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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Single Primary Heat Extraction and Removal Emulator (SPHERE) Long Duration Testing

Zachary D. Sellers, Ilyas Yilgor, Jeremy Hartvigsen, Piyush Sabharwall
Microreactor Program, Idaho National Laboratory
2525 Fremont Ave, Idaho Falls, ID 83401
zachary.sellers@inl.gov; ilyas.yilgor@inl.gov; jeremy.hartvigsen@inl.gov; piyush.sabharwall@inl.gov

ABSTRACT

For the development of heat-pipe cooled microreactors, it is crucial to thoroughly understand the characteristics and functioning of heat pipes across a wide spectrum of operating conditions. Passive heat removal and its long-term performance stability are critical factors in this context. Experimental data is vital for evaluating the operational lifespan of alkali metal heat pipes. Idaho National Laboratory (INL) has successfully conducted an extended duration test on a high-performance sodium-filled heat pipe, closely monitoring the axial temperature profile, power supplied by the heaters, and heat removed by a gas-gap calorimeter.

The results from this testing provide valuable data that are instrumental in supporting heat pipe validation efforts. Specifically, this data aids in the development and validation of Sockeye, the Multiphysics Object-Oriented Simulation Environment (MOOSE) tool under the US-DOE NEAMS program designed for heat pipe modeling. By comparing experimental results with Sockeye's predictions, the tool's accuracy and reliability can be assessed and improved, thereby enhancing its capability to simulate heat pipe operations under various conditions.

KEYWORDS
Heat pipes, microreactors, thermal hydraulics, two-phase flow

1. INTRODUCTION

Idaho National Laboratory (INL) is completing research, design, and construction of microreactors, which are small-scale nuclear reactors generating less than 50 MWe of power. These cutting-edge reactor concepts are also under examination throughout the nuclear industry for their economic feasibility. The main drivers for microreactor implementation include rapid setup and takedown, minimal operational staff requirements, and ease of manufacturing to fit mid-sized containers for transport. Given the operational conditions, passive safety emerges as a crucial element of these designs. An area of significant research focuses on the passive heat removal of the core's thermal power, with heat pipes garnering considerable interest from multiple industry stakeholders for this purpose.

High-power alkali metal heat pipes, typically used in microreactors, consist of an outer wall, a small annular gap, a wick structure, and a centerline cavity. They operate by utilizing latent heat transfer, traditionally divided into three regions: the evaporator (heat input), the adiabatic region, and the condenser (heat removal). As heat is applied to the evaporator, the working fluid undergoes phase change to vapor, creating a differential pressure across the pipe's axial length and driving the vapor flow down the center gap. The vapor transitions through the adiabatic region to the condenser, where heat removal induces phase change back to liquid. The wick structure employs capillary forces to return the liquid to the evaporator, assisted by surface tension from the annular gap. This mechanism maintains near-isothermal conditions along the heat pipe’s axial length, akin to other two-phase heat transfer mechanisms.

To support this research, INL has established the Single Primary Heat Extraction and Removal Emulator (SPHERE) facility, designed for experimentation with high-performance, sodium-filled heat pipes. Selection of working fluids for heat pipes is driven by operating temperatures, with sodium-filled heat pipes typically functioning between 450–900°C, making them well-suited for microreactor designs. Additionally, INL has developed the Multiphysics Object-Oriented Simulation Environment (MOOSE) suite of software tools for reactor modeling, including Sockeye, the tool for modeling heat pipes under the US-DOE NEAMS program. SPHERE provides critical experimental data to the Sockeye development team, aiding in the verification and validation of heat pipe models.

A 1000-hour long-duration test was conducted in the SPHERE facility to further support Sockeye development as well as microreactor licensing efforts. The heat pipe was ramped to operating temperature following the procedure outlined in Section 3 of this report. This experiment aimed to observe and collect data on performance degradation over extended operation. The axial temperature profile, power supplied, and power removed by the calorimeter were measured throughout the test. Details of the experimental setup are provided in Section 2.

2. METHODS

2.1. Facility Design

The SPHERE facility houses horizontal heat pipe test articles inside an environmental chamber constructed from multiple 12-inch diameter stainless steel sanitary tubes to isolate the heat pipe from the ambient atmosphere. The environmental chamber is equipped with a gas supply system and a vacuum pump to purge the system of air and backfill it with inert gas, achieving a controlled atmosphere. Once backfilled with inert gas, removing any residual oxygen, the system is maintained under vacuum for the duration of the testing. Heat removal from the heat pipe is facilitated by a gas-gap calorimeter, as illustrated in Figure 1. The calorimeter allows water to flow in an annular gap formed by a stainless-steel coiled tube, which is encased in steel ducting to minimize heat loss to the environment at the condenser region of the heat pipe. The water is supplied by a ThermoFisher chiller, which also serves as the final heat removal system for the SPHERE test bed. A deltaT meter and flowmeter, integrated into the water flow line, provide data for calculating the heat removed from the heat pipe.

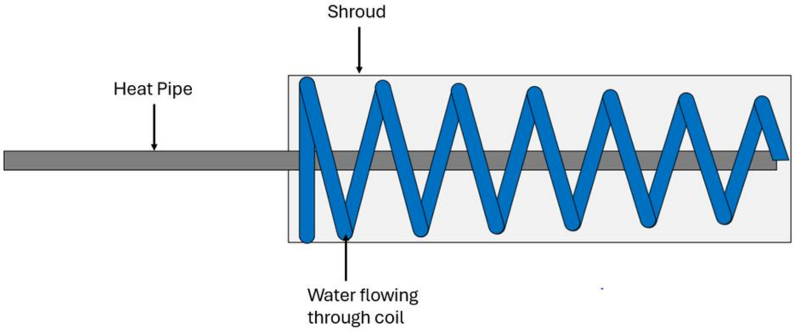

Figure 1. The SPHERE gas-gap calorimeter schematic.

Several measures are implemented to reduce heat loss from the heat pipe. The inner diameter of the sanitary tubing is insulated with a zirconia ceramic-fiber insulation blanket, which is also used to insulate the adiabatic region of the heat pipe. The exterior of the sanitary tubing is further insulated with a thin layer of Nomex aramid insulation to serve as personnel touch protection. Instrumentation leads run through a spool piece behind the evaporator region. The instrumentation lead and wiring section of the tubing remains uninsulated and is cooled by blowing ambient air over the tubing to ensure that the leads do not reach temperatures outside their specifications. A picture of the experimental setup can be found in Figure 2, where both the insulated and uninsulated sections are visible.

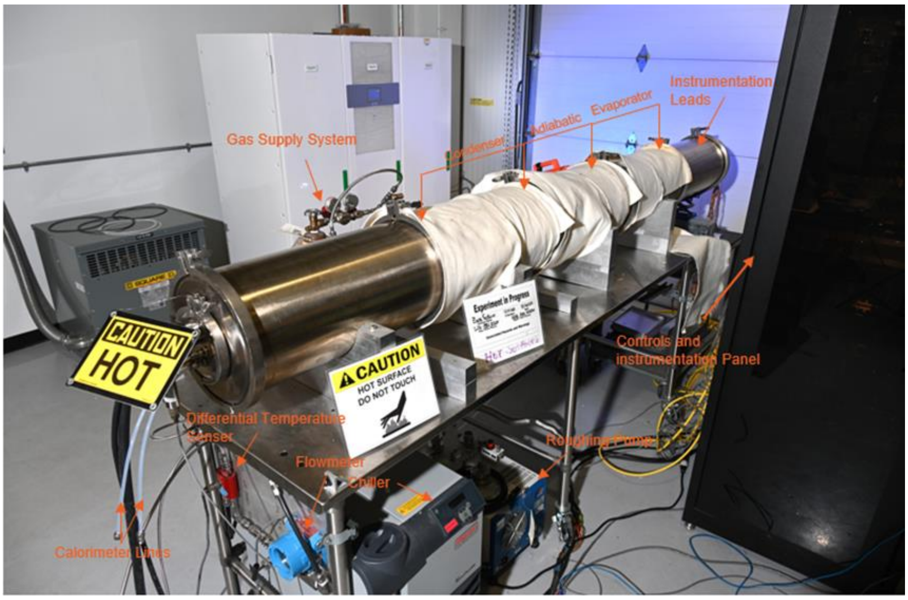

Figure 2. SPHERE long duration test setup.

The configuration of the heat pipe sections is dictated by the dimensions of the core block and the calorimeter. The evaporator region measures 20 inches, the adiabatic region spans 32.25 inches, and the condenser region extends 23 inches. Additionally, a 4-inch section of the heat pipe is designated as the inactive region due to sodium overfilling. During filling, the heat pipe is charged with inert gas, and the overfilling of sodium ensures the complete removal of this gas. During operation, the excess sodium pools as a liquid in this inactive region. Figure 3 shows these regions, as well as the thermocouple (TC) locations along the axial length of the heat pipe. TCs are spaced 4 inches apart in the evaporator region, starting from the tip of the heat pipe, with two TCs installed at each location, 180° apart azimuthally. Beyond the evaporator exit, TCs are spaced 6.5 inches apart until the end of the condenser region at 75.5 inches.

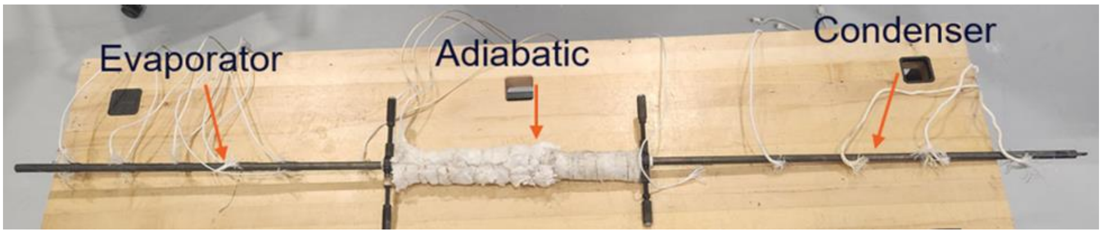

Figure 3. Physical view of the heat pipe's different sections.

Heating is achieved using two 7.5 kW ceramic fiber heaters, as exemplified in Figure 4. These heaters have two holes located at the top and bottom of the cylinder formed by the two halves.

Figure 4. Watlow ceramic fiber heater.

2.2 Experimental Procedure

The long duration testing in the SPHERE facility was conducted in two distinct stages: the startup phase and the power ramping phase to achieve the maximum operating temperature of the heat pipe, which is 800°C at the evaporator exit. During the startup phase, the system was heated at a controlled ramp rate of 5°C per minute. This ramp rate was maintained until the condenser region of the heat pipe reached a temperature of 500°C. At this juncture, the chiller was activated to commence heat removal from the system. The ramp rate continued until the evaporator temperature approached approximately 750°C. This initial steady-state condition was maintained for the first 500 hours.

Upon reaching this milestone, the second stage commenced by following the same procedure, further increasing the temperature until the evaporator exit reached 800°C. This higher temperature was sustained for the remaining 500 hours of the 1000-hour test duration. Following the completion of the testing, the system was ramped down at the same controlled rate of 5°C per minute until ambient temperature losses permitted a slower ramp rate, at which point the heaters and chiller were powered off.

2.3 Instrumentation

The list of instruments, their labels, locations, and uncertainties can be seen in Table I. A sampling rate of 1 Hz was used for all measurements. The experiment was heated using six cartridge heaters with 1 kW capacity. Each heater is controlled using a dedicated Watlow Din-A-Mites silicon-controlled-rectifier (SCR)-based power controller, with the setpoint from a PID controller or a 4–20 mA control signal provided from the National Instruments SCXI (Signal Conditioning Extensions for Instrumentation) data-acquisition system. The process values for PID controllers were obtained from the type-K thermocouple that are integrated inside the cartridge heaters. Power drawn by each heater was monitored continuously using precision power meters designed for measurement of SCR-controlled loads.

The condenser cooling power was determined based on the following relation for calorimetry by using a differential temperature meter and a turbine flow meter

$$Q_{out} = \dot{m}_c c_p \left(T_{c,out} - T_{c,in}\right) = \rho_c \dot{V} c_p \left(T_{c,out} - T_{c,in}\right)$$

where Q_{out} is the cooling power, $\dot{m}_c$ is the coolant mass flow rate, C_p is the specific heat at a constant pressure of the coolant water. $T_{c,out}$ is the temperature at the outlet of the calorimeter. $T_{c,in}$ is the temperature ft the inlet of the calorimeter. ρ_c is the density of the coolant water calculated at the turbine flowmeter and $\dot{V}$ is the volumetric flowrate at the turbine flow meter.

Table I. A list of instrumentation showing their labels, locations, and uncertainties.

Instrumentation Type	Instrumentation Label	Instrumentation Location	Uncertainty
Type K Thermocouple	Heat Pipe 4" Top	On heat pipe at 4"	±2.2°C
Type K Thermocouple	Heat Pipe 4" Bottom	On heat pipe at 4"	±2.2°C
Type K Thermocouple	Heat Pipe 8" Top	On heat pipe at 8"	±2.2°C
Type K Thermocouple	Heat Pipe 8" Bottom	On heat pipe at 8"	±2.2°C
Type K Thermocouple	Heat Pipe 12" Top	On heat pipe at 12"	±2.2°C
Type K Thermocouple	Heat Pipe 12" Bottom	On heat pipe at 12"	±2.2°C
Type K Thermocouple	Heat Pipe 16" Top	On heat pipe at 16"	±2.2°C
Type K Thermocouple	Heat Pipe 16" Bottom	On heat pipe at 16"	±2.2°C

Type K Thermocouple	Heat Pipe 20" Top	On heat pipe at 20"	±2.2°C
Type K Thermocouple	Heat Pipe 20" Bottom	On heat pipe at 20"	±2.2°C
Type K Thermocouple	Heat Pipe 26"	On heat pipe at 26"	±2.2°C
Type K Thermocouple	Heat Pipe 32.5"	On heat pipe at 32.5"	±2.2°C
Type K Thermocouple	Heat Pipe 39"	On heat pipe at 39"	±2.2°C
Type K Thermocouple	Heat Pipe 45.5"	On heat pipe at 45.5"	±2.2°C
Type K Thermocouple	Heat Pipe 51.5"	On heat pipe at 51.5"	±2.2°C
Type K Thermocouple	Heat Pipe 57.5"	On heat pipe at 57.5"	±2.2°C
Type K Thermocouple	Heat Pipe 63.5"	On heat pipe at 63.5"	±2.2°C
Type K Thermocouple	Heat Pipe 75.5"	On heat pipe at 75.5"	±2.2°C
Turbine Flow Meter	Flowrate (GPM)	Located on panel outside of environmental chamber	±0.1%
DeltaT Differential Temperature Transducer	DeltaT	Located on panel outside of environmental chamber	Similar dual probe sensors: ±0.5 °C
PC5 Watt Transducers	Watts 1 and Watts 3	Located in control panel	<1% F.S. Scale: 0-5kW
Honeywell FP5000 Pressure Transducer	Pressure (psia)	Located on a flange on the environmental chamber	0.2 %FSS Scale: 0.36 psia to 5,000 psia

3. RESULTS AND DISCUSSION

Testing on a high-performance sodium heat pipe was conducted over a long duration of 1000 hours. Figure 5 showcases the axial temperatures during the startup procedure and the first 67 hours after startup. The maximum temperature for this portion of testing was recorded at the 8-inch TC and was

781.4°C. The evaporator exit temperature at 20 inches was recorded at 749.6°C. The lowest temperature on the heat pipe, at the end of the condenser region located 75.5 inches from the beginning of the evaporator, was 209.7°C. This lower temperature indicates that the heat pipe wasn't operating within the latent heat transfer regime between the 63.5-inch TC and the 75.5-inch TC. The region between 63.5 inches and the end of the heat pipe is where the liquid pooling of the sodium begins. The lower temperature was a result of ambient losses in the system through both the evaporator and adiabatic region. The recorded power input to reach these temperatures was 1558 W, divided between two ceramic-fiber heaters each supplying approximately 779 W. It is worth noting that multiple TCs experienced induced voltage from the control panel, resulting in significant signal noise. This issue was resolved later during testing by isolating the induced voltage signal on the instrumentation board. The solution was found by systematically unplugging TCs until the TCs inducing the voltage were located. The TCs experiencing this issue were excluded from Figure 5.

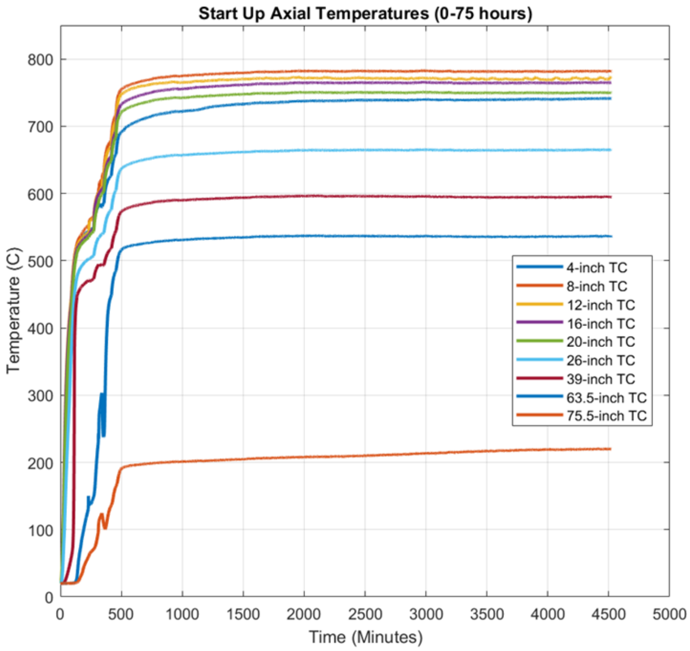

Figure 5. Startup axial temperatures for hours 0–75.

Figure 6 illustrates the axial temperatures during the end of the first stage of testing at just under 500 hours. The maximum temperature recorded at the end of the first stage was 787.5°C, once again at the 8-inch TC. The evaporator exit temperature was 756.8°C and the minimum temperature was 222.7°C at the 75.5-inch TC. Both the startup temperatures and the temperatures at the end of the first stage are tabulated in Table II. The differences between the beginning and end temperatures were 6.1°C, 7.2°C, and 13°C for the maximum, evaporator exit, and minimum temperature respectively. These temperature differences are within the uncertainty range of the TCs, at ±1% of actual temperature, resulting in minimal to negligible differences over the first 500 hours.

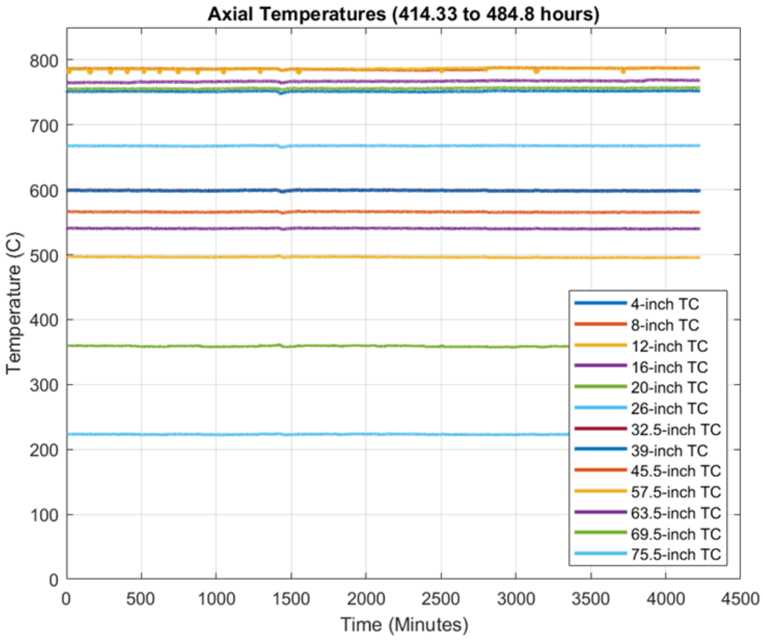

Figure 6. Axial temperatures at the end of the first stage of testing for hours 414.3 to 484.8.

Table II. Maximum, minimum, and evaporator exit temperatures at the beginning and end of the first stage of testing.

Location	**Temperature (°C)**	
	Beginning of Stage Two	**End of Testing**
Minimum (75.5-inch)	209.7	222.7
Maximum (8-inch)	781.4	787.5
Evaporator Exit (20-inch)	749.6	756.8

The second important metric for heat pipe performance that was recorded was the power supplied to the evaporator and removed by the calorimeter. Figure 7 shows the power in and power out for the first 75 hours. The power in for the first 75 hours was averaged to be 1558 W with a power out from the calorimeter averaging 400.6 W. Several factors may be attributed to the losses through the system. The performance indicates low thermal coupling between the heat pipe condenser region and the gas gap calorimeter.

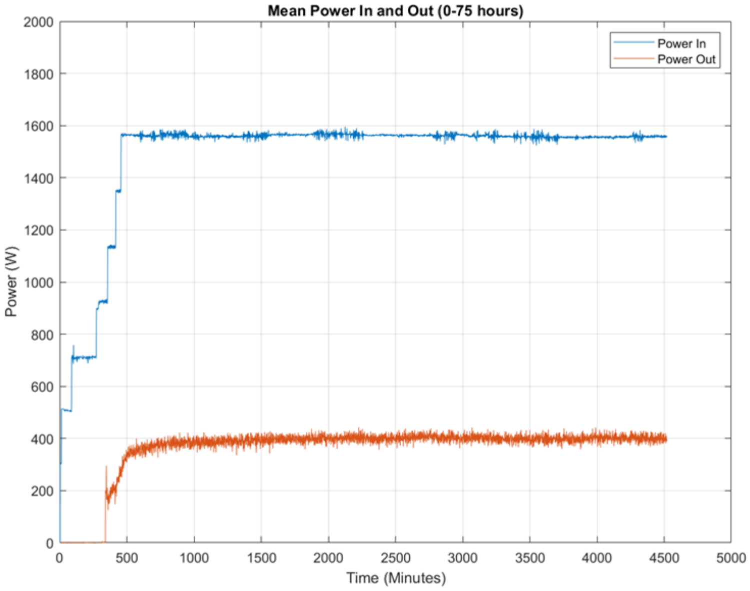

Figure 7. Mean power in and out for Hours 0–75.

Figure 8 illustrates the power supplied to the system and power out recorded by the calorimeter for the end of the first stage of testing. The results from both the first 75 hours and the end of the first stage are detailed in Table III. The power supplied at the end of the first stage averaged to be 1552 W with an average recorded power out by the calorimeter of 488 W. The differences between the beginning and end of the first stage of testing are 6 W and 87.4 W, respectively.

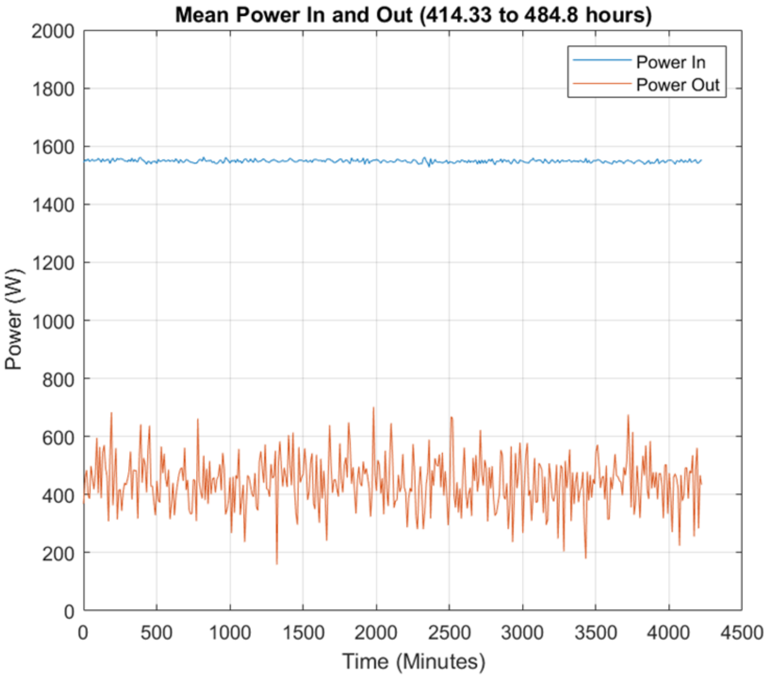

Figure 8. Mean power in and out for end of the first stage of testing (Hours 414.3–484.8).

Table III. Power in and out and percent removed for startup and end of first stage.

	Start up	**End of first stage**
Average power in (W)	1158	1552
Average power out (W)	400.6	488

During the second stage of the experiment, the power supplied to the heaters was ramped up to achieve an evaporator exit temperature of 800°C. This transient is shown in Figure 9 below. During the ramp to achieve the desired evaporator exit temperature, power to the system was lost for a brief period, seen at approximately 1800 minutes. The effect of the power loss is shown in the other figures for this period. The maximum temperature recorded after steady state was reached was 822.3°C at the 8-inch TC. The evaporator exit temperature reached 800.5°C at 20 inches. The minimum temperature was once again at 75.5 inches and was 230.4°C.

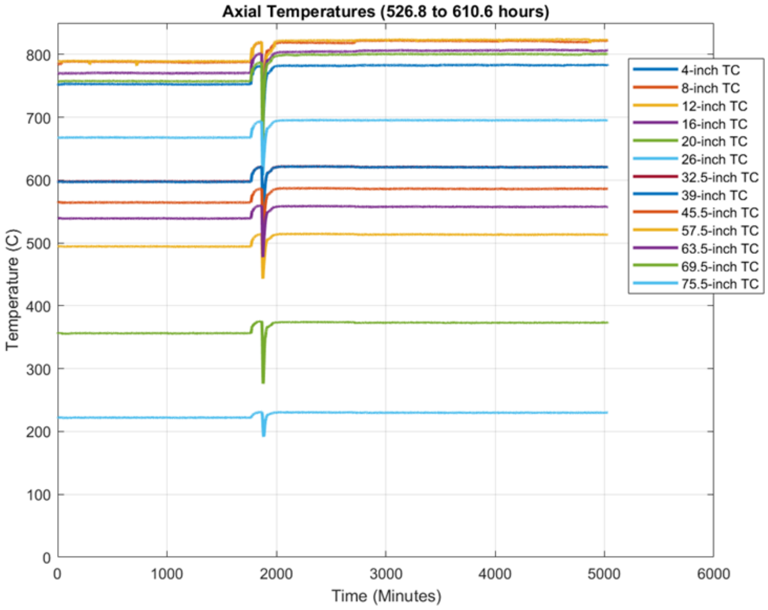

Figure 9. Axial temperatures at shift to second stage of testing for hours 526.8–610.6.

The experiment concluded at 1000 hours of testing. Figure 10 showcases the axial temperature profile of the heat pipe during the final hours of testing. The maximum temperature recorded was at the 8-inch TC with a value of 824°C. The evaporator exit temperature was 800.5°C. The minimum temperature was 231.8°C. These temperatures resulted in differences of 1.7°C, 0°C, and 1.4°C for the maximum, evaporator exit, and minimum temperatures, respectively. This is again within the uncertainty range of the TCs at ±1% of actual temperature. The temperatures for the beginning and end of the second stage of testing are detailed in Table IV.

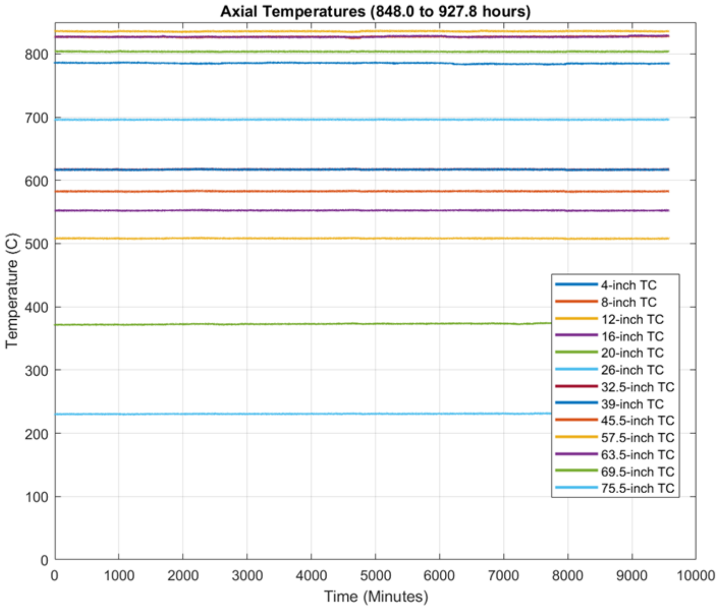

Figure 10. Axial temperatures at end of second stage of testing for Hours 848.0–927.8.

Table IV. Maximum, minimum, and evaporator exit temperatures at the beginning and end of the second stage of testing.

Location	**Temperature (°C)**	
	Beginning of Stage Two	**End of Testing**
Minimum (75.5-inch)	230.4	231.8
Maximum (8-inch)	822.3	824
Evaporator Exit (20-inch)	800.5	800.5

The power supplied to the heaters and recorded power out were measured for the second stage of testing. Figure 11 illustrates the results from the transient portion of this stage. The average power input was 1722.8 W, while the average power output was 488.3 W.

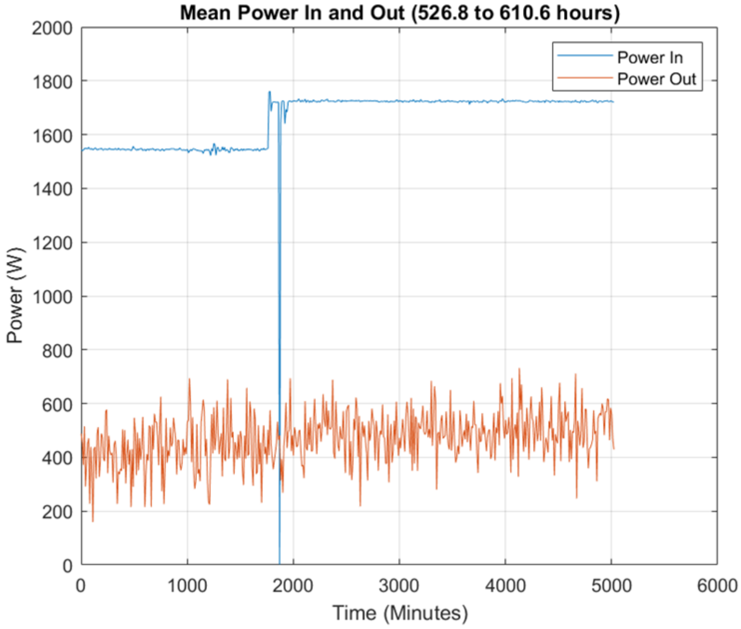

Figure 11. Mean power in and out from the calorimeter for beginning of the second stage of testing (Hours 526.8–610.6).

The power supplied to the heaters and measured power out by the calorimeter for the final portion of the second stage is shown in Figure 12. The values from this portion remained relatively consistent from the beginning of the second stage. The average power input was 1718 W, while the average power output was 479.1 W. The results of power in, power out, and the percentage of power out to in are tabulated in Table V.

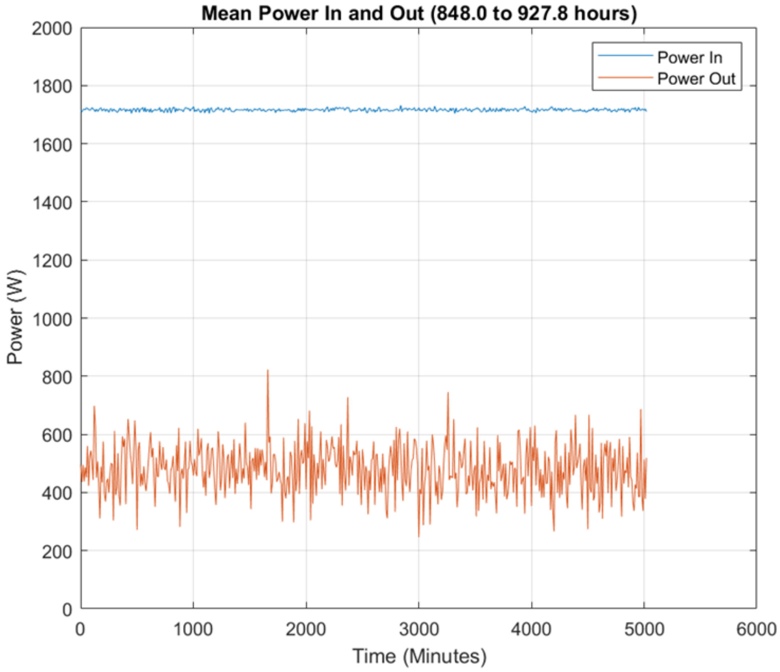

Figure 12. Mean power in and power out from calorimeter (Hours 848.0–927.8).

Table V. Power in, out, and percentage of heat removed by calorimeter at the beginning and end of the second stage of testing.

	Start up	**End of first stage**
Average power in (W)	1722.8	1718
Average power out (W)	488.3	479.0

4. CONCLUSIONS

SPHERE was designed and constructed at INL for heat-pipe characteristic testing to aid in the development and validation of a transient heat-pipe model in Sockeye, as well as to assist in microreactor licensing efforts. In continuation of this project, a long-duration test was performed on a high-performance sodium-filled heat pipe supplied by Advanced Cooling Technologies. This heat pipe was placed in a testbed heated by two half-cylinder ceramic fiber heaters to reach maximum operating temperature, closely aligning with proposed microreactor concepts. This was done in two stages. The first stage was performed with an evaporator exit temperature of 750°C. In the second stage, the evaporator exit temperature was 800°C. The purpose of this testing was to observe and record data on any performance degradation over the 1000 hours of testing. The axial temperature profile, power supplied by the heaters, and power removed by the calorimeter were all recorded over the 1000 hours of testing. The long-duration testing resulted in minimal differences between the beginning and end results for both stages. The long-duration steady-state test data will be provided to the Sockeye development team for validation efforts for heat pipe modeling.

REFERENCES

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