INL/CON-24-80237-Revision-0

# High Performance Heat Pipe Power Transient Testing at SPHERE Facility

November 2024

Changing the World's Energy Future

Zachary Don Sellers, Jeremy Lee Hartvigsen, Piyush Sabharwall

Idaho National Laboratory

INL/CON-24-80237-Revision-0

# High Performance Heat Pipe Power Transient Testing at SPHERE Facility

Zachary Don Sellers, Jeremy Lee Hartvigsen, Piyush  Sabharwall

November 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

# High Performance Heat Pipe Power Transient Testing at SPHERE Facility

Zachary Sellers[1], Jeremy Hartvigsen[1], Piyush Sabharwall[1]

[1]Idaho National Laboratory, Idaho Falls, Idaho,
Zachary.sellers@inl.gov

*[Placeholder for Digital Object Identifier (DOI) to be added by ANS]*

## INTRODUCTION

Microreactors are being researched, designed, and built at Idaho National Laboratory (INL). Microreactors are small reactors, defined at less than 20 MW of power. These reactor concepts are also being looked at throughout industry for various applications. An important aspect of these reactor designs is economic feasibility—i.e., lower overnight capital cost. The driving factors for implementing microreactors are quick setup and takedown, minimal operators, ready manufacture, and sizing to fit in mid-sized containers for transport. 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 partners. Because of this interest, INL developed a test facility to facilitate experimental tests—the Single Primary Heat Extraction and Removal Emulator (SPHERE) facility—to run experiments on high-performance sodium-filled heat pipes. Again, heat pipes are passive heat-transfer devices. Radially, heat pipes are broken up into an outer wall, a small annular gap, a wick structure, and a centerline gap. They function by employing latent heat transfer. Heat pipes are traditionally separated into three regions, an evaporator (heat input), an adiabatic region, and finally a condenser region (heat removal). As heat is being applied to the evaporator, the working fluid undergoes a phase change to a 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 a liquid. The wick structure is then used to drive the flow back towards the evaporator by capillary forces. This backflow is aided by the annular gap. Because this heat-transfer mechanism functions with latent heat transfer, the heat pipe is close to isothermal down the axial length.

Heat pipes can operate with a wide range of working fluids. Considerations for these working fluids are primarily driven by operating temperatures, among other important factors, based on overall performance. Sodium-filled heat pipes operate from 450 to 900°C. This temperature range works well for current microreactor designs. In conjunction with this experimental capability, INL developed modeling software to simulate heat-pipe physics within reactor cores. This modeling software, Sockeye, functions under the established INL Multiphysics Object Oriented Simulation Environment (MOOSE). SPHERE also supports Sockeye development by providing the modeling team with experimental data on an array of setup and operating parameters to support validation efforts. A power-transient experiment was performed in the SPHERE facility to continue to aid with Sockeye development. The testing followed a proposed test plan to ramp up and down the temperature of the heat pipe. Sockeye models steady-state heat-pipe operation with high accuracy, the data provided by the power transient testing are targeted to assist with the validation effort and further enhance transient-modeling capability of the tool [2]. It's worth noting that we are operating below some currently proposed heat pipe cooled microreactor conditions. This difference in specifically temperature was due to uncertainty in current Sockeye datasets. This uncertainty was found within the operating regime performed with this set of testing. The next steps for testing would be to operate at higher temperatures to continue to aid in Sockeye develop, but those higher temperature limitations correlate more with capillary limits within the heat pipes.

## RESULTS

The temperature values on the outside faces of the core block are outlined in Figure 1. The maximum and minimums for these values at the various steps are tabulated in Table I. Both the 30-minute and 10-minute hold times are shown in Figure 1. Location 2 and Location 3 are centered in the evaporator region of the core block. These regions are most representative of the microreactor core because this experimental setup represents a subsection of an actual core block. It would be anticipated that the core block will be nearly isothermal due to the symmetric heating configuration. Location 2 was selected due to the geometry of the system. Both Location 1 and Location 4 had external cooling factors to consider. In Figure 1, thermocouples C and D are at higher temperature than A and B. This is a geometry-driven interaction. The core block was positioned on two pieces of Unistrut to center the core block and heat pipe in the sanitary tubing. This configuration pressed the insulation firmly against the core block wall, allowing better thermal contact between the two materials. Another reason for this temperature difference is the larger gap between the top of the core block and the walls of the sanitary tubing. To center the heat pipe, the core block was offset slightly. The offset leads to uncertainty in the symmetry and other thermal effects for the heat-pipe core block. Figure 2 shows the temperature profile of the heat pipe in the evaporator region. Table II lays out the maximum and minimum temperatures of the evaporator region of the heat pipe. The data from these points were collected using multipoint thermocouples that were inserted into notched holes within the core block. The final temperature profile presented is the temperatures in the adiabatic region of the heat pipe shown in Figure 3. Ideally, the temperature profile for this section would be nearly isothermal. Because the heat pipe was well under operating limits, there was a large temperature drop down the axial length of the adiabatic section. This temperature drop would decrease significantly if the power input was increased. The maximum and minimum temperatures for this region are outlined in Table III.

Heat removed from the heat pipe at the condenser region was measured using a gas-gap calorimeter. This was coupled with a deltaT meter and a flowmeter to calculate heat removal. These values range from 500–700 W. The recorded power out matches the mean power input at around 15–21% of the power input. These values are consistent with previous heat-pipe experiments at the SPHERE facility. Most of the heat loss can be accounted for with the radial heating profile of the core block. The instrumentation and power wires protruding from the end of the core block also lead to significant heat losses for the system. Another reason for the low power output is the heat pipe’s operating in the lower temperature range and, therefore, at lower power.

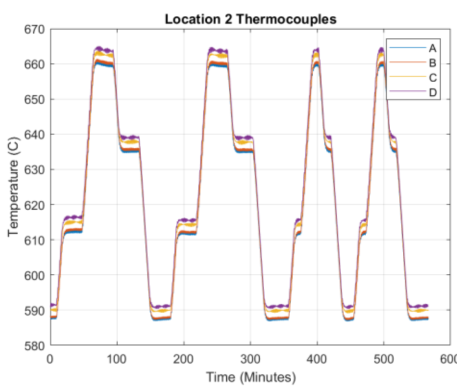


Fig. 1. Temperature profile on core block for normal operation.

Table I. Max. and min. temperature for each step for both 30-minute and 10-minute hold times (TC A–D).

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature °C | Min. Temperature °C | Step Number | Max. Temperature °C | Min. Temperature °C |
| 1 | 591.8 | 587.8 | 1 | 591.7 | 587.6 |
| 2 | 616.7 | 611.9 | 2 | 616.1 | 611.8 |
| 3 | 663.6 | 660.1 | 3 | 664 | 659.9 |
| 4 | 639.7 | 635.3 | 4 | 639.6 | 635.2 |
| 5 | 591.2 | 587.5 | 5 | 591.2 | 587.2 |
| 6 | 615.3 | 611.9 | 6 | 615.9 | 611.4 |
| 7 | 664.2 | 658.9 | 7 | 664.7 | 659.4 |
| 8 | 639.4 | 635.3 | 8 | 638.8 | 634.8 |
| 9 | 591.7 | 587.6 | 9 | 591.6 | 587.2 |

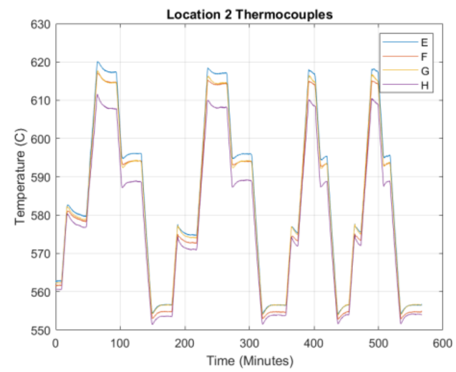


Fig. 2. Temperature profile on heat pipe evaporator for normal operation.

Table II. Max. and min. temperature for each step for both 30- and 10-minute hold times (TC E–H) during normal operation.

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature (°C) | Min. Temperature (°C) | Step Number | Max. Temperature (°C) | Min. Temperature (°C) |
| 1 | 562.9 | 560.6 | 1 | 556.6 | 553.8 |
| 2 | 582.5 | 578.9 | 2 | 576.8 | 572 |
| 3 | 620 | 607.6 | 3 | 618.1 | 588.1 |
| 4 | 596.2 | 588.8 | 4 | 595.2 | 608.7 |
| 5 | 556.5 | 553.5 | 5 | 556.4 | 588.1 |
| 6 | 577.3 | 570.9 | 6 | 577.4 | 553.8 |
| 7 | 618.4 | 608 | 7 | 519.9 | 609.2 |
| 8 | 596.1 | 588.9 | 8 | 595.7 | 588.4 |
| 9 | 556.6 | 553.8 | 9 | 556.5 | 554 |

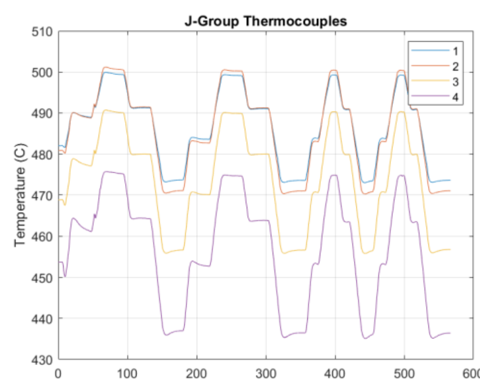


Fig. 3. Temperature profile for the adiabatic region of heat pipe for normal operation.

Table III. Max. and min. temperature for each step for both 30- and 10-minute hold times (Adiabatic 1–4) during normal operation.

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature (°C) | Min. Temperatur e (°C) | Step Number | Max. Temperature (°C) | Min. Temperature (°C) |
| 1 | 482 | 450.3 | 1 | 473.6 | 436.4 |
| 2 | 489.2 | 462.3 | 2 | 483.8 | 453.4 |
| 3 | 500.8 | 475.5 | 3 | 500.5 | 474.9 |
| 4 | 491.5 | 464.4 | 4 | 491 | 463.5 |
| 5 | 473.5 | 436.8 | 5 | 473.3 | 435.8 |
| 6 | 483.7 | 453.2 | 6 | 483.9 | 453.3 |
| 7 | 500.3 | 474.7 | 7 | 500.4 | 474.7 |
| 8 | 491.3 | 463.9 | 8 | 491 | 463.5 |
| 9 | 473.6 | 436.4 | 9 | 473.6 | 436.4 |

Figure 4 showcases temperature profiles for the heat pipe in the evaporator region for a test run with asymmetric heating at 30% power reduction. The maximum and minimum temperatures for these regions are found in Table IV. In this scenario, two heaters operated with a 30% power reduction relative to the baseline case. The reduced heat input results in Thermocouple C on the core block and Thermocouples F and G experiencing a drop in temperature relative to the baseline case. This temperature drop is consistent across the different set points and hold times.

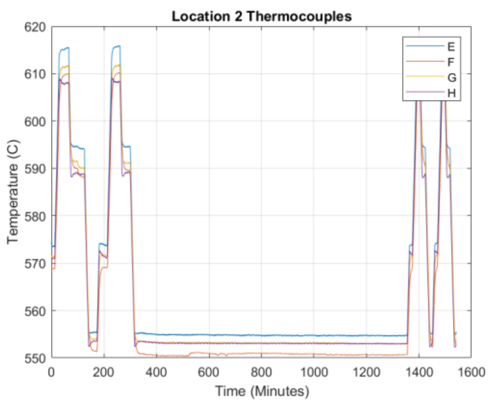


Fig 4. Temperature profile on heat pipe evaporator for 30% reduced power operation.

Table IV. Max. and min. temperature for each step for both 30- and 10-minute hold times (TC E–H) during 30% reduction case.

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature (°C) | Min. Temperature (°C) | Step Number | Max. Temperature (°C) | Min. Temperature (°C) |
| 1 | — | — | 1 | 555.3 | 550.8 |
| 2 | 573.4 | 568.9 | 2 | 573.8 | 568.9 |
| 3 | 615.5 | 608.1 | 3 | 615.3 | 607.8 |
| 4 | 594.2 | 588.1 | 4 | 594.4 | 588.5 |
| 5 | 555.5 | 551.4 | 5 | 555.2 | 552.3 |
| 6 | 574.0 | 569.1 | 6 | 574.2 | 569.2 |
| 7 | 615.7 | 608.1 | 7 | 615.5 | 608.4 |
| 8 | 594.5 | 588.9 | 8 | 594.3 | 588.7 |
| 9 | 555.3 | 550.8 | 9 | 555.1 | 552.4 |

The adiabatic region of the heat pipe for the 30% reduced-power case had a similar temperature profile to the baseline. The main differences for this case were that the temperatures recorded at each thermocouple were lower. The lower temperature is expected with the lower power output of the system. The temperature profile for the adiabatic region is shown in Fig 5, and the maximum and minimum values are tabulated in Table V.

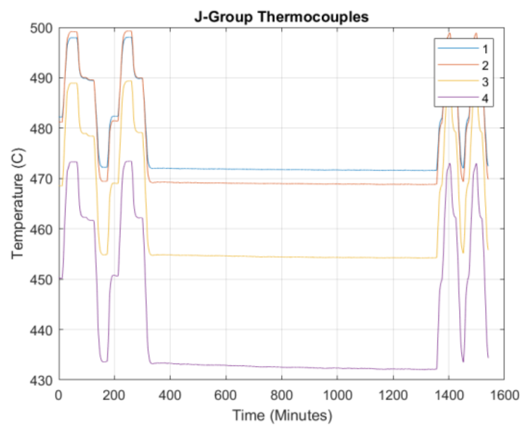


Fig 5. Temperature profile for the adiabatic region of heat pipe for 30% reduced-power operation.

Table V. Max. and min. temperature for each step for both 30- and 10-minute hold times (Adiabatic region 1–4) during 30% reduction case.

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature (°C) | Min. Temperature (°C) | Step Number | Max. Temperature (°C) | Min. Temperature (°C) |
| 1 | — | — | 1 | 472.0 | 433.3 |
| 2 | 482.3 | 450.7 | 2 | 481.7 | 449.6 |
| 3 | 499.1 | 473.3 | 3 | 498.8 | 473.0 |
| 4 | 489.6 | 461.7 | 4 | 490.0 | 462.0 |
| 5 | 472.2 | 433.6 | 5 | 472.2 | 433.5 |
| 6 | 482.3 | 450.7 | 6 | 481.9 | 450.1 |
| 7 | 499.2 | 473.2 | 7 | 498.8 | 473.0 |
| 8 | 490.0 | 462.2 | 8 | 489.8 | 462.0 |
| 9 | 472.0 | 433.3 | 9 | 472.4 | 434.4 |

The profiles mimic those of the baseline run, but at lower calculated power output. The lower power output correlates to lower temperatures found in the adiabatic region of the heat pipe. Lower temperatures in the adiabatic region indicate that less heat is transferred axially, resulting in lower power output at the calorimeter. The power output for the 30% reduction case was between 8.7 and 12.7% of the power input.

Finally, a 70% reduction case was conducted. The results closely mimicked that of the 30% power reduction, but with substantial levels of difference in temperature recorded. The results from the 70% reduction case are tabulated in Tables VII and VIII. Table VII showcases the maximum and minimum temperatures on the evaporator region of the heat pipe while Table VIII shows the temperature profile of the adiabatic region.

Table VII. Max. and min. temperature for each step for both 30- and 10-minute hold times (TC E–H) during 70% reduction case.

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature (°C) | Min. Temperature (°C) | Step Number | Max. Temperature (°C) | Min. Temperature (°C) |
| 1 | 554.8 | 552 | 1 | 550.9 | 543 |
| 2 | 569.5 | 561.1 | 2 | 569.4 | 559.9 |
| 3 | 611.7 | 601.4 | 3 | 610.8 | 599.5 |
| 4 | 591.3 | 581.5 | 4 | 590.9 | 581.4 |
| 5 | 551.4 | 543.4 | 5 | 551.4 | 544 |
| 6 | 569.8 | 561.6 | 6 | 569.9 | 560.1 |
| 7 | 612.2 | 601.1 | 7 | 611.1 | 600.3 |
| 8 | 591.1 | 581.5 | 8 | 591.2 | 582.2 |
| 9 | 550.9 | 543 | 9 | 551 | 542.9 |

Table VIII. Max. and min. temperature for each step for both 30- and 10-minute hold times (Adiabatic region 1–4) during 70% reduction case.

| 30-Minute Hold Time | | | 10-Minute Hold Time | | |
|---|---|---|---|---|---|
| Step Number | Max. Temperature (°C) | Min. Temperature (°C) | Step Number | Max. Temperature (°C) | Min. Temperature (°C) |
| 1 | 479.2 | 436.5 | 1 | 473.6 | 424.2 |
| 2 | 485.9 | 446.8 | 2 | 484 | 444.1 |
| 3 | 500.8 | 469.6 | 3 | 500.2 | 468.7 |
| 4 | 492.7 | 458.1 | 4 | 492.4 | 457.6 |
| 5 | 473.6 | 425.1 | 5 | 473.9 | 425.3 |
| 6 | 484.9 | 445.9 | 6 | 484.4 | 445.4 |
| 7 | 500.6 | 469.2 | 7 | 500.4 | 468.8 |
| 8 | 492.6 | 457.9 | 8 | 492.6 | 457.7 |
| 9 | 473.6 | 424.2 | 9 | 473.4 | 424.2 |

The heat output measured by the calorimeter mimicked the results of the 30% power reduction. The power output recorded for the 70% reduction case was between 9.6 and 14.8%. These low-power outputs are a result of the lower overall power input and temperature of the heat pipe.

## CONCLUSION

SPHERE was designed and constructed at Idaho National Laboratory for heat-pipe characteristic testing to aid in the development of a transient heat-pipe model, Sockeye. In continuation of this project, a power-transient test was performed on a high-performance heat pipe. The heat pipe was placed in a simulated subsection of a microreactor core that used cartridge heaters as simulated fuel rods. The system went through a range of temperature set points to collect data on the heat-pipe transients as it increased and decreased in temperature. This was done as a baseline, symmetric heating array, and then again with an asymmetric heating array. The different hold-time cases were the primary addition to the current Sockeye data set in order to enhance modeling capability and reduce uncertainty. The asymmetric heating data were collected as an additional data set to be supplied to the Sockeye team. Asymmetric heating profiles are important for accurate modeling because asymmetric heating can occur when heat pipes operate in this configuration. Temperature profiles were gathered for the evaporator and adiabatic regions of the heat pipe. The condenser region was equipped with a gas-gap calorimeter that was used to record the heat removed from this region of the heat pipe. These values were measured against the power input recorded by SPHERE’s watt transducers. This experiment resulted in transient data that was supplied to the Sockeye development team for further development of the transient modeling capability using the Sockeye tool.

## REFERENCES

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