Sodium Heat Pipes for Spacecraft Fission Power Generation

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This paper reports on the final stage of development of alkali metal heat pipes for the Kilopower System to be tested at NASA Glenn Research Center (GRC). Currently, fission power systems are being developed by NASA GRC for future space, Lunar and Martian surface power applications. The systems are envisioned in the 1 to 10 kWe range and address the gap between thermoelectric and fission surface power systems. The heat generated by the nuclear reactor is carried by the alkali metal heat pipes to the Stirling convertors for power generation. The entire system must be tested on Earth before launch and must be able to operate in micro-gravity, as well as on the Moon and Mars. Grooved and arterial wicks are the traditional design for heat pipes operating in micro-gravity; however, these heat pipes are not suitable for a nuclear power system since they must also be capable of operating in the following orientations: operation in space, with zero gravity; operation on earth, with a slight adverse orientation; ground testing, with the heat pipes operating gravity aided; and launch, with the evaporator elevated above the condenser. During vertical ground testing, the heat pipe wick will de-prime, and will need to re-prime for operation in space after launch. Hybrid screen-groove and self-venting arterial heat pipes were chosen for this application since they are able to spontaneously re-prime. This paper reviews the performance of self-venting arterial heat pipes, alkali metal heat pipes for ground testing, and hybrid groove-screen heat pipes developed by Advanced Cooling Technologies, Inc. (ACT) for the Kilopower system. The recently developed hybrid groove heat pipe demonstrated satisfactory performance and provided insight for improvement in future development efforts.

Nomenclature

FSPS	=	Fission Surface Power System
RPS	=	Radioisotope Power System
ACT	=	Advanced Cooling Technologies, Inc.
NCG	=	Non-Condensable Gas

1. Introduction

NASA Glenn Research Center is examining small fission power systems for future spacecraft applications and surface missions, such as the Kilopower system. These systems are designed to produce 1 to 10 kWe in order to address the technology gap between Radioisotope Power Systems (RPS), which operate below 500 We, and Fission Surface Power Systems (FSPS), which operate above 10 kWe. The Kilopower design, shown in Figure 1, utilizes alkali metal heat pipes to transfer thermal energy from the fission reactor to the Stirling convertors for electrical power generation and titanium water heat pipes to transfer waste heat to radiators for rejection to space. The Kilopower system will be designed to operate in space as well as on the Earth, Moon, and Mars. The Kilopower heat pipe must accommodate four different operating conditions:

1. Operation in space under zero-gravity. Liquid returns from the condenser to the evaporator by capillary forces in the wick.
2. Operation on earth with a slight adverse orientation to estimate zero-gravity performance. Liquid returns from the condenser to the evaporator, overcoming gravitational forces, by capillary forces in the wick. Typical adverse elevations are 0.1, 0.2, and 0.3 in.

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3. Operation on ground in an aided orientation, for system testing. Liquid returns from the condenser to the evaporator by gravitational forces.
4. Restart after launch orientation – significant adverse orientation. The wick de-primes during launch, and must re-prime in space for operation.

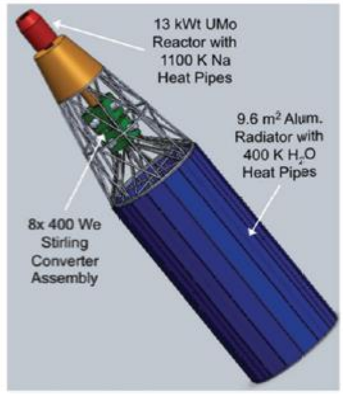

Figure 1. Kilopower 1 kWe Design.[1]

Previous surface fission designs included heat pipes that depend on gravity forces to return condensate to the evaporator, known as thermosyphons, and therefore, were unable to work in space environments; however, the Kilopower system uses wicked heat pipes enabling surface and space operation.

2. Heat Pipes Requirements

A. Heat Pipe Wicks

The length of the Kilopower alkali metal heat pipes can be up to several meters. There are four types of wicks that carry significant power over these long distances in space:

1. Arterial heat pipes with sintered powder (or screen) wicks
2. Grooved heat pipe wicks
3. Hybrid grooved screen wicks
4. Russian self-venting arterial heat pipes

In addition, the wicks must be able to re-prime after the liquid is removed from the wick, which will happen during ground testing. For ground testing, the Kilopower system will be oriented so that the heat pipes will be operating vertically as thermosyphons. In this orientation, the wicking strength is unable to overcome the gravity head of the liquid in the wick; therefore, the liquid drains from – or de-primes – the wick.

Arterial and grooved heat pipes are not suitable for this application. The arterial pipes will de-prime during testing and during launch and do not reliably re-prime. Grooved heat pipe designs that will work in space have also been developed but the grooved wick is unable to prime the evaporator in a vertical orientation, which is necessary for ground testing of Kilopower.

The two wicks that can be used for the Kilopower system are the hybrid screen-groove wick and the self-venting arterial heat pipe. The hybrid wick has a porous wick in the evaporator and grooves in the adiabatic and condenser sections. The self-venting arterial heat pipe was developed by Goncharov et al. at Lavochkin in Russia[2]. Standard arterial heat pipes utilize a single artery as well as a screen or sintered wick for liquid return. The combination of a single artery with a screen wick gives the heat pipe the benefit of a wick with high effective liquid permeability as well as a small pore size and thus a high capillary limit. When the artery is primed (full of liquid), arterial heat pipes can transfer high heat loads over long distances. On the other hand, the heat pipe fails if the artery is de-primed by non-condensable gas generation or vapor generation in the artery. These standard arterial heat pipes are not suitable for Kilopower, as discussed below, since the arteries will de-prime during ground testing. To allow the arteries to re-prime, self-venting arterial heat pipes use small venting pores that are located in the evaporator section of the heat pipe.

B. Kilopower Requirements

The heat pipes developed on the current program will be used in a 1 kWe Kilopower reactor that is being developed by NASA Glen and the Department of Energy. Table 1 gives the heat pip design requirements. The minimum power that each heat pipe must carry is 380 W, but higher powers are desirable to demonstrate operation if one of the heat pipes fail. The heat pipes must operate both as gravity aided thermosyphons and in space. Space operation is simulated by testing the heat pipes almost level, with a slight adverse elevation (0.1 in). When tested in horizontal orientation, the wick spontaneously re-primes. When tested in a vertical orientation, the wick de-primes.

Table 1. Kilopower Heat Pipe Design Requirements.

Total Thermal Power, kW	3
Number of Heat Pipes	8
Heat Pipe Power, W	380
Operating Temperature, °C	720 - 800
Working Fluid	Sodium
Envelope Material	Haynes 230
Wick Material	Stainless 316
Heat Pipe O.D., in. (cm)	0.5 (1.27)
Wall Thickness, in. (cm)	0.035 (0.089)
Evaporator Length, in. (cm)	14 (35.6)
Adiabatic Length, in. (cm)	34 (86.4)
Condenser length, in. (cm)	3.5 (8.89)

The potential working fluids in the temperature range of interest are sodium and potassium. Potassium was eliminated from consideration, since it reacts strongly with fast neutrons. Haynes 230 was chosen as the heat pipe envelope material because it has high creep strength at elevated temperatures. A schematic of the Kilopower sodium heat pipes is shown in Figure 2. The evaporator is located next to the reactor core, fitting into a semi-circular groove. The adiabatic section jogs out and then back in, around the reactor shielding. The annular heat pipe condensers are attached to a mounting plate. Heat is conducted from the condenser to the Stirling convertors through the mounting plate. This design is not thermally efficient; it was chosen so that the Stirling convertors will be easy to remove after testing. The heat pipes have a Non-Condensable Gas (NCG) reservoir to aid in startup. Given the number (8) of heat pipes required by the Kilopower system and the cost and risks associated with the wick development, it was decided that thermosyphons and wicked heat pipes will be developed. Note that the geometry of both types of heat pipes is the same, with the only difference being the wick inside the heat pipe envelope.

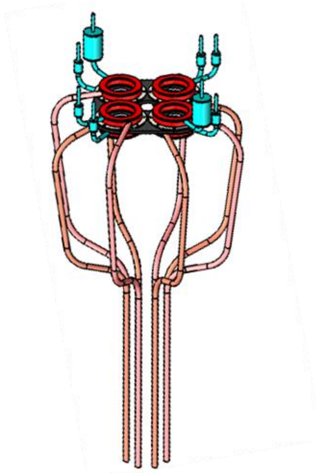

Figure 2. Kilopower Sodium Heat Pipes.

3. Self-Venting Arterial Development

A series of two self-venting arterial heat pipes were fabricated and tested. In both designs, the wick was made of stainless steel screen with a square shaped artery with venting holes in the evaporator section. The artery went the entire length of the evaporator up to the entrance of the annular condenser. The condenser wick did not have an artery. A thick layer of screen was attached to the internal adiabatic surfaces of the condenser to decrease the hydraulic resistance for the liquid return in compensation for the lack of artery. Both arterial heat pipes were tested in vacuum at 0.4 in adverse elevation, both before and after a bending process. The performance of the self-venting arterial heat pipes is summarized in Table 2.

Table 2. Summary of Self-Venting Arterial Heat Pipe Performance.

Pipe #	Performance (W)	
	Straight	Bent
1	370	210
2	405	290

As seen in Table 2, the heat pipe performance decreased after bending both pipes. Since the final performance for each pipe was below the requirements (380W), further development efforts were focused on the thermosyphons and the hybrid screen-groove wick.

4. Thermosyphon Development

As mentioned above, thermosyphons were developed for the Kilopower system in tandem with the wicked heat pipes as a low risk parallel development effort. Thermosyphons rely on gravity to drive the liquid condensate to the evaporator; therefore, they are designed for ground testing in vertical orientation. Two sets of nine thermosyphons were developed for the Kilopower system. The first set was delivered to NASA Glenn in September 2015 for testing on an electrically heated reactor core, and the second set, which included improvements to the first, was delivered in October 2016 for testing on a depleted uranium system.

The first set of thermosyphons transported heat successfully at operating temperature; however, their startup was sporadic and unstable. Startup issues are common with sodium heat pipes because of the large amount of superheat required. This is caused when the alkali metal cleans off the oxides on the wick surface, suppressing nucleation sites for boiling. Two modifications were made to the second set to improve startup behavior of the sodium thermosyphons: additional screen in the evaporator and adjustments in the geometry of the pipe to reduce the required charge volume. In the evaporator, additional screen was added, filling the inner diameter entirely except a 0.125 in diameter hole in the center for vapor venting. The additional portion of the screen has a larger pore size allowing the primary wick to retain the liquid during normal operation. The startup performance of a first generation thermosyphon is shown in Figure 3 and contrasted with a second generation thermosyphon, shown in Figure 4. The smooth startup of the second generation thermosyphon confirms the improvement made by adding additional screen to the evaporator. The instrumentation layout is shown in Figure 5.

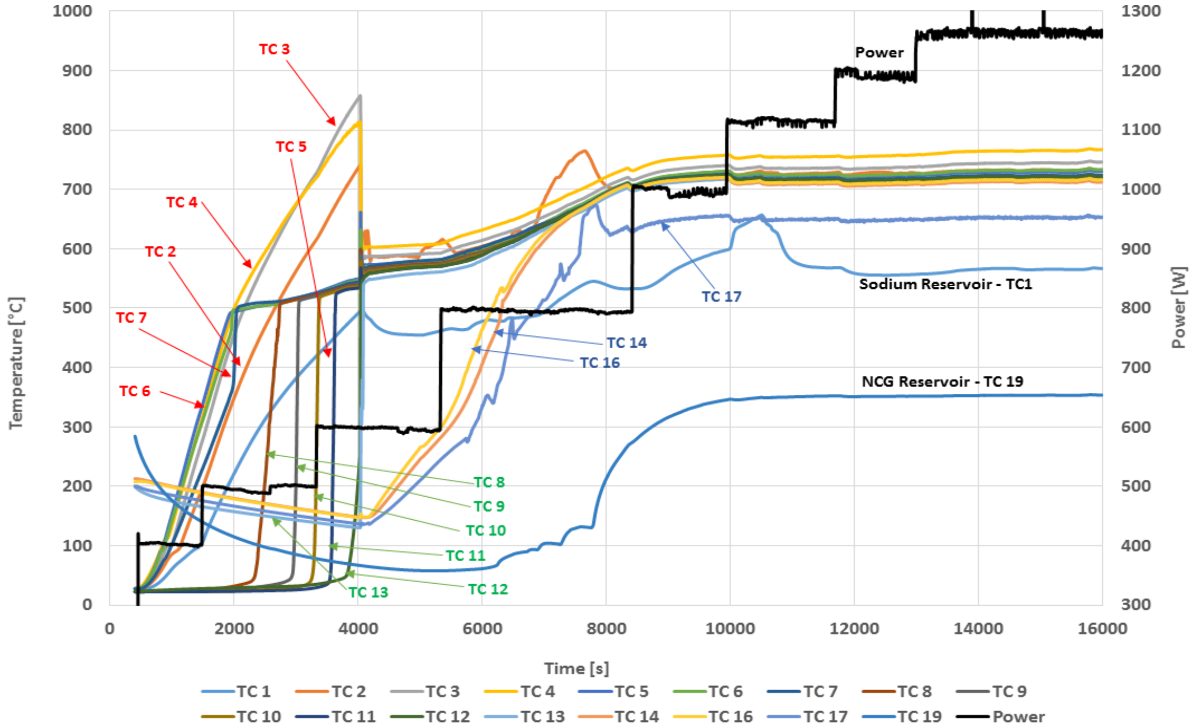

Figure 3. Startup Results of First Generation Thermosyphon.

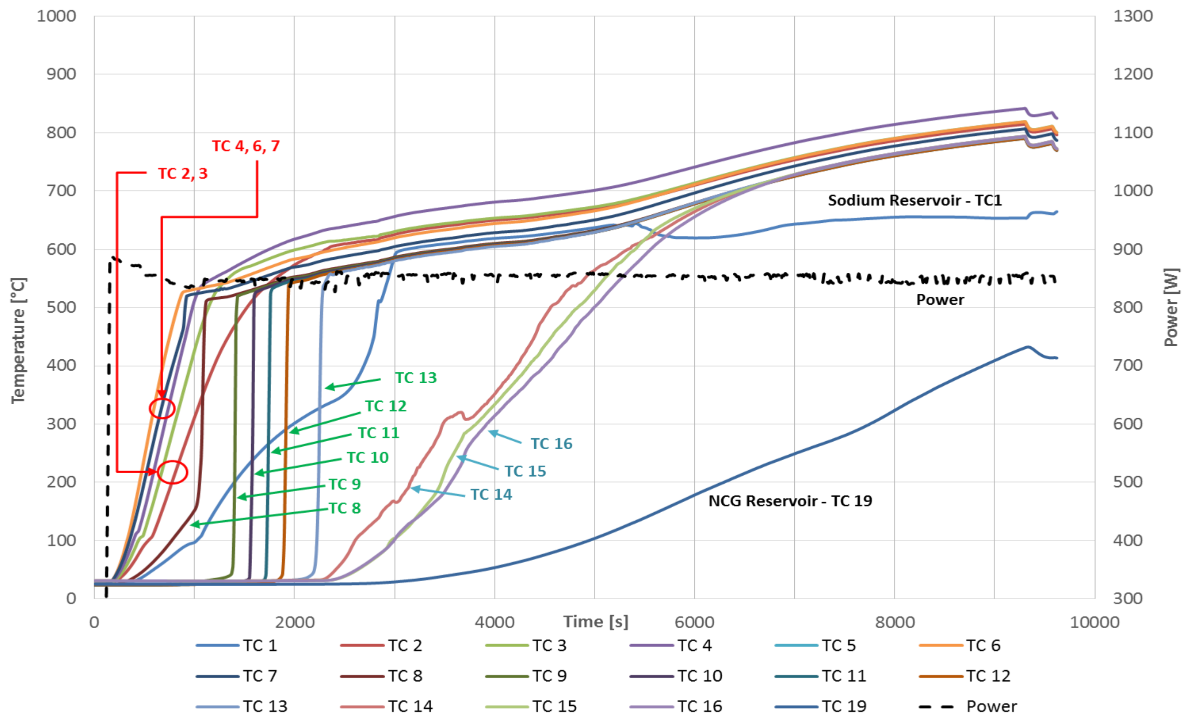

Figure 4. Startup Results of Second Generation Thermosyphon.

5. Hybrid Screen-Groove Development

Further heat pipe development efforts were focused on the hybrid screen-groove wick because of the poor performance of the self-venting arterial heat pipes. Additional groove geometries were considered; an optimal design was chosen and fabricated from 316 stainless steel. The hybrid heat pipe was fabricated in five pieces and joined together along with the annular screened condenser.

The heat pipe was charged and prepared for testing: the instrumentation layout is shown in Figure 5. The heat pipe was tested in vacuum at multiple inclinations against gravity: 0.126, 0.251, 0.419, and 0.838 in. Heat losses were determined to be 400 W at a vapor temperature of 770°C. The thermocouples were attached along the heat pipe in a different manner than the thermosyphons and self-venting arterial heat pipes. Instead of tack-welding the thermocouples to the pipe, they were bound with 316 stainless steel wire, causing a significantly higher thermal resistance (this was done to prevent hole formation during tack welding). However, the thermocouples were still tack welded to the condenser. As a result, these thermocouples had a positive bias in the evaporator and a negative bias along the adiabatic section. This is readily observed in the test results by comparing the condenser and adiabatic temperature measurements.

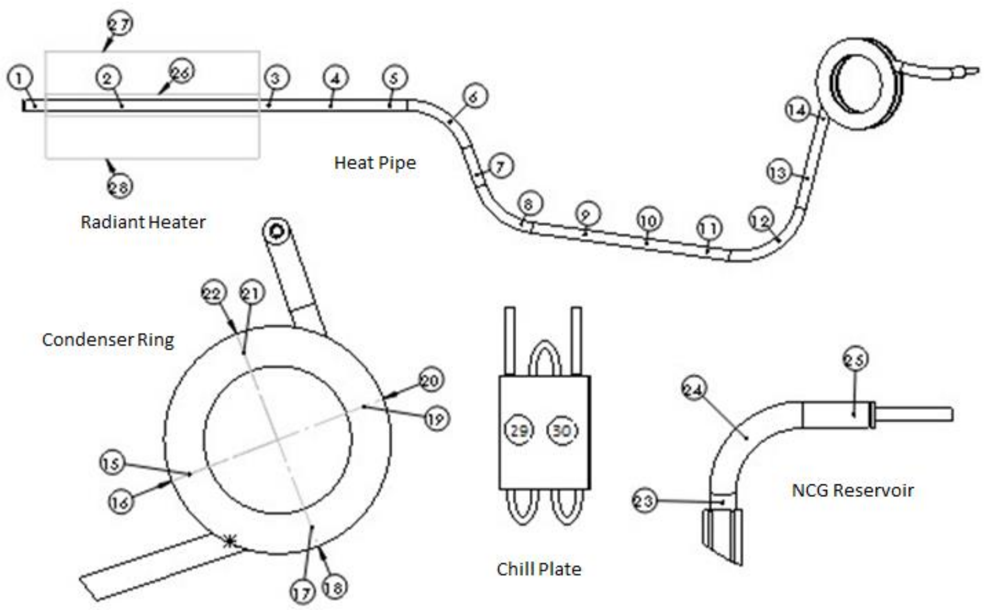

Figure 5. Instrumentation Layout of Alkali Metal Kilopower Heat Pipes.

Performance test results are shown for the hybrid heat pipe at 0.126 in adverse elevation in Figure 6. During this test, the vapor temperature was held constant at 770°C while step increases in power were applied until dryout. The net power carried just before dryout was 600 W after considering heat losses. The additional tests are plotted against prediction in Figure 7. Error bars are included for each test data point and represent the uncertainty in net power and elevation. The uncertainty in power is the difference between the dryout power and the last successful power carried. Test results show good agreement with predictions.

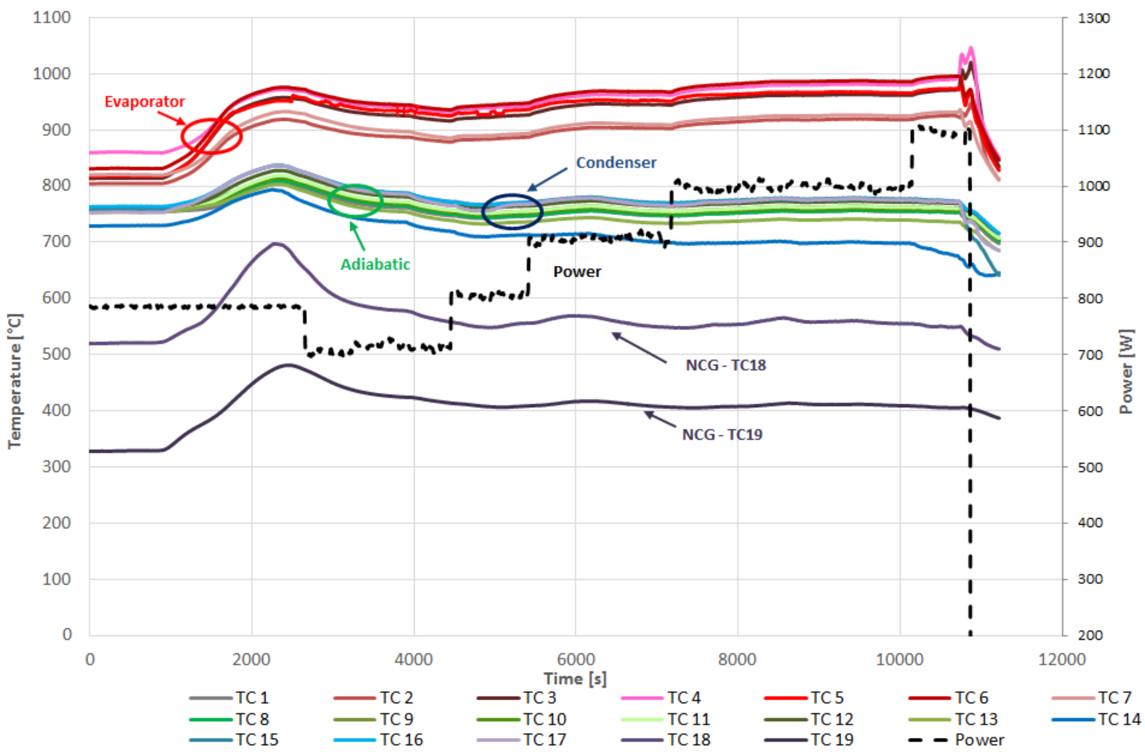

Figure 6. Performance Test Results at 0.126 in Adverse Elevation of Hybrid Screen-Groove Heat Pipe.

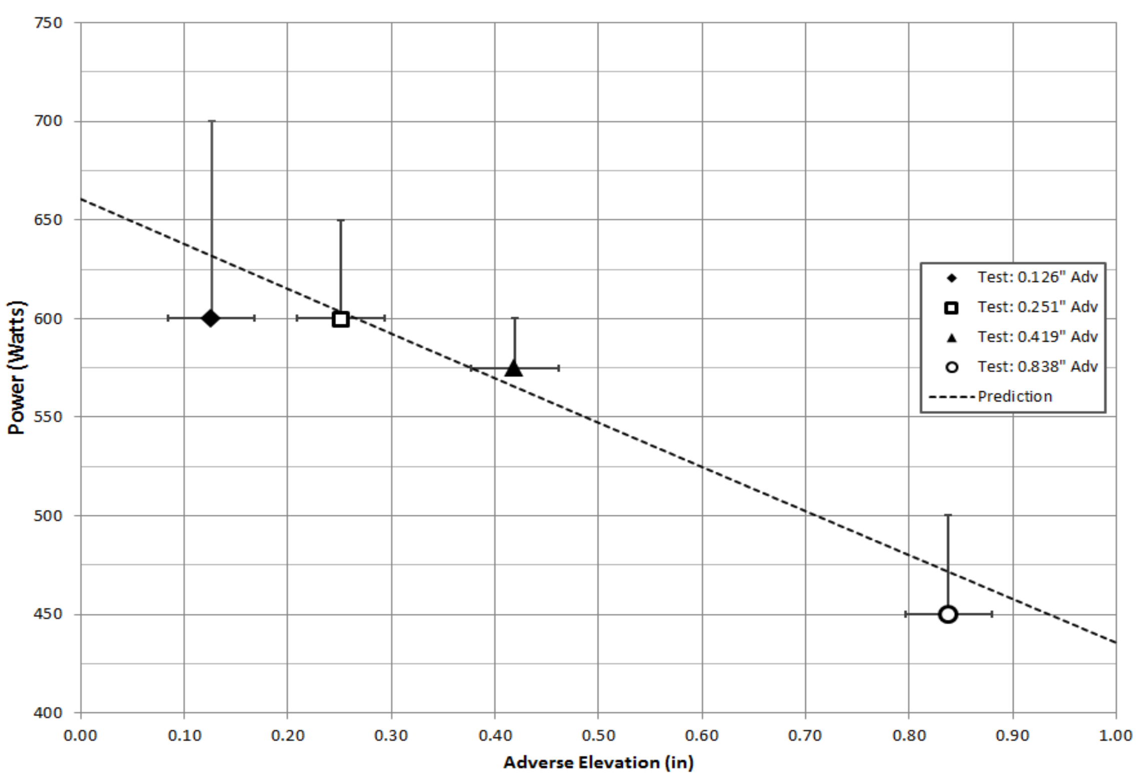

Figure 7. Performance Summary of Hybrid Screen-Groove Heat Pipe.

After testing, the hybrid heat pipe was prepared for bending. During the bending process, part of the grooved section of the heat pipe collapsed in tooling causing irreparable damage. Investigation of the failure and additional testing point to the following potential factors: improper fitment of the pipe in the bending mandrel, unfavorable material properties of the 316 stainless steel after heating to 800°C, and thinner pipe walls than the thermosyphons and self-venting arterial heat pipes. A picture of the damage heat pipe is shown in Figure 8.

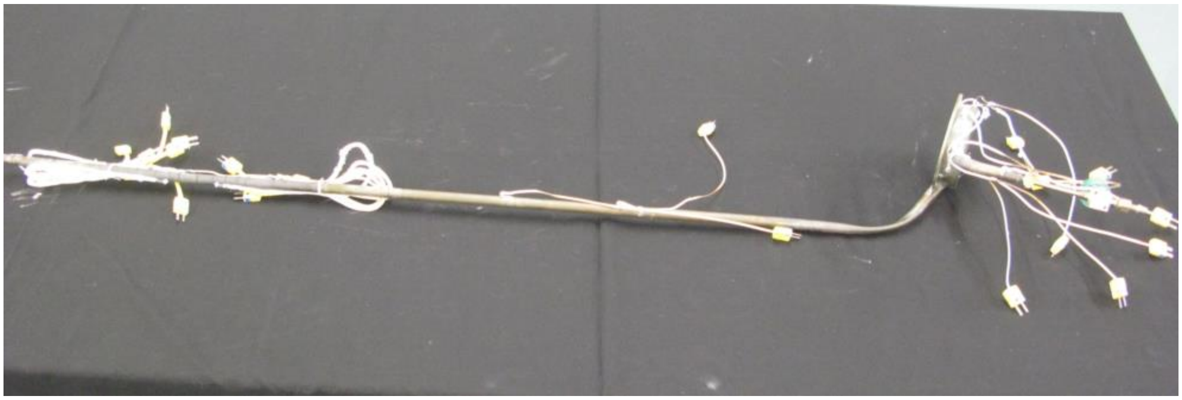

Figure 8. Picture of Hybrid Screen-Groove Heat Pipe Damaged from Bending.

Although this hybrid heat pipe collapsed during the bending process, bending grooved heat pipes is common and has a small impact on the heat transport performance. Since this heat pipe, while straight, carried power in excess of the required 510 W, it was expected that it would also meet the requirements in the bend configuration. In a future design, the heat pipe will be constructed of Haynes 230 and bent before exposure to elevated temperatures.

5. Conclusion

Several heat pipes were fabricated and tested for the Kilopower program, including self-venting arterial heat pipes, thermosyphons, and a hybrid screen-groove heat pipe. The self-venting arterial heat pipes carried sufficient power while straight, but were unable to meet the transport requirements after bending. Two sets of thermosyphons were fabricated and delivered to NASA Glenn for integration into Kilopower test setups. Startup improvements were made to the second generation thermosyphons allowing a stable and smooth startup. A hybrid screen-groove heat pipe was developed that successfully carried 600 W at an adverse elevation of 0.126 in while straight, but was irreparably damaged during bending.

NASA Glenn Research Center is currently working on a thermal vacuum test of the Kilopower fission power system. The depleted uranium system will be tested in 2017. In 2018, a second unit will be tested with a live reactor core. The second generation thermosyphons will be used for the 2018 nuclear test.

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References

[1]L. Mason, M. Gibson, and D. Poston, “Kilowatt-class Fission Power Systems for Science and Human Precursor Missions,” Nuclear and Emerging Technologies for Space (NETS-2013), Albuquerque, NM, February 25-28, 2013.

[2]T. Kaya and K. Goncharov, “Analysis of a Gas-Tolerant High-Capacity Single-Artery Heat Pipe,” 15th International Heat Pipe Conference (15th IHPC), Clemson, SC, April 25-30, 2010.