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

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Microreactor Program

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ABSTRACT

For heat-pipe cooled microreactor development, it is essential to understand the characteristics of heat pipes and how they function under a wide range of operating conditions. An important process for heat-pipe cooled microreactor development is the passive heat removal and how the performance may change over long periods of time. Increased experimental data provides additional information to assess the operational lifetime of alkali metal heat pipes. Idaho National Laboratory has completed testing over a long duration of a high-performance sodium filled heat pipe while monitoring axial temperature profile, power supplied by the heaters, and heat removed by a gas-gap calorimeter. The results from this testing can aid in heat pipe validation efforts.

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ACRONYMS

INL	Idaho National Laboratory
MOOSE	Multiphysics Object-Oriented Simulation Environment
SPHERE	Single Primary Heat Extraction and Rejection Emulator
TC	thermocouple

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1. INTRODUCTION

Idaho National Laboratory (INL) is researching, designing, and building microreactors. Microreactors are small nuclear reactors producing less than 25 MWth of power. These emerging reactor concepts are also being examined throughout the nuclear industry. An important aspect of these reactor designs is economic feasibility. The driving factors for implementing microreactors are quick setup and takedown, minimal operators, and the ability to manufacture them readily and to fit in mid-sized containers for transport. Because of the operational conditions, passive safety is a key element of these designs. A specific area of research to aid in successful integration of these factors within the designs is passive heat removal of the core's thermal power. Interest in heat pipes to achieve this passive heat removal has been shown across multiple industry stakeholders. The typical physical structure of high-power alkali metal heat pipes for microreactors is composed of an outer wall, a small annular gap, a wick structure, and a centerline cavity. Heat pipes function by using latent heat transfer. Heat pipes are traditionally separated into three regions: an evaporator (heat input), an adiabatic region, and a condenser region (heat removal). As heat is applied to the evaporator, the working fluid undergoes a phase change to vapor. This phase change causes a differential pressure across the axial length of the pipe driving flow down the center gap of the heat pipe. The vapor flows down past the adiabatic region to the condenser where the heat is removed. This heat removal forces the working fluid to phase change back to liquid. The wick structure is used to drive the flow back toward the evaporator by capillary forces. This backflow is aided by surface tension from the annular gap. Because this heat transfer mechanism functions with latent heat transfer, the heat pipe is close to isothermal down the axial length, similar to other heat transfer mechanisms in the two-phase region of the working fluid.

INL developed a test facility, the Single Primary Heat Extraction and Removal Emulator (SPHERE) facility, to run experiments on high-performance, sodium-filled heat pipes. Heat pipes can operate under a wide range of working fluids. Considerations for these working fluids. Among other important factors, are primarily driven by operating temperatures based on overall performance. Sodium-filled heat pipes typically operate from 450–900°C. This temperature range works well for microreactor designs. In conjunction with SPHERE's experimental capability, INL has developed the Multiphysics Object-Oriented Simulation Environment (MOOSE) suite of software tools to model reactors. The MOOSE tool being developed under US-DOE NEAMS program modeling heat pipes is called Sockeye. SPHERE also supports Sockeye development by providing the modeling team with experimental data on an array of setups and operating parameters, in order to support verification and validation needs.

A long-duration test of 1000 hours was performed in the SPHERE facility to continue to aid 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. *The aim of this experiment was to observe and collect data on any performance degradation after operating a high-performance heat pipe for 1000 hours. The axial temperature profile as well as power supplied, and power removed by the calorimeter was measured throughout the testing.* The physical setup of the experiment is described in Section 2.

2. EXPERIMENTAL SETUP

In this configuration, multiple 12-inch diameter stainless steel sanitary tubes were used to build the environmental chamber for the heat pipe and ceramic-fiber heaters. The environmental chamber is equipped with a gas supply system and vacuum pump to purge the system of air and backfill with inert gas. Once the system is backfilled with inert gas, removing any oxygen from the system, vacuum is pulled on the system. The experiment continues under vacuum for the remainder of the testing. The system is also equipped with a calorimeter for heat removal of the heat pipe. A schematic of the calorimeter is shown in Figure 1. The calorimeter allows water to flow in an annular gap formed by a stainless-steel coiled tube. This coiled tube is surrounded by steel ducting to minimize heat loss to the environment on the condenser region of the heat pipe. The water is provided to the system by a ThermoFisher chiller, which is also used as the final heat removal for SPHERE test bed. In line with the water flow, a deltaT meter and flowmeter are used to collect data. The temperature and flowrate give enough information to calculate the heat removed from the heat pipe. The inner diameter of the sanitary tubing was insulated using a zirconia ceramic-fiber insulation blanket. This insulation was also used to insulate the adiabatic region of the heat pipe. The outside of the sanitary tubing is insulated with a thin layer of Nomex aramid insulation. This insulation primarily serves to protect personnel from touching the assembly. The instrumentation leads run to a spool piece behind the evaporator region. The instrumentation lead and wiring section of tubing is uninsulated to verify that the leads would not reach temperatures outside their specifications. This section is also cooled by blowing ambient air over the outside of the tubing. A picture of the experimental setup comprises Figure 2.

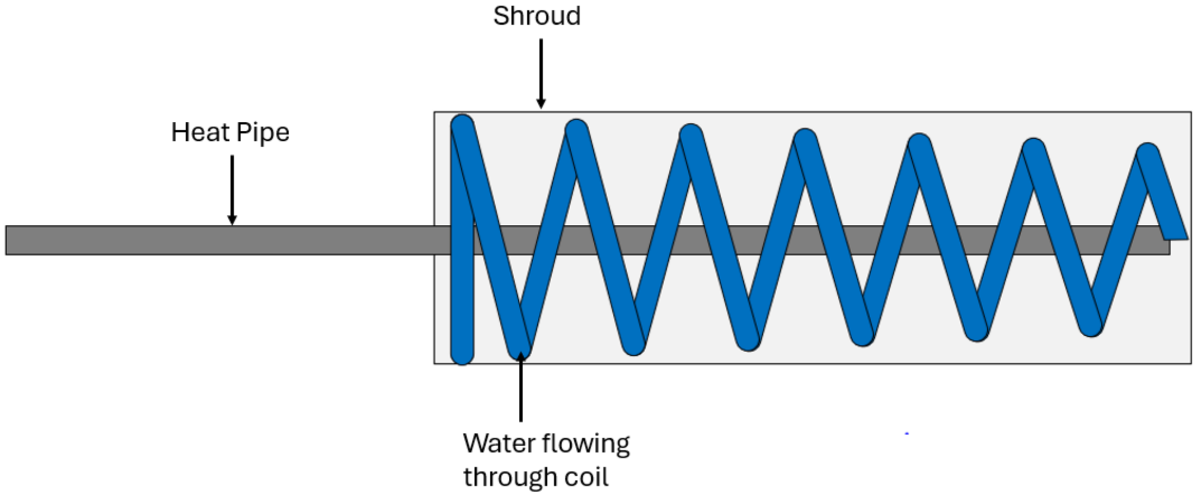

Figure 1. The SPHERE gas-gap calorimeter schematic.

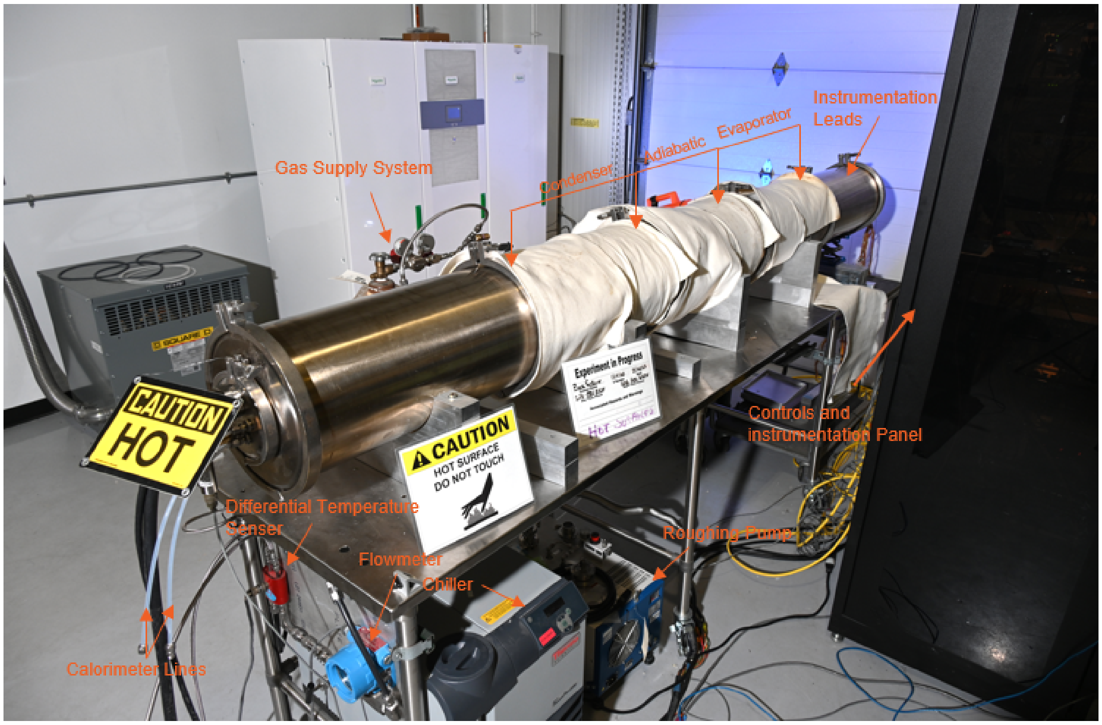

Figure 2. SPHERE long duration test setup.

The heat pipe sections are broken down by the dimensions of the core block and the calorimeter. This results in the evaporator region's being 20-inches long, the adiabatic region being 32.25-inches long, and the condenser region being 23-inches long. A small region of the heat pipe, measuring 4 inches, is defined as the inactive region of the heat pipe. The inactive region of the heat pipe is due to an overfill of sodium. During filling, the heat pipe is filled with incompressible inert gas. The overfilling of sodium allows for the system to fully remove the gas. While operating, this excess sodium is pooled as a liquid in this inactive region. These regions are shown in Figure 3. Figure 3 also shows the thermocouple (TC) locations along the axial length of the heat pipe. The TCs are spaced 4-inches apart in the evaporator region starting from the tip of the heat pipe. In the evaporator region, two TCs are installed at each location at 180° apart azimuthally. After the evaporator exit, the TCs are then spaced 6.5-inches apart until the end of the condenser region at 75.5-inches.

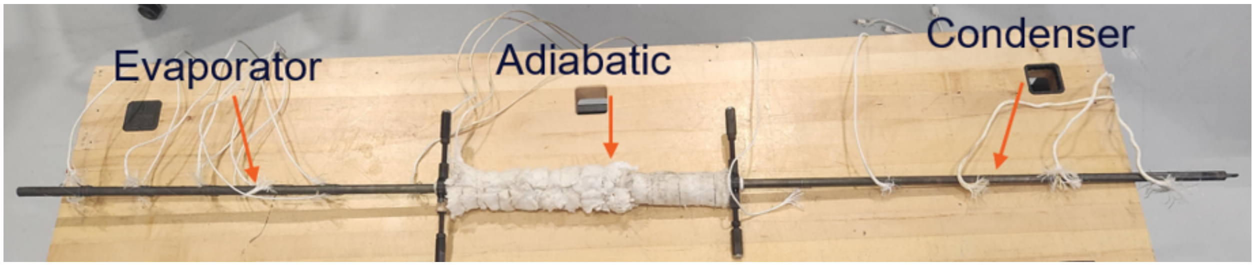

Figure 3. Physical view of the heat pipe's different sections.

The experiment is heated using two 7.5 kW ceramic fiber heaters. An example of these heaters is shown in Figure 4. The heaters have two holes located at the top and bottom of the cylinder formed by the two halves.

Figure 4. Watlow ceramic fiber heater.

3. TEST PROCEDURE

SPHERE long-duration testing was conducted in two stages: the startup and the ramping of power to achieve a maximum operating temperature of the heat pipe, 800°C, at the evaporator exit. During the startup, the system was heated at a ramp rate of 5°C per minute. This ramp rate was applied until the condenser region of the heat pipe reached 500°C at which point the chiller was powered on to begin removing heat from the system. The ramp rate continued until an evaporator temperature of approximately 750°C was reached. This first steady state point was held for the first 500 hours. At this point, the second stage was reached by following the same procedure until the evaporator exit was at a temperature of 800°C. This temperature was held for the remainder of the 1000 hours. After testing was completed, the system was ramped down at the same ramp rate of 5°C until ambient temperature losses allowed for a slower ramp rate at which point the heaters and chiller were powered off.

4. RESULTS AND DISCUSSION

Testing on a high-performance sodium heat pipe was performed over a long duration: 1000 hours. Figure 5 showcases the axial temperatures during the startup procedure as well as 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-inch 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 in to reach these temperatures was 1558 W. This power was 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 that resulted in large amounts of signal noise to be present. 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 left out of Figure 5.

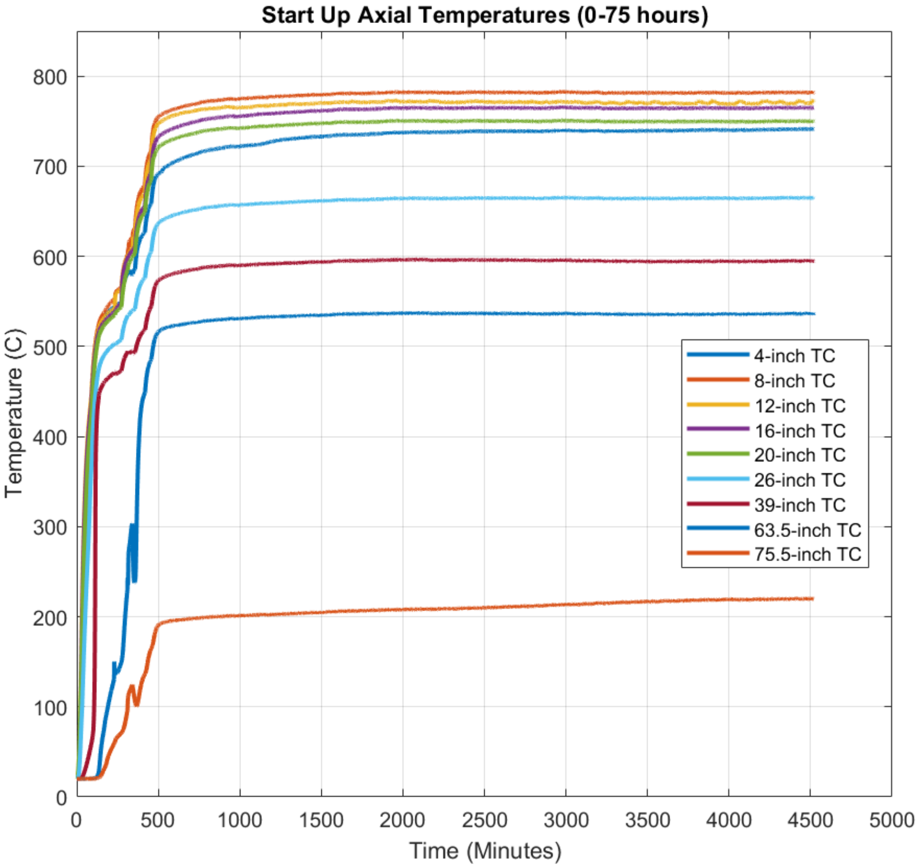

Figure 5. Startup axial temperatures for hours 0–75.

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 temperature and the temperatures at the end of the first stage are tabulated in Table 1. The difference between the beginning and end temperatures were 6.1, 7.2, and 13°C for the maximum, evaporator exit, and minimum temperature respectively. These temperature differences are within uncertainty of the TCs, at ±1% of actual temperature, resulting in minimal to negligible differences for the first 500 hours.

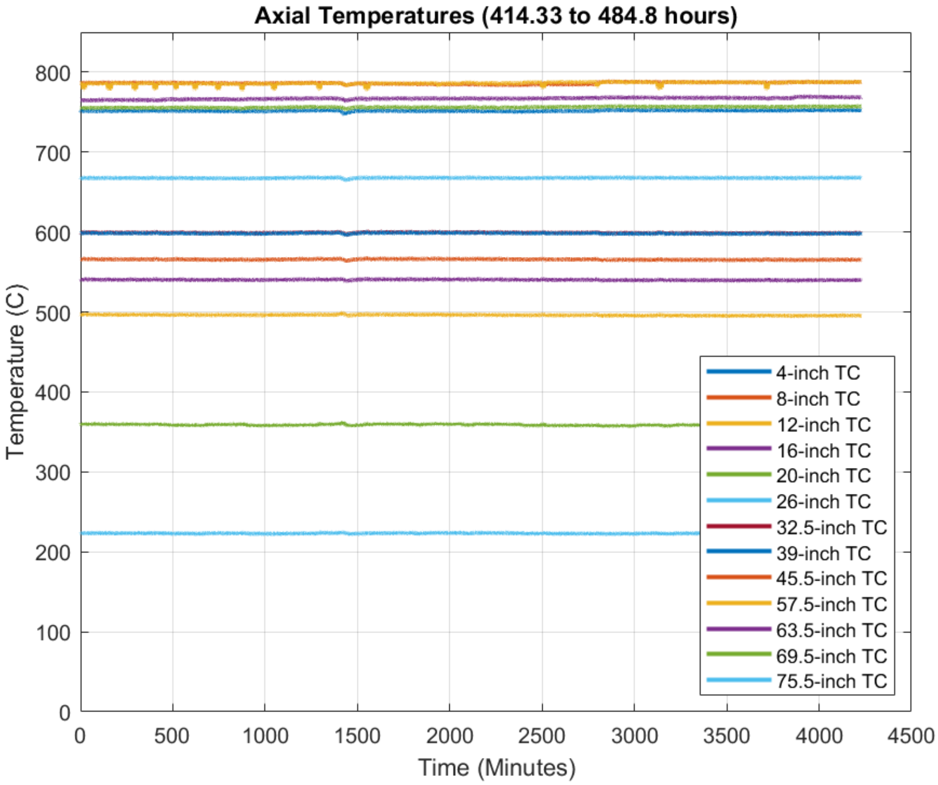

Figure 6. Axial temperatures at the end of the first stage of testing for hours 414.3 to 484.8.

Table 1. Maximum, minimum, and evaporator exit temperatures at the beginning and end of the first stage of testing.

Location	Temperature (°C)	
	Startup	End of first stage
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 averaged to 400.6 W. A few 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.

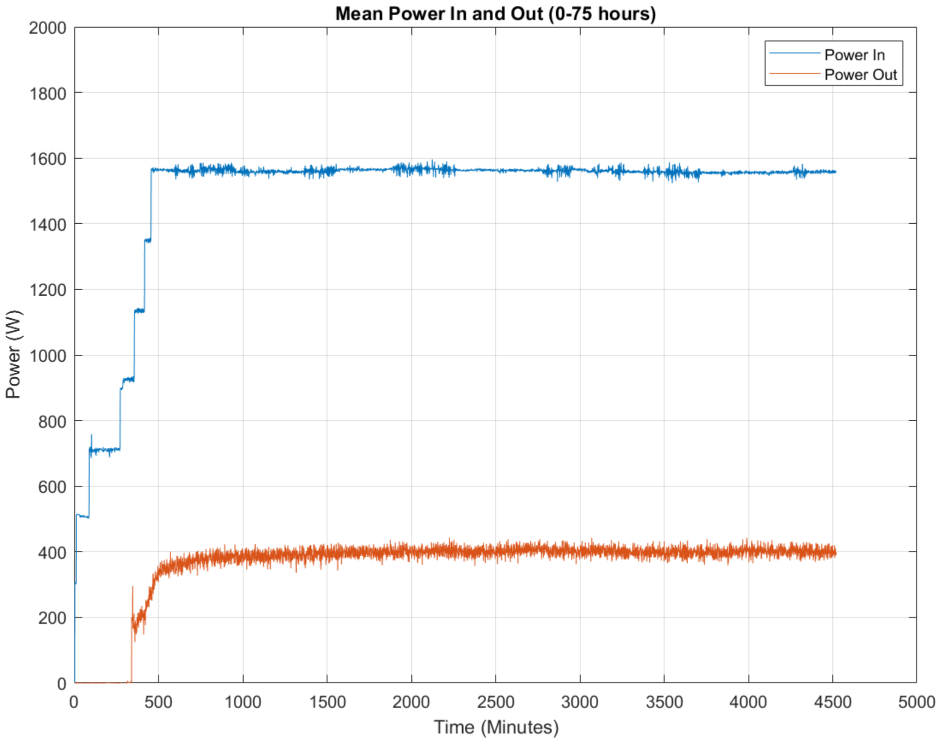

Figure 7. Mean power in and out for Hours 0–75.

Figure 8 and **Error! Reference source not found.** illustrate 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 can be found in Table 2. The power supplied at the end of the first stage was 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 and 87.4 W.

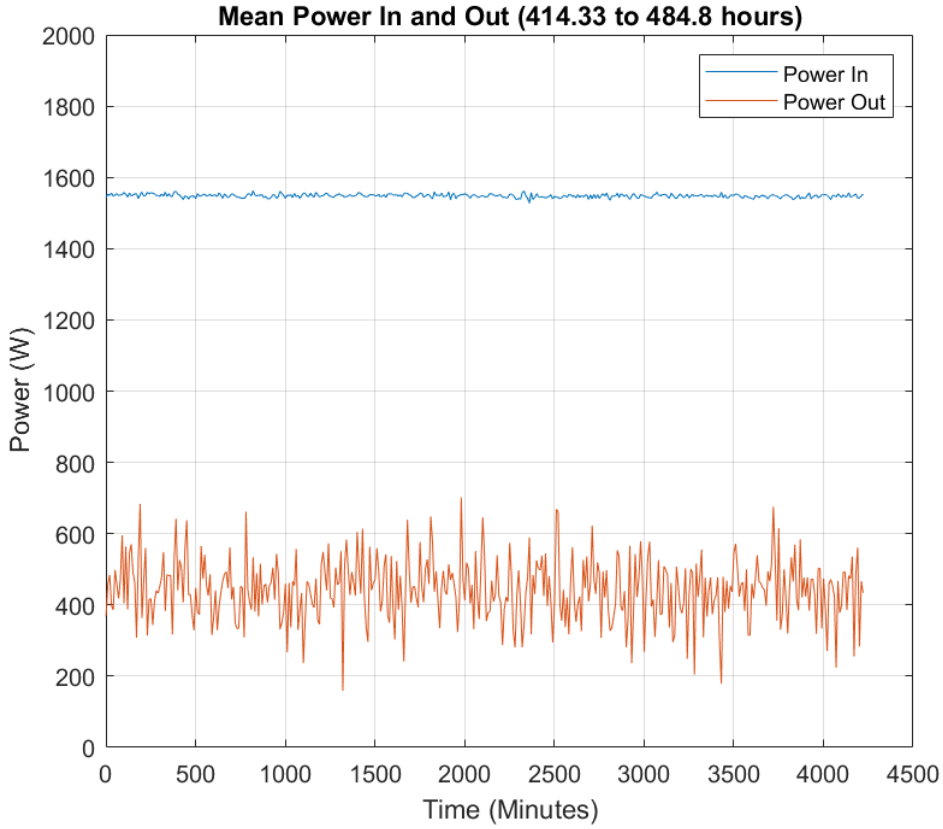

Figure 8. Mean power in and out for end of the first stage of testing (Hours 414.3–484.8).

Table 2. Power in and out and percent removed for startup and end of first stage.

	Start up	End of first stage
Average Power In (W)	1558	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. This is 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 reach 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-inch and was 230.4°C.

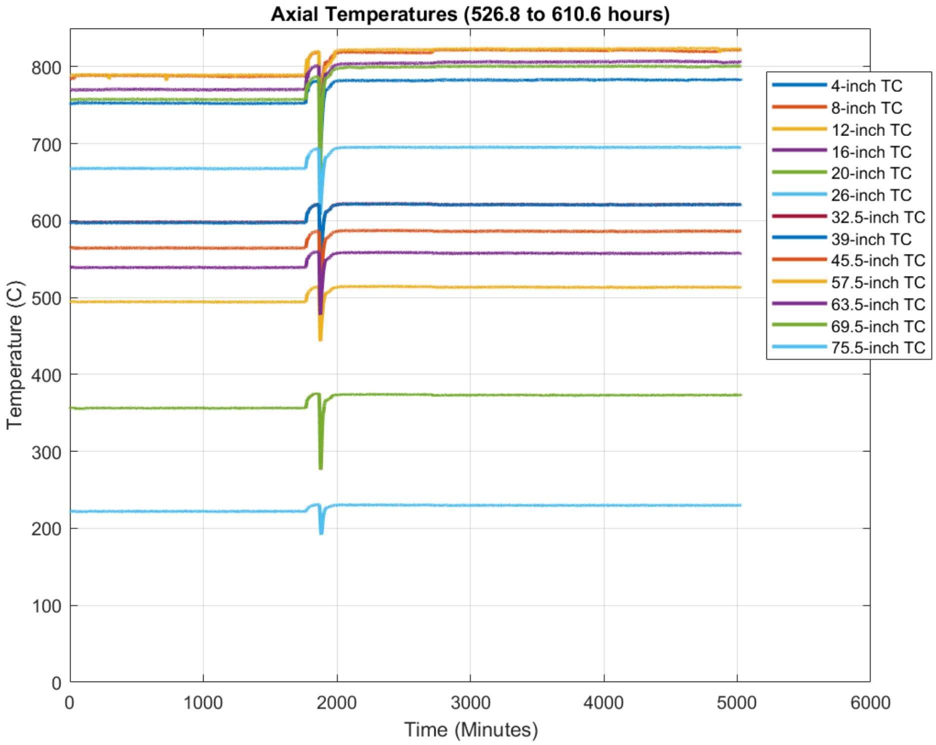

Figure 9. Axial temperatures at shift to second stage of testing for hours 526.8–610.6.

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 for a value of 824°C. The evaporator exit was at 800.5°C. The minimum temperature was 231.8°C. These temperatures resulted in a difference of 1.7, 0, and 1.4°C for the maximum, evaporator, and the minimum temperatures. This is again within uncertainty of the TCS at ±1% of actual temperature. The temperatures for the beginning and end of the second stage of testing are in Table 3.

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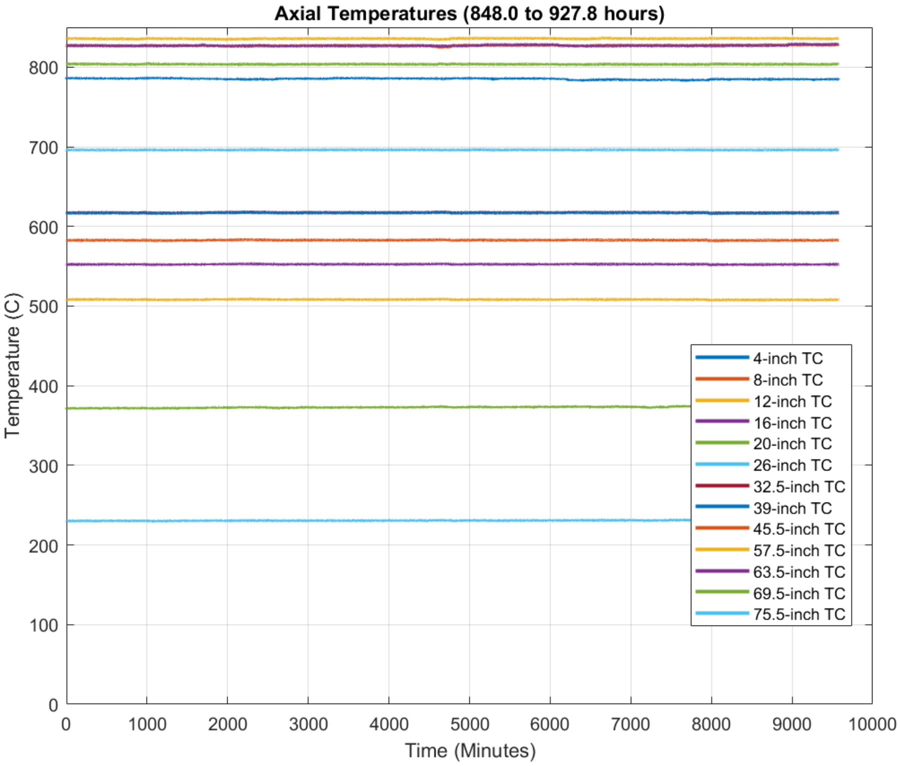

Figure 10. Axial temperatures at end of second stage of testing for Hours 848.0–927.8.

Table 3. 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 of testing. The average value of power in was 1722.8 W while the average power out was 488.3 W.

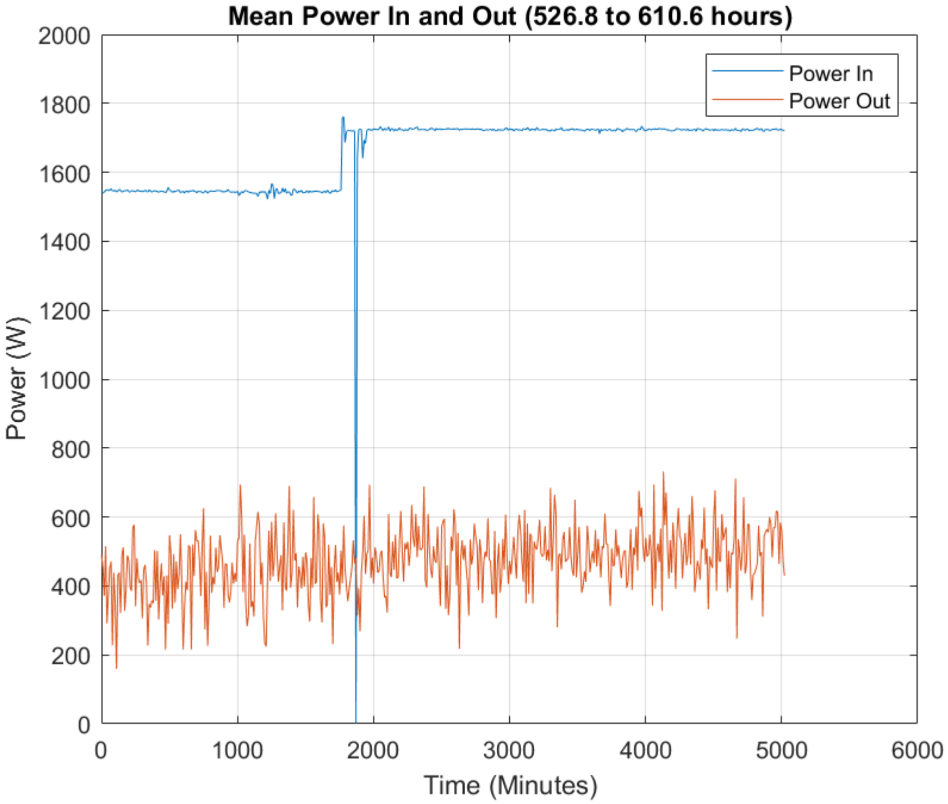

Figure 11. Mean power in and out from the calorimeter for beginning of the second stage of testing (Hours 526.8–610.6).

The power supplied to the heaters and measured power out by the calorimeter for the final portion of the second stage can be found in Figure 12. The values from this portion stayed relatively consistent from the beginning of the second stage. The power in was averaged to 1718 W while the power out was averaged to 479.1 W. The results of power in, power out, and percent of power out to in are tabulated in Table 4.

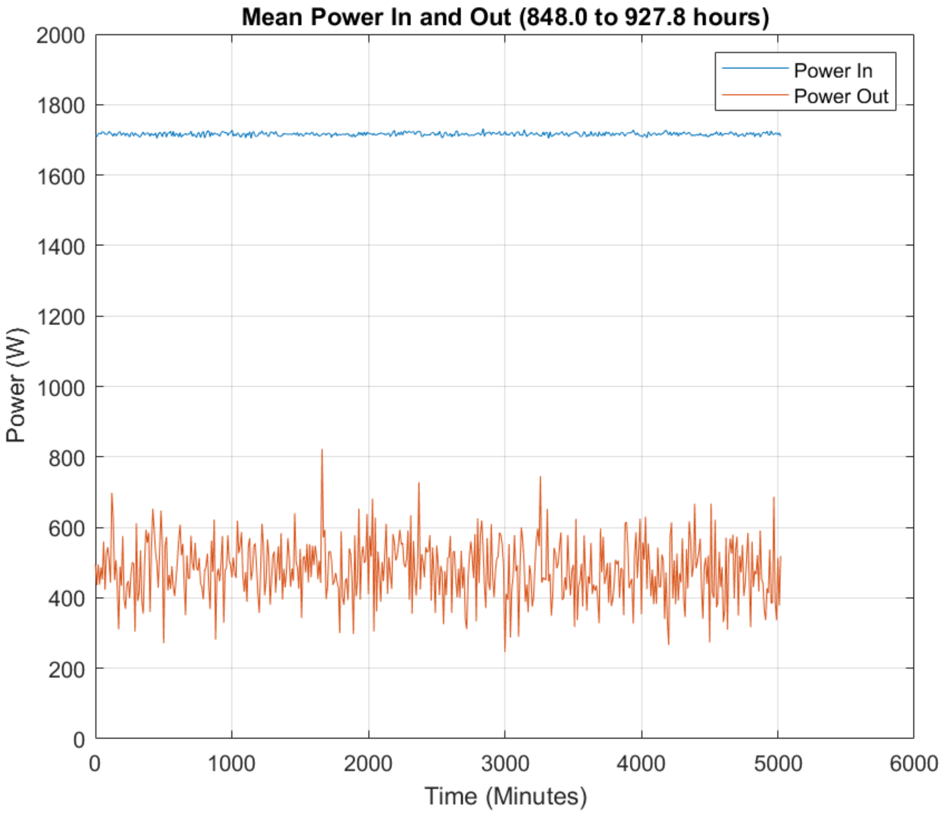

Figure 12. Mean power in and power out from calorimeter (Hours 848.0–927.8).

Table 4. Power in, out, and percentage of heat removed by calorimeter at the beginning and end of the second stage of testing.

	Startup	End of testing
Average Power In (W)	1722.8	1718
Average Power Out (W)	488.3	479.01

5. CONCLUSION

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 that closely aligns with purposed 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.

6. REFERENCES

1. SPHERE Factsheet, available on https://gain.inl.gov/SiteAssets/MicroreactorProgram/SPHERE_Factsheet_MRP_May2022.pdf