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EXPERIMENTAL CAPABILITIES TO SUPPORT DESIGN, DEVELOPMENT AND DEMONSTRATION OF MICROREACTORS

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Changing the World's Energy Future

Piyush Sabharwall, Jeremy Lee Hartvigsen, Terry James Morton, Donna Post Guillen, Troy Unruh

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Sabharwall P.*, Hartvigsen J.L., Morton T., Guillen D.P., Unruh T., Jackson J., and Gehin J.
*Author for correspondence
Nuclear Systems Design and Analysis Division,
Idaho National Laboratory,
1955 N. Fremont Avenue, Idaho Falls, Idaho 83415,
United States of America,
E-mail: piyush.sabharwall@inl.gov, Jeremy.hartvigsen@inl.gov, Terry.Morton@inl.gov, Donna.Guillen@inl.gov, Troy.Unruh@inl.gov, John.Jackson@inl.gov, Jess.Gehin@inl.gov

Trellue H., Mascarenas D., and Reid R.S.
Los Alamos National Laboratory,
Los Alamos, New Mexico 87545,
United States of America,
E-mail: trellue@lanl.gov, dmascarenas@lanl.gov, rsr@lanl.gov

Petrie C.M.
Oak Ridge National Laboratory,
Post Office Box 2008, Oak Ridge, Tennessee 37831,
United States of America
petriecm@ornl.gov

ABSTRACT

This work provides a summary of selected experimental capabilities being developed to support non-nuclear demonstration of microreactors under the U.S. Department of Energy's (DOE's) Microreactor Program. Major capabilities include the single primary heat extraction and removal emulator (SPHERE) and the microreactor agile non-nuclear experimental test bed (MAGNET). The SPHERE facility allows for controlled testing of the steady-state and transient heat rejection capabilities of a single heat pipe using electrical heaters that simulate nuclear heating. The facility is capable of monitoring axial temperature profiles along the heat pipe and surrounding test articles during startup, steady-state operation, and transients. Instrumentation includes non-contact infrared thermal imaging, surface thermocouples, spatially distributed fiber-optic temperature and strain sensors, electrical power meters, and a water-cooled, gas gap calorimeter for quantifying heat rejection from the heat pipe. The facility can be operated under both vacuum and inert-gas conditions. The MAGNET facility is a large scale 250 kW electrically heated microreactor test bed to enable experimental evaluation of a variety of microreactor concepts, that can be supplied to electrically heat a scaled section of a microreactor and further test the capabilities of heat rejection systems. The initial MAGNET experiments will support technology maturation, reduce uncertainty and risk associated with the design, operation, and deployment of monolithic heat pipe-based reactors being constructed. This will assist in the development, demonstration, and validation of microreactor components and systems. Within MAGNET, systems and components can be safely tested, providing valuable information on failure modes, operating regimes, and thresholds. This test bed can broadly be applied to multiple microreactor concepts. MAGNET provides a test platform to perform such testing along with furthering the understanding of interface-coupling challenges with power-conversion units and other collocated systems. MAGNET can evaluate an array of heat pipes in a larger test article to evaluate integral effects. Examples of initial testing will include thermal stresses in the monolith and the impact of debonding of a heat pipe from the core block and how that failure could impact surrounding heat pipes (i.e., understanding the potential for cascading failure).

The experimental data generated in these facilities will be utilized for verification and validation (V&V) in direct support of microreactors and other DOE programs. Further key attributes of the design and experimental plan will be further discussed.

1 INTRODUCTION

There is an increasing need for more reliable and readily available energy in special purpose applications. A microreactor, is designed for use in unique applications where energy generation on the order of megawatts is needed but otherwise unavailable or prohibitively expensive (Kennedy et al 2018). Possible applications include, but are not necessarily limited to, military installations, remote communities, industrial processes and possible integration with hybrid energy systems and microgrids, while providing potential load following capabilities. Typical power needs in these use cases range from 1 to 10 megawatt electric (MWe). In many current applications, power generation at this scale is achieved through the use of diesel generators. However, increasing costs, clean energy goals and supply chain constraints have prompted a desire to examine other options to ensure energy availability and reliability. Microreactors generally produce less than 20 megawatt thermal (MWth), are factory manufacturable, easily transportable and due to neutronic simplicity allows for semi- or fully-autonomous operation (refer MRP website). The use cases for the generated energy may call for electricity production, direct use of process heat, or both. There are many types of microreactors being considered in US but mainly gas cooled reactors, molten salt cooled and heat pipe cooled reactors. These reactors operate in different thermal regimes, and therefore allow for flexibility when selecting a reactor for a specific use case. Ongoing efforts to ensure accelerated deployment the US DOE microrector program is working closely with vendors, Nuclear Regulatory Commission and other US DOE programs to develop capability to demonstrate the concept feasibility through non-nuclear testing and once proven can assist with nuclear testing using nuclear test bed (MARVEL). Performing such testing will evaluate technical readiness levels and system readiness levels for specific reactor concepts. Those readiness level evaluations can then further be used in conjunction with an expanded decision framework to define a path toward first of a kind deployment.

To support the development of microreactor technology, Idaho National Laboratory (INL) is in the process of establishing a 250 kW electrically heated microreactor test bed to enable experimental evaluation of a variety of microreactor concepts. The Microreactor AGile Nonnuclear Experiment Testbed (MAGNET) facility is being constructed at INL to assist with the development, demonstration, and validation of microreactor components and systems. The purpose of the test bed is to support technology maturation that will reduce uncertainty and risk relative to the operation and deployment of this unique class of systems. The stakeholders for this test bed include microreactor developers, energy users and regulators. Regulators can be engaged early in the design and testing to expedite regulatory approval and licensing.

Within MAGNET, systems and components can be safely tested, providing valuable information on failure modes, operating regimes and thresholds. The goal is to provide a test bed that is broadly applicable to multiple microreactor concepts. There are various types of microreactors being proposed, which can be classified according to their core cooling method, heat-pipe, gas-cooled (pebble bed or prismatic), molten salt, or light water. Each reactor type poses a different set of design and operational challenges and performance claims stated by commercial vendors have not been independently verified through rigorous testing. The initial set of tests to be performed in MAGNET are targeted towards demonstrating the feasibility and performance of heat-pipe cooled reactors, since this concept is unique to very small nuclear reactors. However, the testbed will be constructed to accommodate other designs in addition to heat-pipe cooled reactors. INL is partnering with Los Alamos National Laboratory (LANL) and Oakridge National Laboratory to meet the required development of testing and instrumentation needs.

2 NON-NUCLEAR TEST FACILITIES SUPPORTING VERIFICATION AND VALIDATION EFFORTS

The primary experimental hardware capabilities currently under development are focused on non-nuclear thermal and integrated systems testing, advanced moderator development, and the development of test articles to perform experiments. Specifically, this includes the single primary heat extraction and removal emulator (SPHERE), microreactor agile non-nuclear experimental test bed (MAGNET). The capabilities described in this section will generate data, which will further support other US DOE programs and industrial needs. This data will be made available to researchers and developers for a range of testing purposes, to support model development and verification and validation efforts.

2.1 Single Primary Heat Exraction and Removal Emulator (SPHEre)

A process-flow diagram for the SPHERE facility is shown in Fig. 1. Cooling water is recirculated using a 2.5 kW circulating chiller unit. The water flow loop includes a precision turbine flow meter and a delta-T meter that will allow for accurate determination of the heat removal rate from the heat pipe to the cooling water. Prior to testing, the quartz tube is evacuated using a vacuum pump and then backfilled with inert gas (He or Ar). This process is repeated several times (successive dilution) at the beginning of each test to ensure that all of the air has been removed. An oxygen sensor provides a second validation of total removal of air from the system.

The objectives of the single heat pipe testing include:

- Documentation of heat pipe thermal performance under a wide range of heating values and operating temperatures
- Observation of heat pipe startup and transient operation
- Development of effective thermal coupling methods between the heat pipe outer surface and the core block and between the cartridge heaters and the core block

Measurement of heat pipe axial temperature profiles during startup, steady-state, and transient operation using thermal imaging and surface temperature measurement, performing calorimetric measurements with water-cooled gas gap calorimeter; determining heat pipe operational limits, and testing under both vacuum and inert gas conditions (Sabharwall et. al 2020).

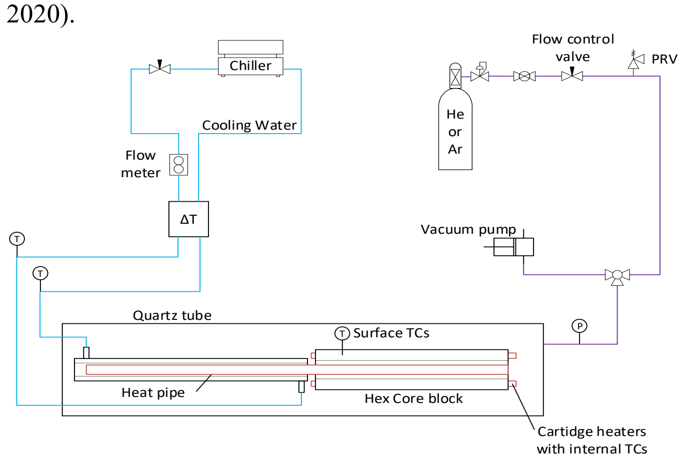
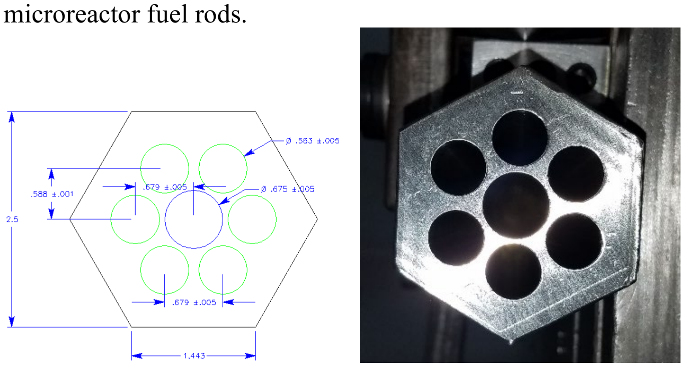


Figure 1 Process-flow diagram for the single heat pipe experiment.

Thermal performance of the operating heat pipes will be determined by measurement of heat pipe heat removal capacity as a function of operating temperature. The heat removal rate is equal to the total heater power input, measured by power meters, minus any heat losses as determined by a combination of measurements and analysis. The body of these heat pipes is stainless steel. The working fluid is sodium and the wick structure is specific to the supplier. The total quantity of sodium in each heat pipe is small, ~60 - 80 gm. After charging, the heat pipes are welded shut. From the standpoint of our operations, the heat pipes are fully closed/fully sealed test articles. As noted previously, the vapor pressure inside the heat pipes will be sub-atmospheric even at their highest operating temperature, so any failure of the heat pipe would not involve a pressurized release of material. The design basis surface heat flux value for the cartridge heaters is 3.8 W/cm2, based on expected microreactor core power densities. For the 6-inch block, this power density yields 317 W per heater and a total power of 1891 W. For the ½ m block, with the same power densities, each heater would operate at 1 kW for a total power of 6 kW. For the 1 m block, each heater would operate at 2 kW for a total power of 12 kW. However, since there is only one heat pipe, with a total heat removal rating of 2 kW (for the LANL heat pipe; 1 kW for the ACT heat pipes), the heat fluxes that will be applied during testing will be limited by the heat transfer rating of the heat pipes. This limitation will result in the use of significantly lower heat fluxes than the full prototypical core design values, especially for the longer core blocks. Heater operating temperatures will be limited to 750°C. Note that the vapor pressure of sodium is still well below 1 atm at this temperature. Therefore, over-pressurization failure of the heat pipe is not a concern. The single heat pipe experiments will be performed using a 7-hole hexagonal core block with the cross-sectional geometry shown in Fig. 2 (a). The core block material is stainless steel 316L. Three different core block lengths have been fabricated: 6-inch, ½ m, and 1 m. A photograph of one of the hex blocks is presented in Fig. 2 (b). The outer ring of 6 holes in the core block will be fitted with cartridge heaters designed to represent heating from microreactor fuel rods.



(a) (b)

Figure 2 (a) Cross section geometry of core block for single heat pipe experiments; (b) photograph of 7-hole hex block end face in fabrication.

Actual heat pipe testing is performed in an inert gas environment consisting of either helium or a helium-argon mixture using a test fixture similar to the one shown in Fig. 3. The heat pipe assembly is housed in a cylindrical inert-gas environment formed by a quartz tube with flanges on either end that include fittings for inlet and outlet gas flows as well as feedthroughs for instrumentation and power. The quartz tube allows for visual observation of heat pipe operation and quantitative thermal imaging. It also provides containment in the unlikely event of a leak of sodium from the heat pipe. A photograph of the quartz tube showing one of the end flanges and several internal MACOR supports is presented in Fig. 4. The MACOR supports are designed to hold the hexagonal core block and the heat pipe centered in the quartz tube. MACOR was selected based on its low thermal conductivity and high allowable operating temperature, plus the fact that it is machinable.

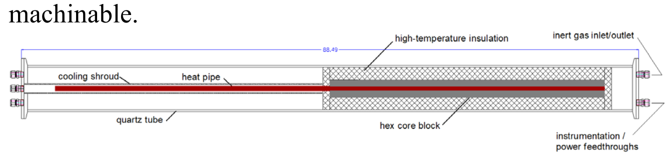


Figure 3 Single heat pipe test fixture.

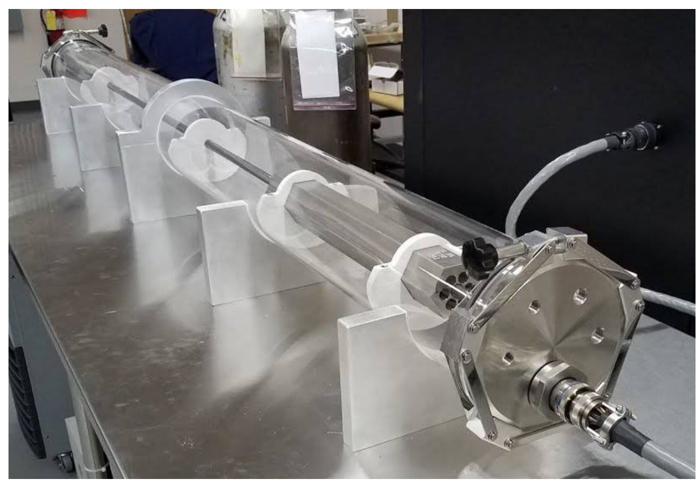


Figure 4 Single heat pipe experiment quartz tube with core block, end flange, and Macor supports.

The SPHERE test bed is currently in final assembly at Idaho National Laboratory (INL) (Fig. 4). The characteristics of the test bed are as follows (Sabharwall et. al 2020).

Test chamber characteristics include:

- Vacuum (10-4 torr) or inert gas
- 8 ft long × 6 in. diameter quartz tube
- Flanges for gas flow connections and instrumentation feedthrough ports

Electrical heating capability requires:

- A test bed designed for up to 20 kW electrical power to heaters
- Maximum test article temperature of 750°C

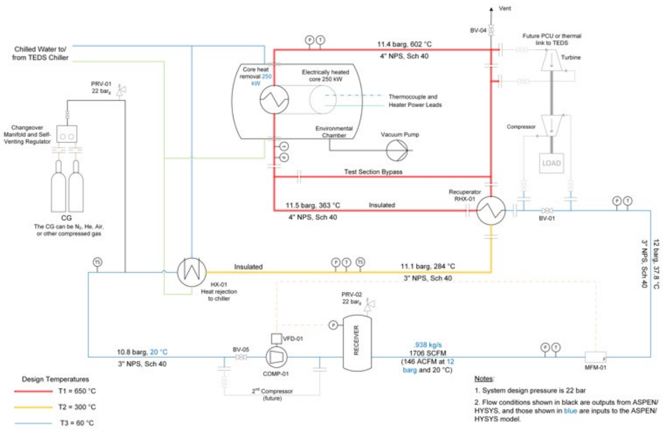
- Heat rejection through passive radiation or coupled with a water-cooled gas gap calorimeter.

2.2 MICROREACTOR AGILE NON-NUCLEAR EXPERIMENTAL TEST BED (MAGNET)

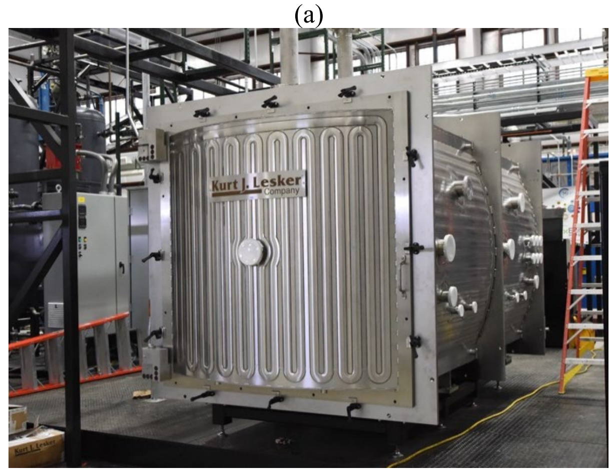
To support the development of microreactor technology, INL has established a 250 kW electrically heated, microreactor test bed to enable experimental evaluation of a variety of microreactor concepts. MAGNET was constructed at INL to assist with the development, demonstration, and validation of microreactor components and systems. The purpose of this test bed is to support technology maturation that will reduce uncertainty and risk relative to the operation and deployment of this unique class of systems. The stakeholders for this test bed include microreactor developers, energy users, and regulators. Regulators can be engaged early in the design and testing to expedite regulatory approval and licensing. The initial set of tests to be performed in MAGNET are targeted towards demonstrating the feasibility and performance of heat-pipe cooled reactors. However, the testbed will be constructed to accommodate other designs in addition to heat-pipe cooled reactors.

MAGNET was constructed at INL with the following objectives and technical goals[1]:

- Provide displacement and temperature data that could be used for verifying potential design performance and to validate accompanying analytical models.
- Show structural integrity of core structures: thermal stress, strain, aging/fatigue, creep, deformation.
- Evaluate interface between heat pipes and heat exchanger for both geometric compatibility, heat pipe functionality, and heat transfer capabilities.
- Develop potential high-performance, integral heat exchangers based on advanced manufacturing techniques, incorporating high-efficiency heat transfer from the heat pipes to the power cycle working fluid.
- Test the interface between the heat exchanger and integrated systems for power generation or process-heat applications.
- Demonstrate the applicability of advanced fabrication techniques, such as additive manufacturing or diffusion bonding, to nuclear reactor applications.
- Identify and develop advanced sensors and power-conversion equipment, including instrumentation for autonomous operation.
- Study cyclic loading and simulated reactivity feedback.
- Enhance readiness of the public stakeholders—particularly DOE laboratories and the United States Nuclear Regulatory Commission—to design, operate, and test new types of high-temperature reactor components.
- Capture data relevant to the development of autonomous microreactor structural integrity monitoring systems (e.g., digital image correlation (DIC)). Use the data to develop and verify models/systems for system integrity monitoring.



(a)



(b)

Figure 5 (a) MAGNET Process Flow Diagram and (b) Environmental Enclosure.

A process flow diagram of MAGNET and a graphic of the MAGNET environmental chamber are shown in 5. Design specifications for MAGNET are shown in Table 1:

Table 1. MAGNET design specifications.

Parameter	Value
Chamber Size	5 ft x 5 ft x 10 ft
Heat Removal	Liquid-cooled chamber walls, gas flow
Coolants	Air, inert gas (He, N2)
Gas flow rates	Up to 43.7 ACFM at 290 psig
Design pressure	22 barg
Maximum power	250 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter

In order to provide capabilities for integrated power conversion testing, a modified, commercially available, Capstone C30 microturbine unit (Capstone 2020) has been acquired (Fig. 6) and will be integrated with MAGNET. Fig. 6 shows the key components of the PCU, including the compressor, turbine, alternator, internal recuperator, gas cooler and power management and distribution (PMAD) subsystem.

Power generated can be fed to the electrical heaters in MAGNET to supplement externally supplied electricity or to a load bank as part of the collocated Microgrid Research Laboratory. The cycle is completely closed, and gas flows through the compressor and recuperator into the heat source heat exchanger, into the turbine, back into the recuperator, and finally into the gas cooler for the rejection of waste heat.

The C30 recuperator is an annular gas-gas heat exchanger that is physically integrated within the PCU housing, whereas the heat source heat exchanger can be a gas-gas or liquid-gas heat exchanger depending upon the reactor design. This power conversion unit (PCU) has been modified to use electrical heating (Wright 2006), rather than fossil fuel combustion, to provide a maximum power output of ~30 kWe in a closed Brayton cycle (CBC) loop with nitrogen as the working fluid. A detailed description of the PCU and the integration into MAGNET is given in (Guillen 2020).

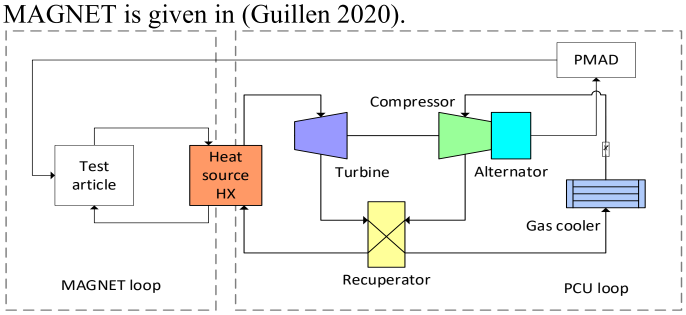


Figure 6 Layout of PCU loop connected to MAGNET loop by the heat source heat exchanger.

3 INSTRUMENTATION AND SENSORS

Some information such as the permanent mechanical deformations caused by plastic strain and/or thermal creep can be gleaned from post-test examination of microreactor components subjected to electrical heating and temperature gradients that are representative of expected conditions during nuclear operation. However, the major benefits to performing electrically heated experiments—besides not having to work with nuclear fuel, reactor constraints, and activated materials—are the ability to incorporate more detailed instrumentation during the tests and better control the environmental conditions. Non-nuclear experiments will provide detailed distributions of environmental parameters such as temperature and strain and quantify fundamental limitations of microreactor components and systems, such as heat rejection capabilities of heat pipes and advanced heat exchangers.

SPHERE is designed to test the heat rejection capabilities of small monolithic stainless steel test articles that include a single heat pipe surrounded by six electrically-heated cartridge heaters. A gas gap calorimeter surrounds the cooled end of the heat pipe. This calorimeter includes flowing water and is instrumented with a flow meter and inlet and outlet temperature sensors to quantify the heat rejected to the coolant. Combining the measured heat rejection and input electrical power will enable measurements of the power that is dissipated through the heat pipe as a function of operating temperature. The test articles are contained inside a quartz tube, which allows control of the internal atmosphere and visualization of the internal components. In addition, feedthroughs at the top of the tube allow for passing instrumentation and electrical power leads in and out of the facility. All SPHERE tests will include electrical power leads for energizing the cartridge heaters and thermocouples for monitoring temperature throughout the facility. Thermocouples are also being embedded directly within the test articles and inside heat pipes to provide a more detailed mapping of temperatures. To provide an even higher degree of spatial resolution, spatially distributed fiber optic temperature sensors based on optical frequency domain reflectometry (OFDR) are being included inside the test articles and heat pipes. Rapid increases in temperature during steady state operation at constant power will serve as indicators that the heat pipe has exceeded its thermal limitation based on sonic velocity at the evaporator exit, capillary flow within the wick, entrainment counter-flow, or boiling/local dryout near the wall.

The SPHERE and MAGNET facilities allow for testing the performance of a single heat pipe and an array of heat pipes, respectively, under expected thermal stresses. The embedded spatially distributed fiber optic temperature sensors and thermocouples will provide a detailed mapping of temperatures to determine expected thermal strains. In addition, spatially distributed fiber optic strain sensors are being embedded within the test articles in an attempt to directly monitor local strains. Understanding these strains is critical to ensuring that the heat pipes and/or electrical heaters (simulating fuel rods) do not debond from the test articles. If this were to occur, there is concern that a single failure could increase the heat rejected to surrounding heat pipes, as well as the temperature gradients throughout the monolith and ultimately lead to a cascading failure event. A 7-hole test article has been fabricated with two Type K thermocouples directly embedded in its walls using an Ultrasonic Additive Manufacturing (UAM) process (Hehr 2017, Petrie 2020a). The test article also includes embedded spatially distributed fiber-optic strain sensors (Petrie 2020b, Petrie 2019a, Petrie 2019b) and cavities for inserting spatially distributed fiber-optic temperature sensors (Wood 2014, Sweeney 2020). Fig. 7 shows pictures of the sensor embedding process and the final 7-hole test article after sensor embedding and post-embedding machining. The sensors survived the embedding process and are currently being characterized at Oak Ridge National Laboratory (ORNL) prior to being sent to INL for testing in SPHERE.

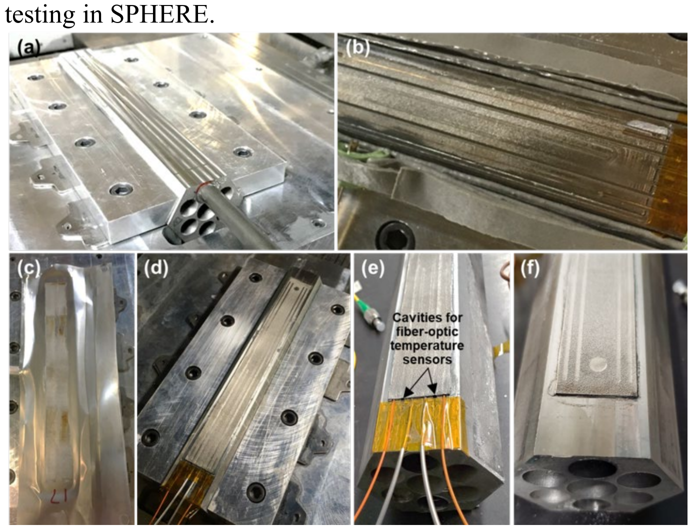


Figure 7 Pictures of a stainless-steel mini hex block during sensor embedding showing the part SPHERE in its fixture (a), UAM layering (b), completion of the UAM layering process (c), post-embedding machining (d), and the finished part (e, f).

In addition to fiber optic strain sensors and traditional strain gauges, the quartz tube that is used as a pressure boundary in SPHERE could allow for the use of non-contact optical techniques for characterizing local strains. Techniques such as digital image correlation (DIC) are being evaluated for potential deployment in SPHERE. DIC has shown itself to be a very attractive technique for measuring strain and deformation at high spatial resolution as a non-contact, imager-based technique that can potentially be used to measure strain/deformation in 2D or 3D. In a typical digital image correlation measurement, a speckle pattern is applied to the structure-under-test and is observed as it undergoes deformation/loading using imagers. While MAGNET does not allow optical access for DIC, all other embedded and spatially distributed sensors can be deployed within MAGNET experiments, which allow for testing an array of heat pipes and could be used to evaluate a potential cascading heat pipe failure scenario.

4. CONCLUSIONS

The current work provides a summary of selected experimental capabilities being developed to support non-nuclear demonstration of microreactors under the U.S. Department of Energy's (DOE's) Microreactor Program. The primary experimental hardware capabilities currently under development focus on non-nuclear thermal and integrated-systems testing, and the development of advanced moderator and test articles to perform experiments. Specifically, this includes the single primary heat extraction and removal emulator (SPHERE) and microreactor agile non-nuclear experimental test bed (MAGNET). State-of-the-art instrumentation and sensors are being used to obtain detailed maps of temperatures to determine temperature profile and expected thermal strains. In addition, spatially distributed fiber-optic strain sensors are being embedded within the test articles in an attempt to directly monitor local strain. Generated data from these experiments will support industry and other US DOE programs. These data will be made available to researchers and developers for a range of testing purposes, to further improve models and understanding of individual components and the system as a whole.

REFERENCES

[1] Trellue, H., J. O'Brien, R. Reid, D. Guillen, and P. Sabharwall. "Microreactor Agile Nonnuclear Experiment Testbed Test Plan," LA-UR-20-20824, 2019.

[2] Capstone Turbine Corporation, https://www.capstoneturbine.com/products/c30, accessed August 5, 2020.

[3] Guillen, D.P., and D.S. Wendt, (2020) "Integration of a Microturbine Power Conversion Unit in MAGNET: Analysis of a Power Conversion Unit (PCU) for the Microreactor Agile Non-nuclear Experimental Testbed (MAGNET)," Idaho National Laboratory, INL/EXT-20-57712, August 2020.

[4] Kennedy, J., P. Sabharwall, K. Frick, M. McKellar, S. M. Bragg-Sitton, D. V. Rao, and P. McClure. "Special Purpose Application Reactors: System Integration Decision Support," INL/EXT-18-51369, Idaho National Laboratory, Idaho, September 2018.

[5] MRP Website: https://gain.inl.gov/SitePages/MicroreactorProgram.aspx, accessed NEED DATE. (March 20)

Hehr, A. et al., (2017) "Five-Axis Ultrasonic Additive Manufacturing for Nuclear Component Manufacture," *Journal of The Minerals, Metals& Materials Society*, vol. 69 p. 485-490. https://doi.org/10.1007/s11837-016-2205-6.

Petrie, C.M., et al., (2019a) "Embedded metallized optical fibers for high temperature applications," *Smart Materials and Structures*, vol. 28 p. 055012. https://doi.org/10.1088/1361-665X/ab0b4e.

Petrie, C.M., et al., (2019b) "High-temperature strain monitoring of stainless-steel using fiber optics embedded in ultrasonically consolidated nickel layers," *Smart Materials and Structures*, vol. 28 p. 085041. https://doi.org/10.1088/1361-665X/ab2a27.

Petrie, C.M., N.D.B. Ezell, (2020a) "Demonstrate embedding of sensors in a relevant microreactor component," ORNL/SPR-2020/1742, Oak Ridge National Laboratory, Oak Ridge, TN. https://doi.org/10.2172/1720216.

Petrie, C.M., and N. Sridharan, (2020b) "In situ measurement of phase transformations and residual stress evolution during welding using spatially distributed fiber-optic strain sensors," *Measurement Science and Technology*, vol. 31 p. 125602. https://doi.org/10.1088/1361-6501/aba569.

Sabharwall, P., J. Hartvigsen, T. Morton, Z. Sellers, and J.S. Yoo, (2020) "SPHERE Assembly and Operation Demonstration," INL/EXT-20-60782, Idaho National Laboratory.

Sweeney, D.C., A.M. Schrell, and C.M. Petrie, (2020) "An Adaptive Reference Scheme to Extend the Functional Range of Optical Backscatter Reflectometry in Extreme Environments," *IEEE Sensors Journal*, vol. 21, p. 498-509. https://doi.org/10.1109/JSEN.2020.3013121.

Wood, T.W., et al., (2014) "Evaluation of the Performance of Distributed Temperature Measurements with Single-Mode Fiber Using Rayleigh Backscatter up to 1000°C," *IEEE Sensors Journal*, vol. 14 p. 124-128. https://doi.org/10.1109/JSEN.2013.2280797.

Wright, S.A., R.J. Lipinski, M.E. Vernon, and T. Sanchez, (2006) "Closed Brayton Cycle Power Conversion Systems for Nuclear Reactors: Modeling, Operations, and Validation," Sandia National Laboratories Report SAND2006-2518. https://doi.org/10.2172/1177051.