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Revision 0

Strain gauge for testing microreactor hexagonal core blocks in the Single Primary Heat Extraction and Removal Emulator

August 2022

Advanced Sensors and Instrumentation Program

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ABSTRACT

To support the development and deployment of microreactor technologies, experiments that help verify and validate reactor systems and components are performed at non-nuclear test facilities. The Single Primary Heat Extraction Removal Emulator at Idaho National Laboratory is one of these test facilities and was used to monitor a test article that has a prototypic geometry of a heat-pipe cooled microreactor core block. To collect crucial temperature and strain data during testing, temperature and strain sensing fiber optics were embedded to the surface of the test article using an ultrasonic additive manufacturing technique. To support and provide benchmark strain data for the embedded sensors, a commercial resistive strain gauge was attached. This report will discuss the results from the deployment of the commercial strain gauge which includes the setup/attachment strategies, data acquisition, and analysis of the strain data.

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CONTENTS

FIGURES

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ACRONYMS

INL	Idaho National Laboratory
SPHERE	Single Heat Pipe Extraction and Removal Emulator
DOE	Department of Energy
ORNL	Oak Ridge National Laboratory
UAM	Ultrasonic additive manufacturing
ASI	Advanced Sensors and Instrumentation
RSG	Resistive strain gauge
SS304	Stainless steel alloy 304
CTE	Coefficient of thermal expansion

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1. INTRODUCTION

The Idaho National Laboratory (INL) supports the development of microreactor technologies through its establishment of non-nuclear test facilities that allows for the verification and validation of reactor systems and components. One of these non-nuclear facilities is the Single Primary Heat Extraction and Removal Emulator (SPHERE), which allows for the testing of simulated startups and transients, and provides data that enables for a better understanding of microreactor design and performance [1]. The testing in SPHERE accelerates the U.S. Department of Energy's (DOE) Microreactor Program's ability to better understand heat-piped-cooled microreactors and enables for the technology's successful demonstration and deployment.

To provide critical data on mechanical properties during testing, a prototypic seven-hole hexagonal test article that is based on the core block design of a heat pipe-based microreactor was instrumented with embedded sensors (Figure 1) at Oak Ridge National Laboratory (ORNL). ORNL used an ultrasonic additive manufacturing (UAM) technique to embed a distributed strain sensing fiber optics, distributed temperature sensing fiber optics, and type-K thermocouples onto the surface of the test article [2]. The U.S. DOE's Advanced Sensors and Instrumentation (ASI) program provided added support for the testing of the UAM embedded strain sensing optical fibers by providing and attaching weldable resistive strain gauge (RSG) to the core block. RSGs are a well-established and allow for the active measurement of strain at strategic locations on a component [3], making it an ideal sensor that can provide benchmark strain data for the spatially distributed strain sensing fiber optics. This report describes the RSG attachment strategies, data acquisition, and results from the thermal transients and steady-state testing of the core blocks in SPHERE.

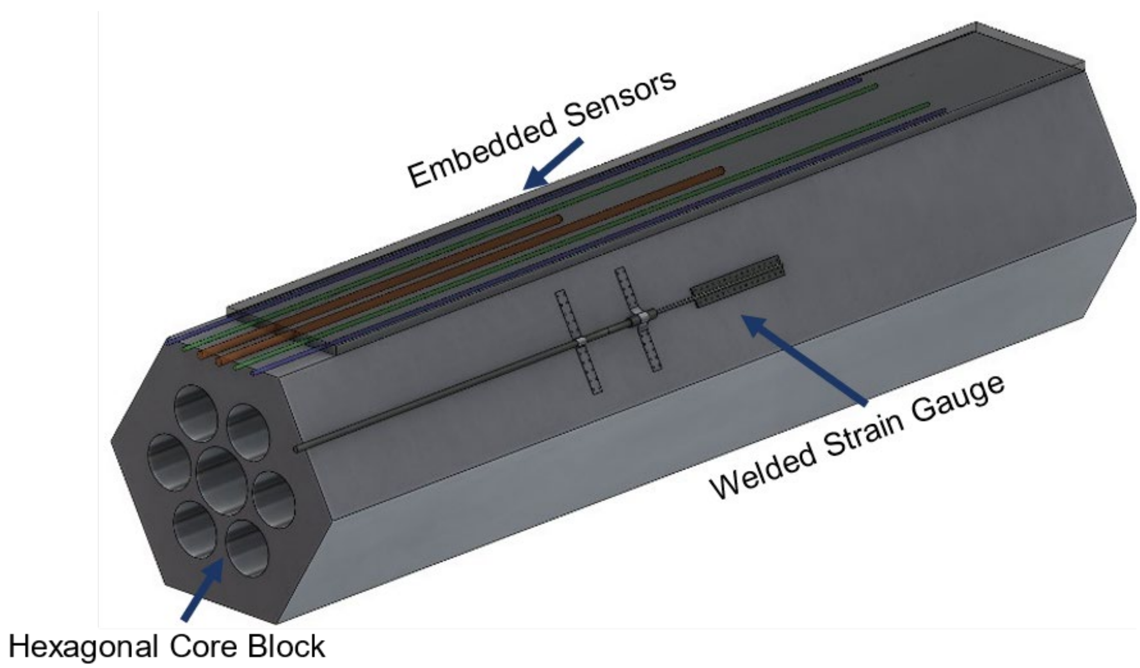

Figure 1. Schematic of instrumented core block with embedded fibers, embedded thermocouples, and the welded strain gauge.

2. EXPERIMENTAL METHODS AND MATERIALS

2.1 Materials

Commercially available RSGs (Kyowa, KHC-20-120-G9-13) were attached to an additively manufactured stainless steel alloy 304 (SS304) hexagonal core block that was printed at Los Alamos National Laboratory [2]. The RSG are composed of two elements that consist of a primary active strain sensing element and a secondary dummy element that reduces temperature effects and allows for temperature compensation [3]. Figure 1 shows photos of the two core blocks that were used to for testing in SPHERE. Core block-A (Figure 1a) is made up of two 280 mm long core blocks that were welded together. Core block-A was used for initial attachment trials of the strain gauge and preliminary systems testing in SPHERE. Core block-B (Figure 1b) had the UAM embedded sensors from ORNL and was used to support the testing outlined and discussed in Holden et al. [2].

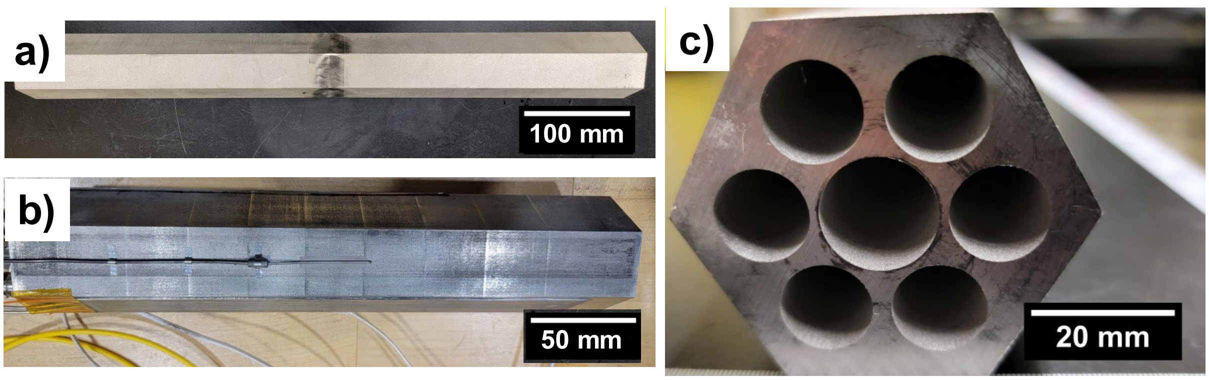

Figure 2. Core block used during a) preliminary testing and b) embedded sensors testing in SPHERE. c) Representative side profile of the hexagonal core block test article

2.2 Strain Gauge Attachment Strategies

Prior to welding the RSG onto the SS304 hex core block, the surface was hand-polished with 300-grit paper to remove the oxide layer and any surface impurities. The surface was then cleaned with isopropanol to degrease the surface. For welding, a capacitive discharge single pulse resistive spot welder was used (Sunstone, CD100SPM; Figure 3a). The CD100SPM allows for micro spot resistance welding, which locally heats the region of bonding quickly by discharging a large amount of energy within milliseconds. The spot welder was outfitted with a ≈1 mm handheld probe tip was performed at an energy of 30 J with each tack spaced out at 1/32 inches (0.8 mm). Three strain relief foils were welded on to secure both the mineral insulated cabling and connection terminal before welding on the sensing region of the sensor. Figure 3b-c shows the results of welding the strain relief foils and sensing element of the RSG onto the test article.

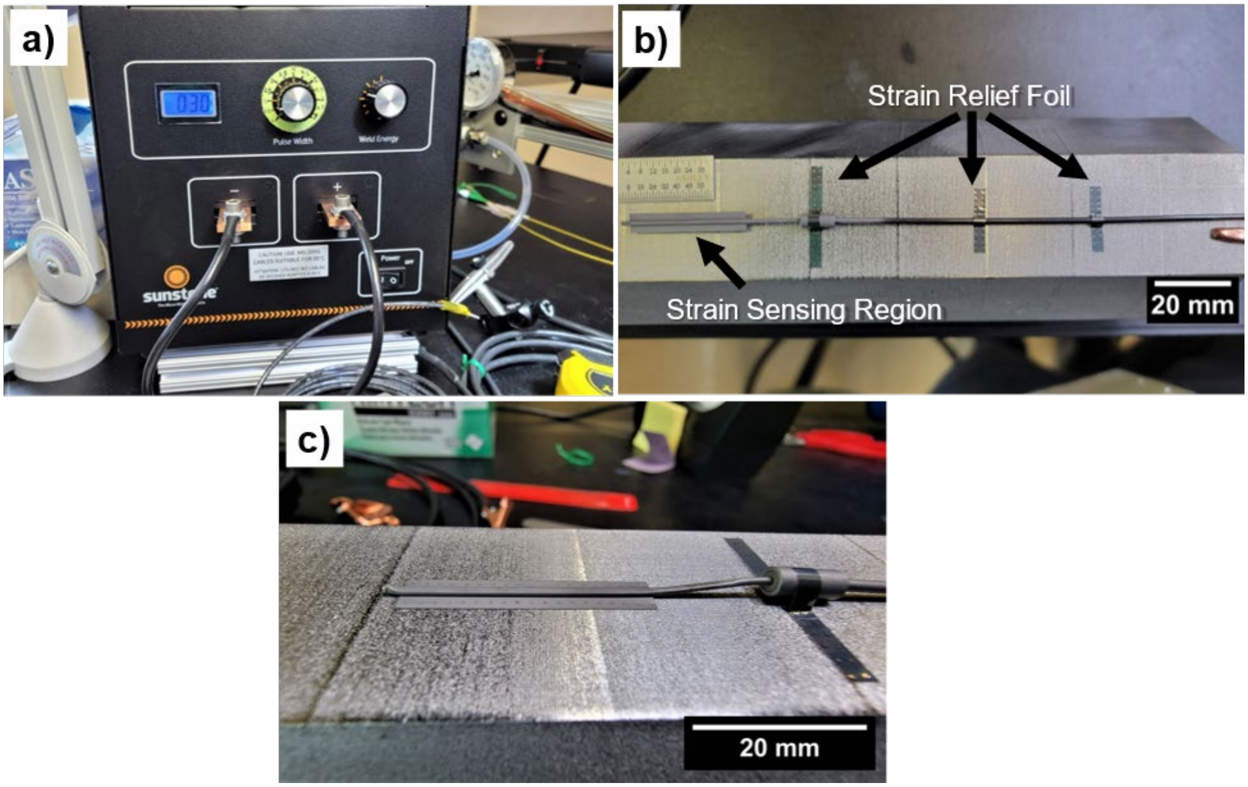

Figure 3. The a) Sunstone resistive spot welder used to spot weld the b) strain relief foils to the gauge and the c) sensing element of the resistive strain gauge.

2.3 Strain Gauge Data Acquisition

The weldable strain gauges were measured using a Wheatstone bridge circuit in a half-bridge configuration. An NI-PXIe-4330 Strain Bridge Module was integrated into a NI-PXI chassis and LabVIEW program that was used for data acquisition and instrument control for SPHERE [1]. Prior to measurement, an offset and shunt calibration were performed on the strain gauge to correct for resistance errors from the lead wires and individual resistors within the bridge. A 2.5 V bridge excitation voltage was used since it was found to allow for stable readings up to the maximum 500 - 550 °C operating limit of the strain gauge. The voltage output of the strain gauge from the bridge module is converted to strain (ε) using the following equation:

$$strain\ (\varepsilon) = \frac{-4 \cdot V_r}{GF \cdot (1 + 2 \cdot V_r)}$$

where V_r is the voltage output in V/V and GF is the gauge factor of the strain gauge. The gauge factor of the strain gauge is provided by the manufacturer and has a nonlinear relationship with temperature (Figure 4).

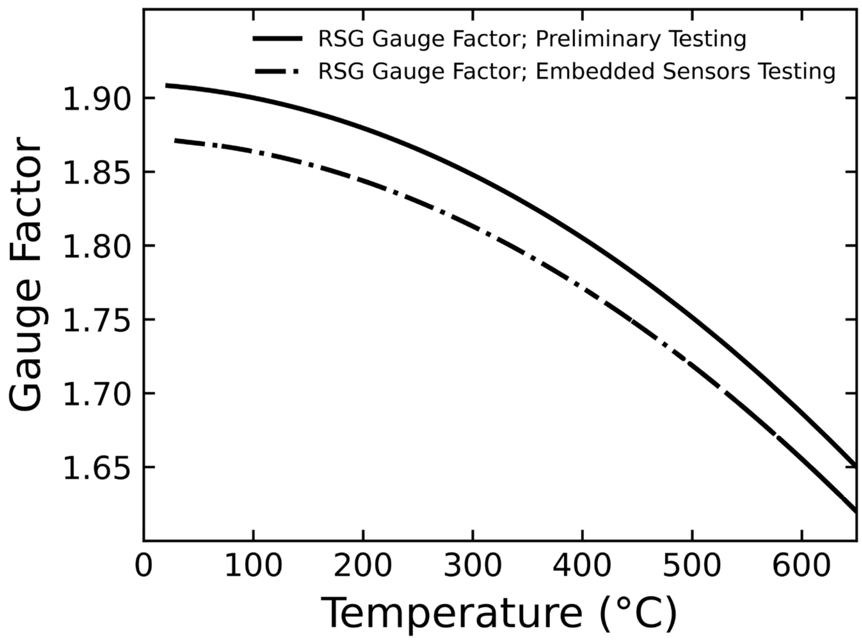

Figure 4. Gauge factor of the strain gauge for preliminary testing (RSG on core block-A) and testing of the embedded sensor (RSG on core block-B) that is provided by the manufacturer, Kyowa, for each gauge.

2.4 Testing Conditions

Figure 5a provides the temperature profile used during preliminary testing with core block-A and Figure 5b the embedded sensors testing with core block-B in SPHERE. Figure 6 shows the six cartridge heaters that were inserted into the core block and a simplified furnace setup of SPHERE. A more detailed diagram and discussion on the setup of SPHERE can be found in Sabharwall et al. [1]. During the preliminary testing, there was no heat pipe used in the center hole of the core block and the test was performed in an air environment. The temperature of the test was gradually increased to the recommended operating limit of the strain gauge (i.e., 500 – 550 °C) and then tested at a temperature above this threshold (i.e., 650 °C) (Figure 5a). During the testing of the embedded sensors, a single heat pipe was inserted and used in the center hole of the core block. In addition, the system was vacuum purged and then backfilled with an ultra-high purity nitrogen gas environment. Similar to the preliminary test, the temperature was gradually increased up to the design limit of the strain gauge before performing transient and steady-state test between 600 °C and 675 °C to test the embedded fiber optics to failure (Figure 5b).

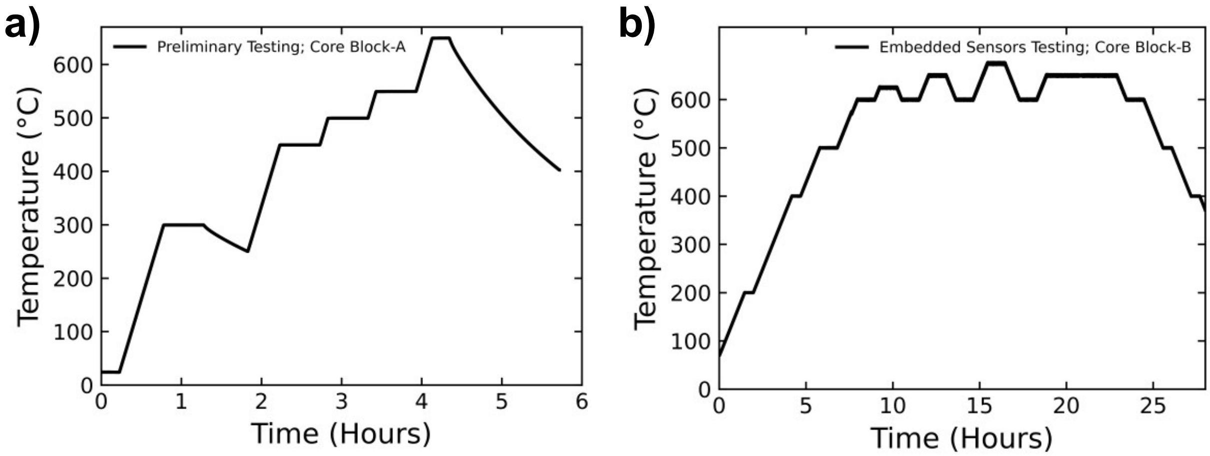

Figure 5. Temperature profile used during a) preliminary testing with core block-A and b) testing of the embedded fiber optics on core block-B.

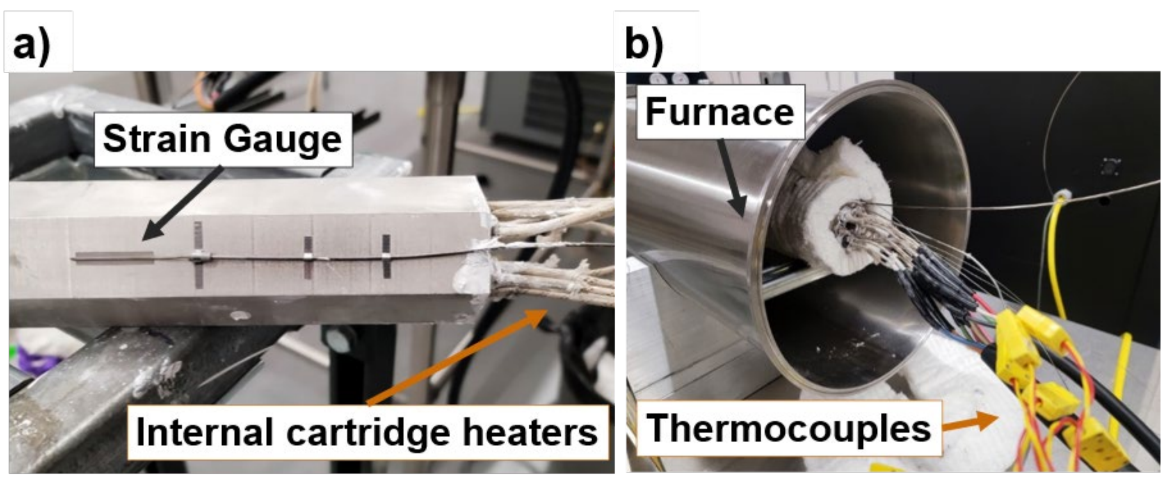

Figure 6. Simplified photo of the test setup with the welded resistive strain gauge and other instrumentation including, but not limited to, the a) cartridge heaters and b) thermocouples in SPHERE.

3. RESULTS AND DISCUSSION

3.1 Preliminary Testing in SPHERE

Figure 7 shows the thermal strain results of the RSG that was welded onto core block-A (Figure 2a). At temperatures up to 500 °C, the strain response had a linear trend with increasing temperature and had minor deviations during the thermal soaks at 300 ° and 450 °C. The thermal strain reached 1.8% on the core block at 500 °C. During the 30-minute soaks at 500 °C and 550 °C, the strain gauge output drifted and became instable. The RSG began to drastically drop in signal at temperatures beyond 570 °C. Subsequent testing showed that taking the RSG up to 650 °C, which is beyond the manufacturer's specified 500 °C operating limit, does not cause irreversible damage to the strain gauge. The strain gauge's response was repeatable with increasing temperature up to 500 °C.

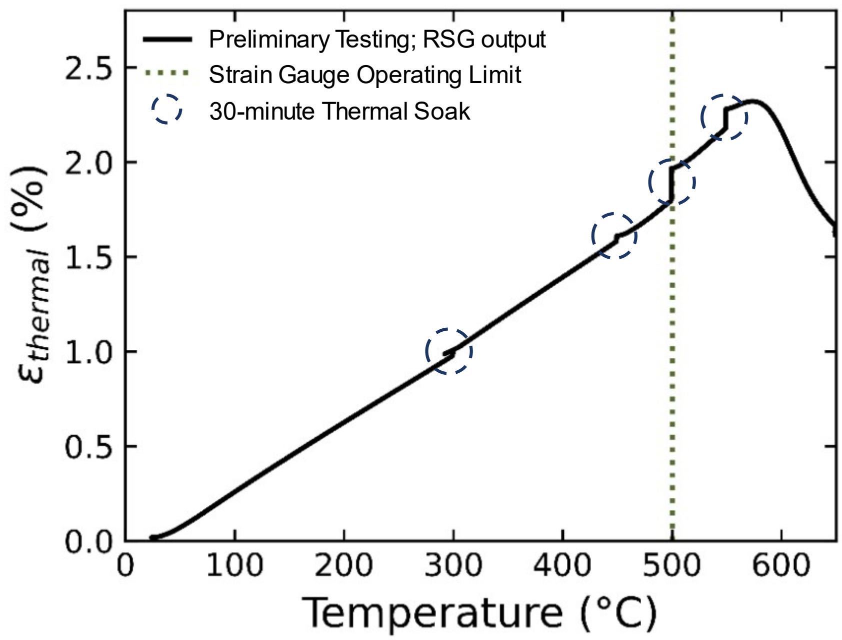

Figure 7. Thermal strain results of the resistive strain gauge welded onto hexagonal core block-A for preliminary testing.

3.2 Testing with Embedded Sensors in SPHERE

The RSG was welded in the middle of core block-B so that it was in-between the junctions of embedded thermocouples and within the sensing region of the embedded strain fibers (Figure 8). Figure 9 shows the thermal strain results of the RSG that was welded onto core block-B (Figure 2b). Similar to the preliminary testing, the strain results had a relatively linear trend at temperatures up to 500 °C and had minor deviations during the thermal soaks at 200 °C and 400 °C. The thermal strain reached 2.1% on the core block at the 500 °C operating limit of the RSG. During the 500 °C soak, the strain gauge also experienced drifting and then had a drastic drop in signal during a thermal ramp beyond 525 °C.

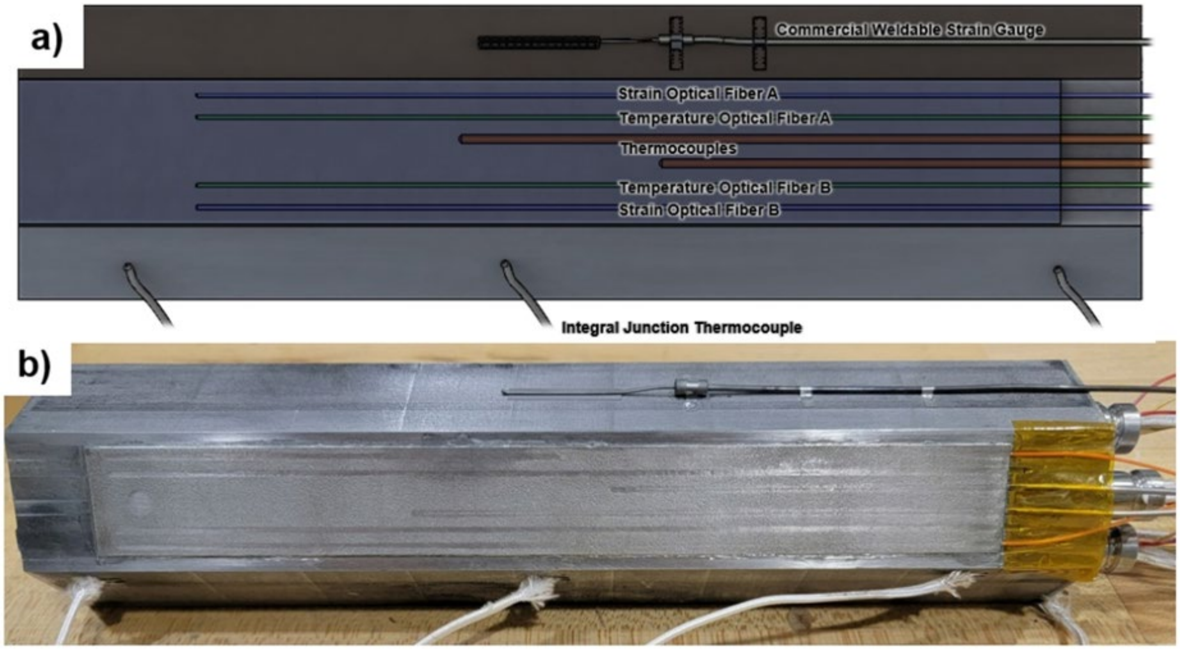

Figure 8. a) Schematic of core block-B with the strain gauge, ultrasonic additive manufactured sensors, and thermocouples attached. b) Photo of the actual instrumented core block.

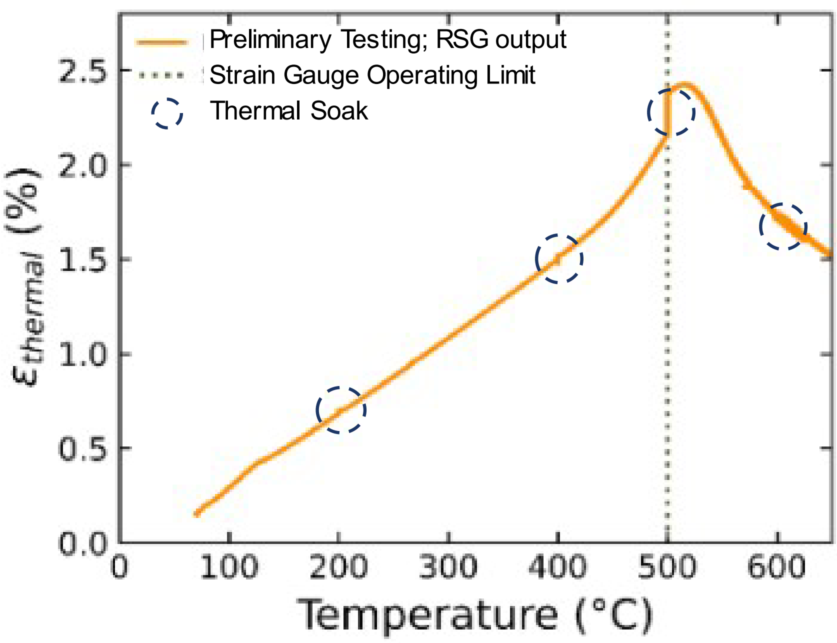

Figure 9. Thermal strain results of the resistive strain gauge welded onto hexagonal core block-B for the testing of the embedded sensors.

3.3 Possible Error from Testing

Assuming the coefficient of thermal expansion of SS304 is 18.6 $\frac{(\mu m/m)}{°C}$ [4] up to 600 °C, the measured thermal strain from the two test on the core blocks are approximately double the calculated expected thermal strain (Figure 10). This discrepancy is attributed to a coefficient of thermal expansion (CTE) mismatch between the Inconel 600 RSG flange/backing and the SS304 test article (i.e., approximately a 3 (µm/m)/°C difference). Inconel 600 has a lower CTE than SS304, so the localized region where the RSG was welded may have observed an additional mechanical stress. These RSGs, however, are supposed to be self-temperature compensating gauges which means that the thermal coefficient of resistance of the elements are heat-treated to offset the difference in CTE between the sensor and test articles. The materials used as the sensing element and insulation are not specified in any documentation provided by the manufacturer.

The RSG output from the embedded sensors testing was also found to be higher than the RSG output measured during the preliminary testing (Figure 10). In addition to the CTE mismatch, thermal gradients in the test article could have also caused variable added stresses on the block. Figure 11 shows that there was also a 40 °C – 60 °C temperature gradient between thermocouple welded on the surface of the core block and the internal thermocouple located in the cartridge heaters. Both the radial and possible axial thermal gradient on the core block could have caused the strain output from the RSG to be higher since the gauge is confined to measuring strain axially in a localized region. The results from the distributed temperature and strain fiber optics are being processed by ORNL and will inform us on the axial thermal and strain gradients along the surface of the core block.

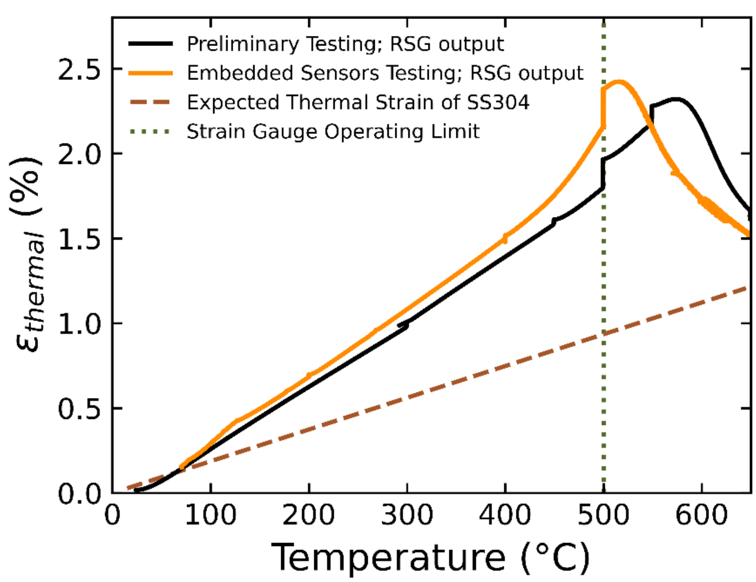

Figure 10. RSG results from preliminary testing and the embedded sensors testing overlayed against one another. The expected thermal strain of SS304 is also plotted and assumes the coefficient of thermal expansion of SS304 is 18.6 (µm/m)/°C.

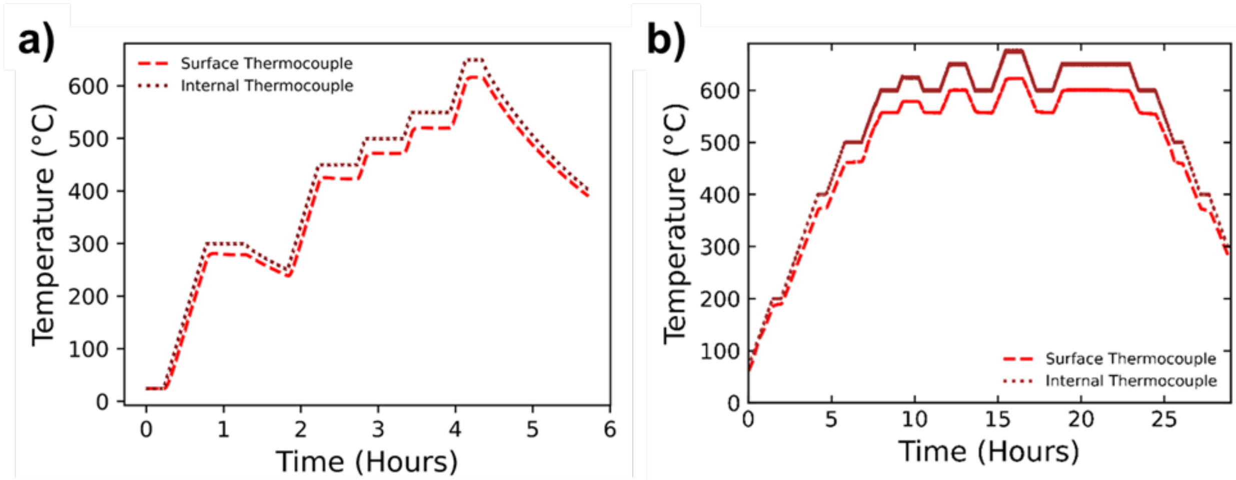

Figure 11. Output from the thermocouples that were attached to the surface of the hexagonal core block and internal within the cartridge heaters for a) core block-A during the preliminary test and b) core block-B during testing of the embedded sensors.

4. SUMMARY AND CONCLUSION

A commercial resistive strain gauge was successfully attached and demonstrated on a prototypic microreactor test article block. These tests helped support the testing of a UAM embedded fiber optic that allow for the structural health monitoring of a hexagonal core block. Although the strain reading is about twice the expected thermal strain of a uniformly heated SS304 bulk specimen, this discrepancy can be explained by a thermal expansion mismatch between the gauge and core block, and/or the temperature gradient along the core block which can causes a higher observed local strain where the RSG is bonded. The strain measurements from the test discussed in this report will be further understood with the spatially distributed results from the embedded fiber optics, when those results are available. These strain results help collect crucial data that inform modeling and simulation efforts that support the development and demonstration of microreactor technologies.

5. References

1. Sabharwall, P., et al., *Microreactor Program: Experimental Capabilities Summary*. 2021, Idaho National Lab.(INL), Idaho Falls, ID (United States).
2. Hyer, H., D. Sweeney, and C. Petrie, *Characterization of Embedded Sensors in Stainless Steel Test Articles and Design/Planning for MAGNET Testing*. 2021, Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).
3. Pettigrew, M.J., *The behaviour of weldable strain gauges under nuclear reactor core conditions.* Nuclear Engineering and design, 2013. 263: p. 350-361.
4. Desai, P. and C. Ho, *Thermal linear expansion of nine selected AISI stainless steels*. 1978, Thermophysical and Electronic Properties Information Analysis Center.