactor integration into end-user applications for broad deployment and use (U.S. Department of Energy, Idaho Operations Office, 2021).

In a broad sense, MARVEL is intended to directly serve that purpose. The MARVEL project will meet the research and development needs identified by DOE and the advanced reactor stakeholder community. This will be accomplished by designing and building a nuclear microreactor application test platform at Idaho National Laboratory (INL) that will demonstrate experimental capabilities for performing research and development. MARVEL will also demonstrate microreactor integrations with end-user applications, such as off-grid electricity generation and the use of process heat.

The MARVEL reactor consists of a small uranium zirconium hydride fueled microreactor cooled by the natural convection of a NaK coolant. The core employs both Be metal and BeO radial reflectors alongside graphite axial reflectors (contained within the fuel pin). Reactivity is controlled by both control drums and a central control rod. Additional information on the MARVEL 90% design is provided by Gerstner and Arafat (2023). Since this evaluation—as will be documented in this report—the project opted against directly mounting Stirling engines on top of the reactor. This is highlighted in the crosssection view of the design in Figure 1. Some additional technical specifications regarding the MARVEL design are summarized in Table 1.

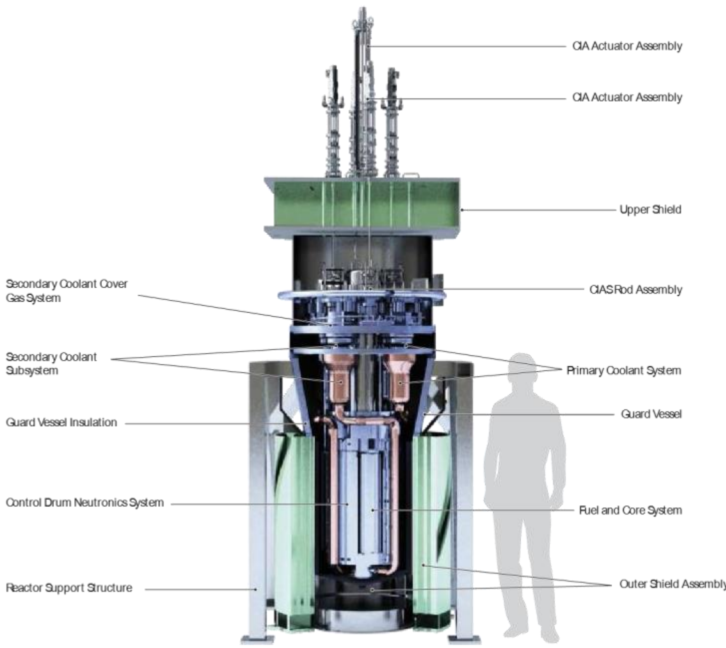

Figure 1. Cutaway view of the MARVEL core without the Stirling engines directly mounted.

Table 1. Summary of MARVEL design specifications.

Key Design Features	
Reactor type	Liquid metal thermal reactor
Thermal power	85 kWth
Electrical power	~20 kWe
Coolant drive	Natural circulation
Primary coolant	Sodium potassium (NaK)
Primary coolant temperature	500°C–550°C
Secondary coolant	Ga-In-Sn
System life	2 years
Fuel	Uranium zirconium hydride TRIGA fuel
Enrichment	19.75 wt%
Reflector material	Be metal + BeO
Reactivity control	B4C Control Drum ×4 B4C Shutdown Rod ×1
Weight	<12 metric ton
Height	<15 feet
Number of operators	2

2. GUARD VESSEL FABRICATION

In December 2023, the MARVEL guard vessel fabrication contract was awarded. Guard vessel fabrication provided valuable insights for the Nuclear Acquisitions Group and Quality Engineering Team. and is expected to be relevant for the broader advanced reactor community as well.

This fabrication started in late January 2024 and was completed in late August 2024. Final testing (pneumatic pressure and helium leak tests) was completed in October 2024. A picture of the finished product is shown in Figure 2. Throughout guard vessel fabrication, INL assigned a resident quality engineer at the supplier's facility to witness all key fabrication, inspection, and test activities.

Prior to the award of the contract, the quality engineer developed an overarching quality surveillance plan that incorporated the essential elements from the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME/BPVC) Section III for activities that INL team members would witness throughout construction. The plan was written in accord with the equivalencies described in the Code of Record (re: COR-0011) (Patterson, 2023), and essentially captured all witness points that an authorized nuclear inspector would verify. As such, the resident quality engineer could observe some challenges the supplier had to overcome and could provide valuable feedback to the project stakeholders at INL.

The supplier performance and execution in the guard vessel fabrication met overall expectations. The project found that the supplier was proactive in identifying potential pitfalls and was responsive to project demands. Nevertheless, it is not uncommon for complex fabrications, such as the MARVEL guard vessel, to present unforeseen challenges. This narrative captures the key issues encountered, their impacts, and opportunities for improvement to enhance future projects.

Figure 2. Completed MARVEL guard vessel (picture taken 01/2025).

2.1. Code Compliance

The MARVEL vessels were designed and fabricated in accordance with the technical requirements of ASME/BPVC, Section III, Division 5. These requirements include component classification, design procedures developing stress and strain limits, material selection, and quality assurance activities.

However, since at the inception of the MARVEL program there were no N-certificate holders qualified to Division 5, most of the administrative requirements of the BPVC are satisfied in their intent through alternate methods, as described in the MARVEL Code of Record (COR-0011). Based on guidance provided in Title 10 of the Code of Federal Regulations Part 851, Appendix A, a national laboratory can be authorized to use an equivalent level of safety to accomplish its scientific mission.

INL subcontracted certain designer roles to a design agent while retaining the rest. The design agent performed the structural design with participation from INL, particularly in thermal, creep, and creep fatigue analyses. This agent prepared a design specification for owner review and acceptance. The INL contractor retains primary responsibility for surveillance and final acceptance of construction, with ongoing support from the design agent.

Vessel fabrication and construction was subcontracted to an experienced NQA-1 provider qualified under ASME/BPVC Section VIII. However, the constructor is unable to apply the N-stamp certification to the vessels due to a lack of necessary qualifications under Division 5. In lieu of an authorized inspector's oversight, INL quality engineers prepared and executed a detailed oversight plan (Clark, 2023) implementing all activities required of the authorized inspector. INL also performed those actions required of the designer and owner during construction. Materials were acquired through a qualified material organization, though with some deviation from the administrative process due to lack of intent to apply the N-stamp.

To establish equivalency, it is necessary to reconcile the actual methods used to ASME/BPVC requirements. This process will involve identifying applicable requirements, determining where alternate methods were used to meet requirements, and then showing how alternate methods meet the intent of ASME/BPVC requirements by providing an equivalent level of safety.

2.2. Preparation Challenges

Early in the fabrication, the INL team noticed that the supplier's manufacturing plans (travelers) lacked sufficient detail to trace the fit-up and welding of individual components, which was missed during the initial document review. Grouping all fit-up and welding activities under a single step made it challenging for project oversight to verify the traceability and welding of individual components. Thus, to verify fit-up and welding at the component level, the reviewer had to consult the supplier weld maps. This highlighted the need for original project specifications to **mandate that the supplier-manufactured travelers possess sufficient fidelity to track the fit-up and welding at the component level.**

MARVEL project quality oversight also discovered an occasion where the supplier's craft personnel proceeded with pneumatic leak testing without a pressure relief device (a mandated requirement in ASME/BPVC Section III, Div. 1, NB-7000). Furthermore, this test was performed in the absence of supplier oversight (another requirement per ASME/BPVC Section III, Div. 5, HBB-6112). **This highlights the need for strict adherence to ASME/BPVC code requirements. Ensuring that all work is conducted per documented instructions and procedures is vital for maintaining quality and safety standards.**

2.3. Welding Challenges

Through the initial fabrication phases, weld distortion was a recurring issue. Excessive distortion occurred on the longitudinal seam of the tapered vessel wall, the flanged sump into the conical bottom, and the conical transition to the vessel wall. A principle contributor to this distortion may have been the fabricator not employing traditional restraint techniques such as strongbacks (temporary stiffening attachments) or heat sinks as shown in Figure 3. It is appropriate to mention that the fabricators weld procedure for welding these seams was the gas tungsten arc welding process. On account of weld travel speed and weld filler deposition rates, this process typically introduces more heat than a semiautomatic process.

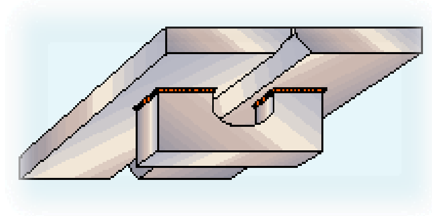

Figure 3. Diagram of a typical strongback configuration.

These particularities highlighted the need for specifications to include stringent requirements for weld distortion mitigation plans, encouraging suppliers to adopt proven fabrication techniques to control distortion. In defense of the fabricator, 316H-grade stainless steel has a propensity to distort more during welding—more than traditional 304/304L and 316/316L grades. The resulting distortions are shown in Figure 4.

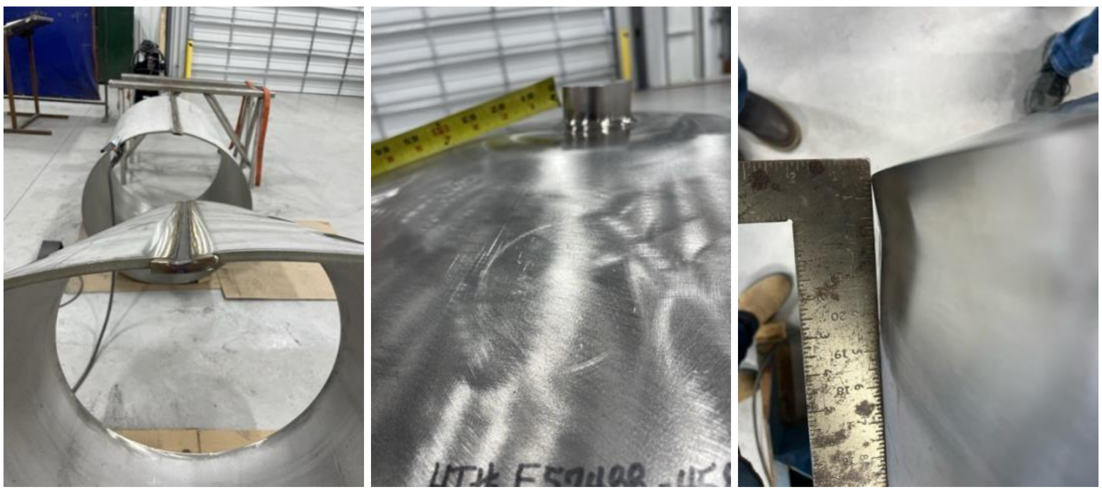

Figure 4. (Left) First occasion of weld distortion on the upper conical section of the guard vessel, where temporary attachments would have retained "roundness" and mitigated distortion (January 2024). (Center) Second occasion of weld distortion after welding the sump to the bottom cone, where the sump "sank" into the mating cone, which should have been restrained (April 2024). (Right) Third occasion of weld distortion following the welding of the lower transition ring on the bottom of the guard vessel (May 2024).

After three instances of excessive, and preventable weld distortion, the MARVEL project mandated that a weld distortion mitigation plan must be in effect for all future welding on the vessel. This plan required the use of strongbacks and chill blocks to dissipate heat from the weld seam. The fabricator was receptive to developing a weld plan, and subsequent welding was successful. A cohesive and a well developed weld plan proved crucial in constructing a design-compliant guard vessel and minimizing rework.

Figure 5. (Left) Strongbacks inside the guard vessel prior to welding the flanged couplings (April 2024). (Center) **A hydraulic jack used in concert with strongbacks to maintain pressure on the flanged couplings during weld out**, which prevented the “sinking” that had been evidenced on the sump plug to the lower cone weld (April 2024). (Right) Strongbacks and stiffeners prior to welding of the bottom cone of the guard vessel (August 2024).

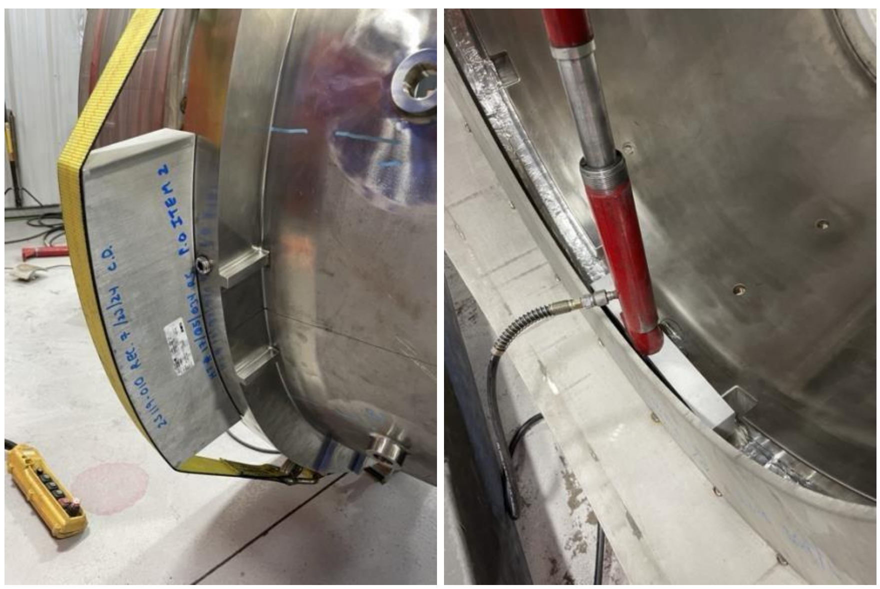

Figure 6. The top ring of the guard vessel necessitated finite tolerancing as this component served as the primary interface with the mating primary coolant system. Minimizing weld distortion in this zone was critical for functionality of the system. Note that the supplier used chill blocks on the inside (left image) and outside (right image) of the weld seam.

Figure 7. Fit-up of the internal shield plates to the vessel shell. Note that the supplier tack welded a temporary stiffener ring.

In addition to an INL request for the supplier to implement temporary fixturing and chill blocks, the fabricator was also proactive in suggesting additional solutions. The original drawings specified a single vee weld joint design for all weld seams on the guard vessel. A single-vee design provides a full penetration weld joint with all welding from one side; however, the ASME/BPVC Section III code also allows for a double-vee joint (i.e., welding from both sides). This approach equalizes the heat input to the joint, thus providing a more even distribution of heat. **To this end, the MARVEL engineering team reevaluated all remaining weld joints on the vessel and issued a drawing change specifying a double vee joint versus single-vee joint where appropriate.** This was a positive lesson learned, contributed to a compliant guard vessel, and further assisted in minimizing weld distortion.

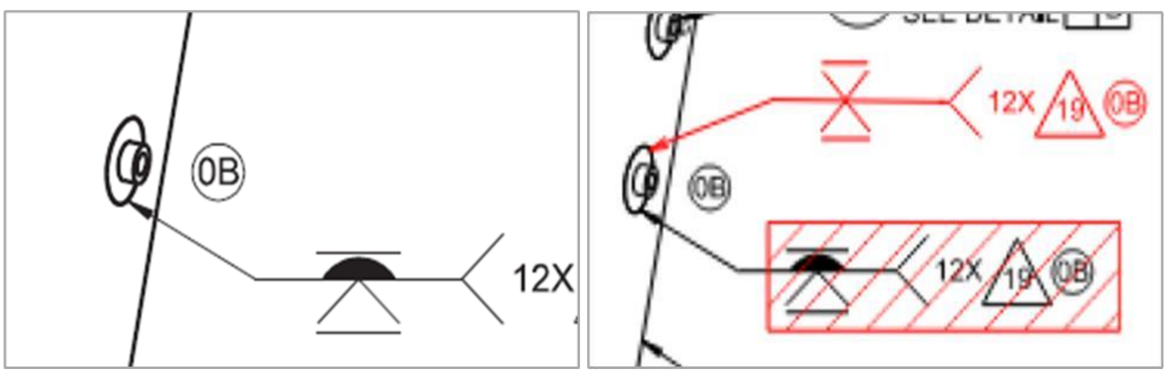

Figure 8. (Left) Weld symbol for a single-vee joint design and (right) redline weld symbol change to a double-vee joint design.

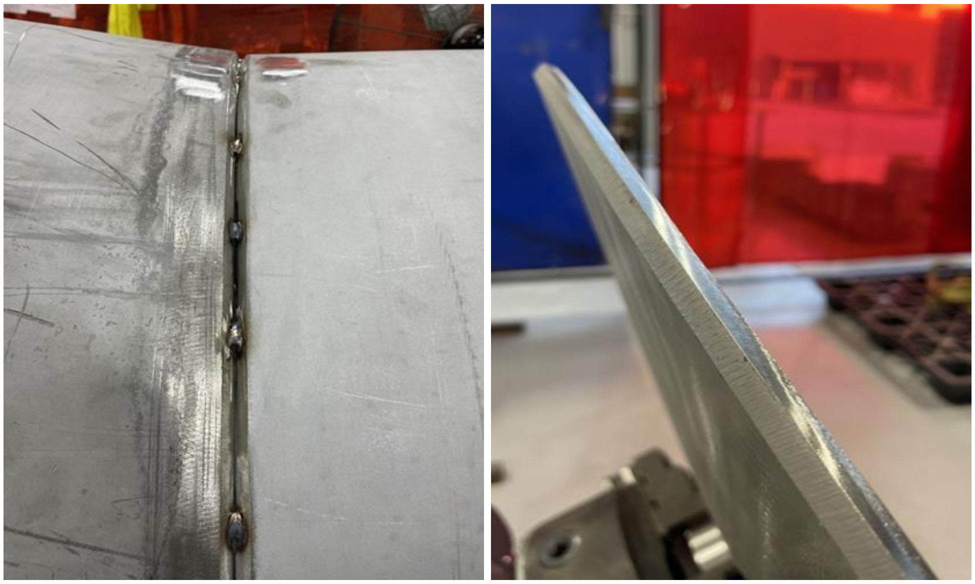

Figure 9. (Left) Image of a single-vee joint design and (right) image of a double-vee joint design.

As previously commented, the fabricator's primary method for welding the guard vessel utilized the manual gas tungsten arc welding (GTAW) process. Due to the high heat input of this process, weld distortion is more prevalent. Following a fit-up of the internal shield plates to the vessel wall, the project requested that the supplier utilize the GMAW (gas metal arc welding) process to make this fillet weld. The GMAW process has a high deposition rate with a faster travel speed, and therefore less heat input. This proved to be crucial in further minimizing weld shrinkage—especially as this portion of the vessel interfaces with the primary coolant system upon final assembly. However, the introduction of the GMAW process presented another layer of lessons learned.

The GMAW process uses four basic modes to deposit filler metal from the electrode to the weld joint: short circuit transfer, globular transfer, spray transfer, and pulse spray transfer. Each transfer mode depends on the welding process, welding power supply, and consumable, and each has its own distinct characteristics and applications. The transfer mode is an essential variable per Section IX of the ASME Weld Code. The weld procedure submitted by the supplier was limited to the short circuit transfer and was the only GMAW transfer mode available to the fabricator. This mode of transfer is ideally suited to thinner base metals (¼ inch or less) and not ideally suited to the 2-inch-thick internal shield plates. Although not ideal, the supplier's procedure did permit them to deposit fillet welds with no restriction on base metal thickness.

An advantage of the spray transfer mode is that it provides good fusion at the toes of the weld, whereas the short circuit mode deposits the filler metal at a colder setting. Thus, upon final inspection of the fillet welds, and although they met the required inspection criteria, it was evident that an alternative transfer mode (such as spray transfer or pulse spray transfer) would have yielded a fillet weld with less weld spatter and a faster deposition rate. To this end, the supplier was strongly encouraged to develop and qualify a procedure using these alternate transfer modes. Nonetheless (regardless of transfer mode), using the GMAW process did minimize heat shrinkage of the vessel wall.

Figure 10. Completed fillet welds on the internal shield plates.

Despite the aforementioned distortion issues, the welder successfully performed over 500 linear feet of welding without any indications of substandard weld quality. This achievement demonstrated the supplier's capability to adhere to stringent welding standards and deliver high-quality workmanship. It also reflects positively on the MARVEL and microreactor program's emphasis on maintaining superior fabrication standards.

Figure 11. MARVEL guard vessel prior to inspection.

A positive outcome from the fabrication is that the vendor gained valuable experience on how to mitigate weld distortion throughout the fabrication. This learning experience is a fundamental benefit that aligns with the goals of the MARVEL and microreactor programs, which aim to reinvigorate manufacturing practices. **The development and application of effective weld distortion mitigation strategies by the vendor represent a significant step forward in enhancing fabrication quality and reliability for future projects.**

2.4. Inspection Challenges

ASME/BPVC Section III, Division 5 was employed for the fabrication, inspection, and testing of the MARVEL guard vessel. This code implements some unique requirements compared to other pressure vessel codes. For example, ASME/BPVC Section III, Div. 1, Article NB-4121.3 states as a requirement that: "material for pressure retaining parts have been machined, the component is to be 100% examined using the magnetic particle or liquid penetrant method" (ASME/BPVC Section III). During the supplier's bid and proposal process, they did account for most machined components; however, there were a few they did not account for. Liquid penetrant examination is both laborious and time consuming; **thus, it is critical to the success of prospective reactor developers that they understand the code and capture this requirement.**

Figure 12. The plenum support ring was machined from billet 316H forging material (ASME SA182), requiring 100% liquid penetrant examination per Section III.

Another nuance in ASME Section III, was the requirement for liquid penetrant examination following the removal of temporary attachments. **While there are a few unique requirements that exist in ASME/BPVC Section VIII, Section III necessitates that liquid penetrant examination applies to the removal of *all* temporary attachments (reference ASME/BPVC Section III, Div. 1, Article NB4435). In addition, this requirement in Section III is more prescriptive than its Section VIII counterpart—where each location is required to be identified, marked, recorded and inspected.** Again, this should be a noteworthy consideration for other reactor developers.

Figure 13. Dye penetrant inspection following the removal of temporary attachments.

Another occurrence of oversight was noted when the fabricator's sub-tier supplier used the incorrect procedure for radiographic examination. Instead of following the approved film radiography procedure, the supplier used a computed radiography procedure. Although both methods are acceptable per ASME/BPVC Section III, the computed radiography technique had not been submitted for review or approval. **This occasion emphasized the importance of pre-job briefings, an understanding of the scope, and need for field quality engineers to verify procedure compliance before work starts.**

Weaknesses were noted during the initial set up of the guard vessel where the fabricator did not implement traditional leveling and layout techniques. Not employing essential fabrication methodology, such as establishing quadrant lines on the vessel and leveling the rolls, hindered the fabricator throughout fabrication. The absence of datum lines on the vessel compounded the challenges with fit-up of the internal shield plates. These components had to be oriented to a specific datum to accommodate the downcomer piping of the primary coolant system. Additionally, the fabricator did not utilize advanced measuring tools (such as a coordinate measuring machine [CMM] or romer arm) during in-process fabrication and fit-up activities. **Had the fabricator employed all the tools at their disposal and adopted traditional vessel layout techniques, the supplier would have reached conclusive dimensional acceptance results. The absence of these layout lines hindered the quality control dimensional inspector in achieving consistent measurements during the final dimensional inspection, thus the project experienced a delay in furnishing "as-built" dimensional inspection reports**.

Figure 14. Completed MARVEL guard vessel.

2.5. Nonconformance Challenges

During fabrication of the guard vessel, the supplier experienced three nonconforming conditions. The first was attributed to a tooling gouge during subcontract machining efforts (repaired in accordance with the Section III code), the second to the bevel on the ends of the internal shield plates (a rework disposition), and the third to some out-of-tolerance conditions on the final dimensional inspection report. Overall, these Nonconformance Reports (NCRs) were not out of the ordinary for a fabrication of this scope.

The resident quality engineer observed an opportunity for improvement in how the supplier managed these nonconforming conditions. **The ASME/BPVC Section III code applies the same rigor to NCR conditions as NQA-1 wherein items are to be identified and segregated prior to evaluation and**

disposition (re: NQA-1 Requirement 15). On the guard vessel fabrication, the supplier had to be prompted to segregate the material and apply the appropriate “red tag” identifying the component as nonconforming.

3. PRIMARY COOLANT APPARATUS TEST (PCAT)

The concept of a primary coolant test was proposed as an EDU to verify that the MARVEL primary coolant could transfer heat from MARVEL fuel through a heat extraction and power generation system utilizing natural convection. The original concept was developed using Stirling engines as a combined heat extraction and power conversion system. For a detailed presentation of the history of the PCAT design reference INL-RPT 24-78530 (Patterson, 2024). This document will focus on the lessons learned since the initial testing of PCAT and subsequent completion of validation testing. One of the lessons firmly demonstrated through the project life of PCAT is that the experience gained in **the design, fabrication, and operation of an EDU is an essential element to identify “unknown unknowns” and mitigate risk to the nuclear reactor**. In the case of the PCAT system, it may have been beneficial to conduct smaller separate effects tests, building up towards a fully integrated, at-scale system. This would have enabled the uncovering of unknowns earlier in the project and de-risking the scope sooner. Conducting earlier tests would have also allowed PCAT to maintain design synchronicity with MARVEL through a further stage of the design. Due to the limited funds and personnel availability these smaller scale tests were not pursued.

3.1. Description of PCAT Test Article

PCAT consists of a 10-inch-diameter primary vessel, with four flow loops (containing NaK primary coolant) arranged radially around the vessel. These loops were intended to be symmetrical to aid in modeling and validation. The vessel is approximately 10 feet tall, with a bolted flange closure. The loops are nominally 2 inches in diameter containing lead-bismuth eutectic (LBE) secondary coolant with a larger section at the top to house the intermediate heat exchangers (IHXs). The IHXs have a free surface design and seat the Stirling engines on a flexible seal. Principal materials of construction for the PCAT fluid systems are type 316L SS (as opposed to 316H SS in MARVEL). This limits PCAT to a maximum temperature of 538°C and operating temperature of less than 525°C. PCAT has an automated data acquisition system that provides automatic recording of all available electronic instrumentation outputs. Figure 15 shows an exterior and cutaway view of PCAT.

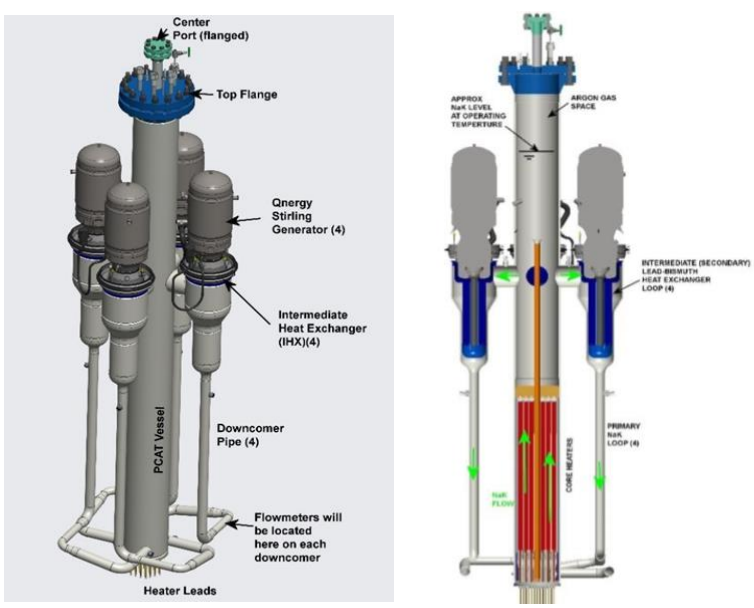

Figure 15. (Left) Exterior and (right) cutaway views of PCAT.

An array of 36 core heating elements is located in the lower portion of the vessel, simulating the general configuration of MARVEL's core. A central tube, occupying the same position as MARVEL's central insurance absorber provides access for instrumentation and eventual draining of primary coolant. The primary system contains NaK coolant, filling the system to a few inches above the upper loop connections at room temperature. This leaves adequate gas space to accommodate thermal expansion. Approximately 15 inches of gas space is present at operating temperature. Electrical power and instrument leads for the heater elements pass through the bottom head of the vessel. PCAT was heavily instrumented to provide ample data for temperature and mass flow for validation efforts.

3.2. Data Acquisition and System Control

The PCAT loops were initially designed for natural circulation, with no pumps or valves. The only significant controls initially developed for the PCAT loops are the core heaters, which respond to either a specified temperature and temperature ramp rate or total power as a target setpoint.

The Stirling engines initially used were controlled using the manufacturer's software. Future heat extraction loops had individual pumps and heat rejection units that were controllable through the LabView control software.

3.3. PCAT Deployment

Following the completion of PCAT fabrication at the Materials and Fuel Complex (MFC) Fabrication Shop, the test article was sent to a vendor for final installation, commissioning, and capability testing. Of particular note from the previous MARVEL lesson learned report were the challenges associated with installing the heater rods into the vessel. The fabrication sequence was to insert cartridge heaters inside the heater tubes and thread the heater wires through the bottom tube caps. Following heater fabrication, insulation damage was observed, as shown in Figure 16, which proved to be a modest technical issue but caused delays during the evaluation and development of corrective actions. **Limited insulation replacement and wire sleeving was required**, causing a few weeks of schedule delay, labor charges, and modest material costs.

Figure 16. (Left) PCAT heater tube and cartridge heater pigtail and (right) heater insulation damage due to end cap welding.

During final inspection, it was discovered that the heat generated from welding the end caps damaged the heater assemblies, which proved to be more significant than the insulation damage. This was more significant because later bowing and twisting during heat up of PCAT could lead to heater failure if the heaters made contact. Further, the uncertain dimensions of the coolant channels between the heaters could introduce unquantified errors into the RELAP5-3D (Reactor Excursion and Leak Analysis Program) model validation that is dependent on MARVEL data. Examples of bowing are shown for one heater in Figure 17.

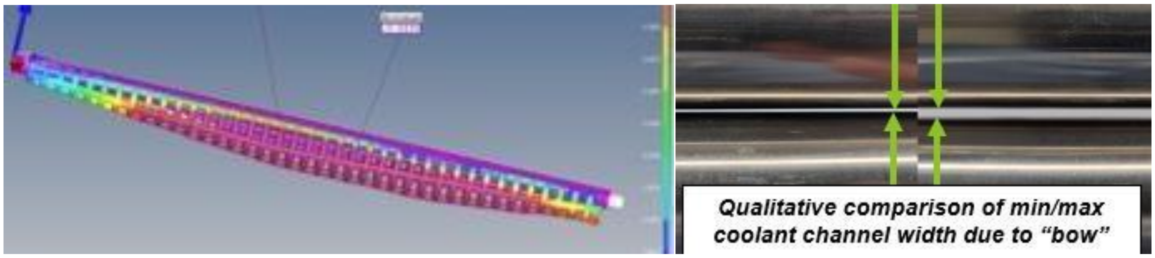

Figure 17. PCAT heater bowing due to end cap welding, including a (left) straightness measurement for PCAT Heater Tube #38, which failed due to heating from end cap welding, and (right) heater deformation changes in coolant channel width and modeling parameters.

To control the bowing, it was determined that three sets of spacers would be welded on each of the heaters to maintain heater and cooling channel spacing during operation. RELAP5-3D and Computational Fluid Dynamics (CFD) modeling was performed to validate the adequacy of the spacers in terms of coolant flow, pressure drop, and heat removal. As PCAT fabrication was completed, **the complexity of the welding and leak test contributed to additional delays in the PCAT weld inspection, which highlights the importance of avoiding overly conservative design requirements that end up challenging to meet in practice**. These requirements included fabrication and testing to nuclear quality standards

PCAT was shipped to the testing vendor in April of 2023 (see Figure 18). Upon arrival at the testing vendor, several challenges were encountered. The cables that were installed at INL to connect the heaters to the control cabinet were intentionally left long due to the unknown nature of the final installation.

Figure 18. PCAT loaded on transport truck.

This additional length caused an increased transmission of noise to the controllers. As a result, the wires were trimmed and re-terminated. Due to engineering requirements and the modification of INLprovided equipment, this was required to be performed by INL personnel specifically, as opposed to the designated testing contractor. These and other issues, such as **calibration questions (typical of a large experiment start-up), delayed completion of PCAT** setup until July 2023, at which time the setup and assembly were completed.

Key parts of the PCAT setup are shown in Figure 19. Thermocouple (TC) wires are shown routed to the intermediate heat exchanger, which would subsequently be filled with LBE. The entire assembled PCAT is shown, without insulation. Blowers on either side of the platform remove heat from the Stirling engines. In September 2023, the PCAT system and associated instrumentation were deemed ready for testing.

Figure 19. MARVEL assembly and setup at Creative Engineers Incorporated (CEI), including (top left) TC wires inside heat exchanger, (bottom left) Stirling engines installed, and (right) PCAT assembled and setup at CEI (without insulation).

3.4. PCAT Testing

3.4.1. Initial Testing

Initial testing of PCAT was performed on September 19, 2023. During this testing, natural circulation of the primary coolant was detected from heat-up. As the four Stirling engines were started sequentially, coolant flow increased in commensurate fashion. Power output was measurable from all four engines. Final assembly of PCAT and the mass flow rate for all four Stirling engines during initial testing is shown in Figure 20.

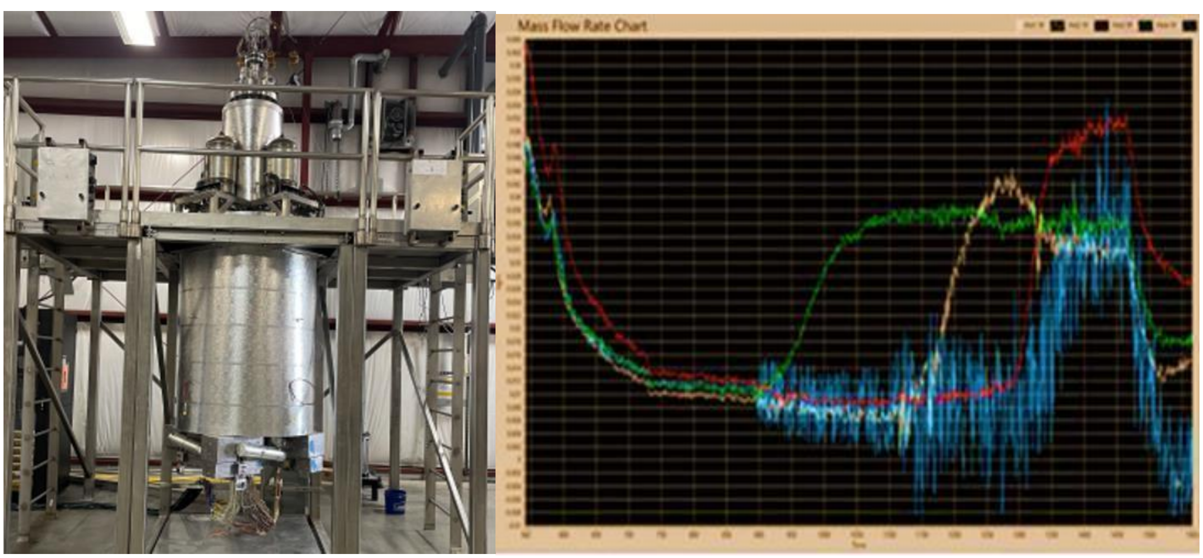

Figure 20. (Left) PCAT assembled and setup at CEI (with insulation), and (right) Stirling engine mass flow rate chart indicating natural circulation in each engine during initial start-up.

During this test, the team was unable to confirm that adequate cooling was being provided to the Stirling engines. While the Stirling engines responded as expected, indications of internal cooling (propylene glycol) flow to the engines were inconsistent. Due to lack of certainty that Stirling engine cooling was sufficient, the MARVEL project team in collaboration with CEI engineers decided to turn the heaters off and allow PCAT to cool. Later investigation of the cooling flow issues revealed that the cause of the inconsistencies was use of propylene glycol versus water (manufacturer's recommended coolant) for cooling. Propylene glycol, while much less reactive than water with NaK, is also higher viscosity which resulted in unexpected system behavior. The internal flowmeter with the Stirling engine package was unable to read the higher viscosity propylene glycol coolant that was used due to safety concerns in the facility. **A lesson learned is the uncertainty in individual components of commercial systems can lead to unexpected results in system-level testing and should be qualified ahead of time as appropriate**. In the case of the MARVEL project, several independent Stirling Engines tests were conducted but not in an environment that is entirely analogous to PCAT (until the actual tests).

Revisions to test plans and extra flow meters were implemented into PCAT to proceed with qualification testing. The new flow meters could work with any conductive liquid, including the glycol mix in the Stirling engine cooling loop, rather than just water. To allow power calculations, additional resistance temperature detectors and TCs were procured and installed within the Stirling engine coolant loops after completing fabrication of thermowells and cables. A programmatic decision to perform commercial grade dedication (CGD) on the PCAT was implemented to control the quality pedigree of the generated data. To maintain requirements implemented by the CGD, PCAT drawings were updated to reflect changes during assembly. To meet engineering requirements for calibration, pedigree calibration for the proprietary PCAT NaK flow meters was completed and witnessed by INL personnel in December 2023. Programming of the PCAT control systems continued during this calibration and into 2024. Due to an increase in the programming requirements, INL personnel traveled to CEI in January 2024 to aid in programming and wiring modifications. In early March 2024, physical changes, calibrations, and programming were complete and PCAT was ready to recommence operation. As part of the process for dedicating the PCAT data for safety calculations, an equipment qualification test (EQT) was developed and added to the requirements. This test was a thorough check of each instrument from the sensor through the writing of the data file.

3.4.1.1. Stirling Engine Failures During Qualification Testing (March 2024)

In preparation for qualification testing at full power, a series of low-power ramp tests were performed in March 2024. During these tests, two engines failed. Later, all of the engines were removed for inspection. There was substantial oxide build-up on the Stirling engine heat exchanger (HX) tubes and a common-mode of tube failure, as shown in Figure 21.

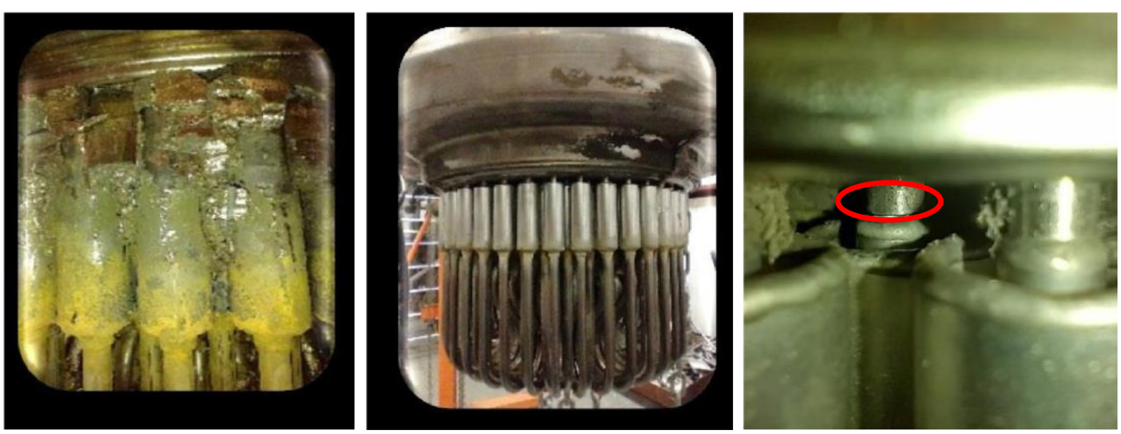

Figure 21. Images showing (left) oxide build-up on Stirling engine HX tubes, (center) Stirling engine HX tubes after cleaning, and (right) Stirling engine HX tube failure.

A multidiscipline team was formed to investigate the Stirling engine failures. All four engines were removed for inspection to facilitate the investigation. One of the bowls containing the Stirling engine was heated and emptied of LBE, after which the team initially identified several additional potential concerns:

- Excessive oxide formation in the LBE pool
- Corrosion of the IHX (NaK to LBE)
- Potential rubbing wear of the engine tubes on one engine.

During the design phase, the PCAT secondary coolant system was not designed with oxygen controls as it was intended to be a short-term test. This was a further indication that there was a poor definition of requirements and a realistic testing duration should have been further defined prior to initiation. Visual inspection of the tube closure welds did not reveal any potential corrosion issues. In addition, no apparent cause was identified for the potential wear.

Based on the investigation team's engineering judgement, the tube failure was caused by the freezing of the LBE. This freezing, and subsequent expansion, caused the support of the Stirling engine to transfer from the engine structure to the HX tubes and subsequently the tube welds. The commercially available Stirling engines procured for PCAT do not account for mechanical load on the tubes and are only tested for leak tightness not structural strength. **This is a result of using commercial items in conditions substantially different from their design conditions.**

Based on the identified primary issue, **the major corrective action was to maintain the LBE in a liquid state** (>123°C) while the Stirling engines were installed. This action was expected to eliminate the mechanical loading of the engine HX tubes. To address additional concerns identified during inspection:

- A light argon purge was placed on the molten LBE pool to reduce the oxygen around the pool and prevent oxide formation. This required the design of a standalone argon system and a modest equipment purchase.
- Prior to installation, the engines were visually inspected and photographed for existing wear. During installation and prior to operation, the inspection verified that the engines sat freely and that there was no initial system contact with the tubes.

3.4.1.2. Stirling Engine Failure (August 2024)

After incorporating the improvements identified following the engine failure in March 2024, PCAT was again slated for testing resumption. Prior to the commencement of testing the engineering team met at CEI to finish the EQT required to rededicate the system. During the final stages of EQT, new Stirling engines were installed into the system. These engines were inspected visually at INL and again at CEI prior to installation. In addition, helium pressure was verified to ensure no leaks were present in the tubes. To meet the requirements of commercial-grade dedication, INL personnel were again onsite at CEI to witness the first testing.

This round of testing also encountered Stirling engine failure. During the start-up of the first two engines, the team noted significant vibration while running the two engines. For reference, the other two engines were installed at this time but were not active. Shortly after the start of Engine #4, an error message was generated by the software system, an audible change in PCAT was observed, and liquid metal (later identified as LBE) began to pool on the floor under the system. The system was emergency stopped per procedure, and the engines were subsequently removed for investigation. When Engine #4 was removed for investigation, a leak described as "hissing" was noted. Upon investigation, it appears the molten LBE leak pathway was through the top of the IHX and was caused by a tube discharging pressure into the IHX pool. Engine 2 continued to operate until it was raised out of the molten LBE. Engines 1 and 3 were never operated.

3.4.1.2.1. Abandonment of Stirling Engines

After these engine failures, it was decided to prioritize completing qualification testing where possible while INL personnel were on location at CEI. In an attempt to proceed with testing, the team brainstormed potential solutions for alternative heat extraction to enable PCAT to complete its stated goal of verifying the thermal-hydraulic performance of the natural circulation loops. Over the next few days, the CEI team performed a thorough check of the instrumentation, identifying several TCs that were providing the wrong signal or no signal at all. These instrumentation faults were likely caused by the strong vibrations introduced by the Stirling engines. After inspecting PCAT and removing the spilled LBE, the team concluded that the facility was ready to perform several of the initial tests of the test plan that would not involve Stirling engines.

The project team decided to perform several unofficial tests at higher temperature and power. This included a test with asymmetric cooling by using a set of prefabricated fins and forced air circulation. This combination of fins and forced air circulation increased the total heat removal, causing an asymmetric cooldown of the primary system, and an increase of the mass flow in Loop #3 by ~20%. For reference, the total mass flow was about 0.15 kg/s. Further tests were performed by switching from temperature control to power control and brought PCAT heaters to ~15% of total power, then 10% of total power. When the mobile fan was turned off and the fins removed, the mass flow in Loop #3 equalized the mass flow of the other loops. The power was finally increased to 30% of total power and maximum heaters temperature to 410°C.

These tests showed satisfactory performance by the PCAT system, and that focus should be placed on an alternative means of heat extraction to perform the remaining tests for validation of the RELAP5-3D models. It should be noted that, due to funding constraints and a pivot on power generation, that no further investigations were conducted into the failure of the Stirling engines. The team nevertheless postulated that directly mounting the engines on a large structure resulted in vibrational challenges that may have led to certain failure modes.

3.4.1.3. Alternative Heat Extraction

Alternative heat extraction method were evaluated. The goal was to select the least obtrusive option to meet the goals of operating PCAT. Ultimately, the team tested a coiled heat extraction loop shown in Figure 22. The alternative heat extraction loop was designed to fit in the location of the former Stirling engines with minimal reconfiguration and utilized the same propylene glycol and water mix and heat offtake as the Stirling engines.

Figure 22. Alternative heat extraction for PCAT.

This initial prototype showed promising results and allowed the team to extract approximately 30 kW of heat from PCAT. With the concurrence of the MARVEL design authority and program sponsor, the team proceeded with the fabrication and installation of the remaining three cooling loops. This work was completed in January 2025. Following the installation of the test loops, portions of the EQT again needed to be repeated. In addition, several of the instruments needed dispositioned in terms of calibration. The team decided to proceed with recalibrating some of the instruments and issuing an NCR to evaluate these instruments for potential calibration after testing if needed.

3.4.1.4. March 2025 Testing

Following the fabrication and installation of the alternative heat extraction units, PCAT testing resumed in March 2025. During the course of testing, the system generally showed good responsiveness and control. The system was able to achieve full power and definitively demonstrated multiple natural circulation loops. Initial testing was completed, and analysis of the data will follow in the Summer of 2025.

During testing, the circulation loop associated with one of the previously failed Stirling engines was exhibiting unexpected behavior and was consequently removed from service by removing the secondary fluid from the corresponding IHX. The team attempted various troubleshooting steps to determine the cause of this behavior but was unable to reach a definitive conclusion. It was postulated that this irregularity was internal to the primary loop, which is not accessible to the team without major rework to PCAT. In the interest of producing data for analysis the team decided to move forward with only three loops. **This demonstrated the need to be agile when testing and improvise when tests are not performing exactly as expected**. The data also indicated a high degree of sensitivity of the steady-state natural circulation flow rates and temperatures, to the start-up and shutdown profiles of the heater rods. This will be further explored during the data analysis that follows testing. Despite these irregularities, an initial review of the data from the three functional loops indicates that the data are useable, with a minor loss of fidelity due to the utilization of only three of the four loops. This is true due to the passive nature of coolant flow in PCAT, and the fact that each loop is individually instrumented for flow rate and temperature. This may result in a need for additional testing to close identified data gaps in the validation cases necessary for confirming the thermal-hydraulic model.

3.5. PCAT Observations and Lessons Learned

Several general observations can be made regarding PCAT performance:

- **Project Initiation**: The entire project was initiated as quickly as possible, with optimistic assumptions for scope, schedule, and budget. This was largely driven by MARVEL's aggressive schedule. The lack of clear scope and subsequent requirements impacted the validity of the cost estimate prepared throughout the testing lifecycle. In addition, the lack of documentation regarding assumptions and the design basis led to misunderstanding of the PCAT design basis level of maturity. The included scope was underestimated. In an attempt to shorten the schedule, procurement were started without a mature design basis. At the time of project initiation, these risks were deemed acceptable by the program.
- **In general, the use of commercially available technology is a viable path to minimize risk. However, it is important to recognize that adapting that technology to a new use creates additional, sometimes unforeseen risks**. Commercial technology should not be considered technically mature if it will be used in a new application. Stirling engines are used commercially, but not with liquid metal coolants, and are constrained to a rigid structure. NASA performs considerable work with Stirling engines in liquid metal systems, but those systems are considerably smaller and are installed directly in a NaK loop without an IHX. NASA's Stirling engines are rigidly mounted and used in an opposed configuration or with electrically controlled mass balancers to control the vibration input into the loop. As a result, considerable repair and rework was required to finish testing with PCAT, with attendant cost increase and schedule delays.
- **Concurrent design (PCAT and MARVEL) and fabrication resulted in short bursts of activity followed by periods of waiting for the next set of design analysis to inform directions for**

fabricators. This was inefficient and contributed to excessive cost for the fabrication and design of PCAT. The lack of reserves to account for unexpected unknowns resulted in slowdown or stoppage of work. Two strategies, roughly defined, for conducting an experiment are:

- Fabricate, assemble, fit, and test—then revise and iterate, building know-how towards a final, rigorously defined test.
- Extensive early planning with rigorous design and control throughout, potentially avoiding mistakes and rework.

On some parts of the execution, the project imposed very strict quality control requirements, while on others, adopted a more agile build-test-repeat model. This inconsistency led to unplanned expensive rework late in the PCAT execution process – which were slow and challenging to implement due to high-level of rigor applied. The nuclear industry's predisposition for conservatism reinforces this tendency. It is important to emphasize that on some areas, the project would have benefited from additional planning ahead of time, while in others, imposing too many inflexible requirements led to execution challenges. **Examples include weld inspections above code requirements, leak test specifications more stringent than achievable with available equipment and performing wiring checks by observation of indications rather than physical double verification of physical conditions**.

Additionally, proceeding with the MARVEL design in parallel to PCAT limits the ability to allow for lessons learned from testing to feed into the reactor design. Notably, while the project decided to move away from integrated Stirling engines following PCAT tests, the MARVEL design itself still contained features that were remnants of an integrated design. **In an ideal scenario, final design for the reactor would have waited until PCAT testing was fully completed.** However, it is important to note that this would have caused substantial delays to execute the full scope.

- **Project Requirements: Unclear engineering and quality requirements led to confusion and rework**. A clear definition of the requirements could have reduced costs and schedule impacts. The commissioning and testing of PCAT was contracted as a research test scope with a focus on the completion as the deliverable. During the project, additional requirements were implemented through the incorporation of specifications and commercial-grade dedication requirements. These quality requirements were not clearly communicated via the change process and resulted in redundancies between INL and the testing contractor personnel providing inspections and qualifications. A requirement that INL personnel need to be physically present at the site to perform equipment qualification and witness initial testing led to increases in cost and schedule relative to the baseline. This was not only a miscommunication between INL and its subcontractor, but between different teams at INL.
- **A calibration plan prioritizing high-impact instruments and a comprehensive methodology for performing in situ calibrations would have reduced rework.** The various challenges faced by PCAT led to large delays in testing execution. This ultimately resulted in the expiry of sensor calibration dates. As a result, multiple re-calibrations needed to be performed on several occasions. Ultimately, a proactive approach was taken where the team would rely on data analysis to validate calibration status and instrument functionality.
- **Integral and Separate Effects Testing**.
  - **Hardware testing is invaluable when qualifying systems for novel use**: The Stirling engines were chosen due their commercial readiness. By changing the specific application (use with molten metal and glycol cooling), many of these benefits were lost and the system performance suffered. While some component testing was performed, a more thorough separate effect test of the Stirling engines may have avoided a significant amount of rework and schedule delay.
  - **Non-nuclear and scaled prototyping can inform the final design**: While developing the alternative heat extraction method, a single loop prototype was developed and tested. This

allowed early proof of concept with minimal cost. The alternative heat extraction methodology employed will help inform the MARVEL reactor heat extraction system. This includes demonstrating that the controllability of coupled natural circulation loops is very challenging and controlled heat extraction will be important to the overall controllability of the MARVEL reactor.

- **Integral effect testing**: The use of PCAT enabled the earlier discovery of failure modes of the Stirling engines than would have been possible on the reactor installation. The overarching purpose of a non-nuclear demonstration is to identify and correct design and performance issues prior to nuclear operations so that corrections can be made in a non-nuclear environment. There were multiple unanticipated hurdles in producing power with Stirling engines and liquid metal coolant, and PCAT has identified many of those. Without PCAT, the MARVEL project would be addressing performance issues in a radiological environment. Because PCAT was operated early, in a very similar configuration to MARVEL's core and primary coolant system, there is time to correct those issues prior to MARVEL construction and start-up.

- **Stakeholder Management**: The initial formulation of the PCAT design and testing plan gave the impression that this was a mature system that would encounter limited challenges. This drastically complicated execution because research testing is inherently immature. Failures and problems are the rule rather than the exception. They need to be solved as part of the research process. Management and schedule reserves were strained due to various limitations or other competing programmatic needs. This made it challenging for the PCAT scope to accommodate off-normal results, which are not uncommon as part of a research test program.

All of the observations above—general and specific—could have potentially **benefited from additional planning**. Ultimately however, no amount of planning can completely eliminate risks from unexpected challenges, but earlier understanding of the requirements and complexity could have better prepared all parties. It is likely that cost and schedule may still have exceeded the original estimates, but additional planning would have produced more reliable cost and schedule estimates and allowed for the development of more effective risk mitigations.

4. CONCLUSIONS

The purpose of a lessons learned report is to document the successes and failure of reestablishing a U.S.-based experience in advanced reactor deployment. A key benefit of pursuing the MARVEL project is the development of a key knowledgebase of engineering and execution professionals. These professionals and DOE's unique facilities and capabilities can be called upon again to support different phases of the MARVEL demonstration and to deploy other designs and concepts. Many of the hardlearned lessons will likely prove invaluable in enabling a more efficient deployment within follow-on projects.

Common to the various challenges encountered is insufficient planning. More extensive planning requires time and funding. In MARVEL's case, a tradeoff between expedience and over-analysis was found to be challenging to meet. In hindsight, the project may have benefited from additional time spent earlier on refining the scope and having more conservative schedules. Tools to guide essential design decisions, such as systems engineering expertise, could have been more effectively employed to inform the project. This is not to imply that excessive or prescriptive documentation or unnecessary requirements would improve project performance. **Most of the project successes come from the innovative use of processes or common-sense tailoring of requirements**. A reasonable balance is needed that can come from a review of these lessons learned. With better planning, there may have still been several surprises, but the team may have been better prepared to recover quickly.

Ultimately, it is important to highlight that overcoming testing roadblocks are successes. Testing is integral to learning and needs to be conducted more often. It is also critical to recognize that planning for first of a kind development is often imperfect. This is particularly the case with the nuclear industry which has very specific requirements and limited experience with construction of new (especially advanced reactors). As a result, execution seldom follows the exact prescribed steps in a plan. It is important for teams to be agile and flexible when iterating between tests. Implementation will likely be imperfect, and it is important for projects to recognize this limitation from the start.

More specifically, the MARVEL guard vessel fabrication has highlighted some valuable lessons learned for both the supplier and INL. First and foremost, the susceptibility for 316H stainless steel material to move during welding emphasized the need for weld joints to be restrained using temporary attachments and implementation of measures to mitigate heat input. The fabrication also underscored the critical need for detailed work instructions, detailed quality assurance oversight plan, and strict adherence to procedures. By implementing the lessons learned and recommended improvements, future projects can achieve higher quality and reliability, ensuring successful outcomes and enhanced safety. To this end, the project is now able to progress to the next key fabrication step: the MARVEL primary coolant system.

On the testing side, despite delays and setbacks, PCAT was instrumental in enabling a viable path forward for the MARVEL reactor. As an EDU, it enabled de-risking of reactor operations by answering fundamental questions regarding integrated Stirling engines. Additionally, it performed important thermal-hydraulic tests of natural circulation phenomena needed for validation of RELAP5-3D models. A better understanding, and communication of, the research nature of thermal-hydraulic testing may have facilitated interactions among stakeholders. For research and development of this nature, large amounts of change, challenges, failures, and learning opportunities should be expected.

5. REFERENCES

Abou-Jaoude, A. and M. Patterson. 2024. “MARVEL Utilization Plan.” INL/RPT-24-78261, Idaho National Laboratory. https://doi.org/10.2172/2371820.

Gerstner, D. and Y. Arafat. 2023. “MARVEL 90% Final Design Report,” INL/RPT-23-74280, Idaho National Laboratory. https://doi.org/10.2172/2208844.

Grecheck, E. S., M. Arenaz, M. Pérès, S. Pierpoint, and S. Raisch. 2024. “MARVEL Independent Assessment Team Report.” Washington DC: Department of Energy.

Clark, R. 2023. “Quality Assurance Surveillance Plan for the Fabrication of the Microreactor

Applications Research Validation and Evaluation (MARVEL) Project”. Idaho National Laboratory, PLN-6907,

Paterson, MW. 2024. “Breakdown of Cost and Scope Growth Through 90% Final Design,” INL/RPT-2478530, Idaho National Laboratory. https://doi.org/10.2172/2406267.

Patterson, MW. 2023, "MARVEL Project Code of Record, COR-0011." Idaho National Laboratory, INL/MIS-23-75410, https://www.osti.gov/biblio/2205228.

U.S. Department of Energy, Idaho Operations Office. 2021. Final Environmental Assessment for the Microreactor Applications Research, Validation, and Evaluation (MARVEL) Project at Idaho National Laboratory. Idaho Falls, Idaho, USA: U.S. Department of Energy.