Water-Titanium Heat Pipes for Spacecraft Fission Power

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NASA is examining small fission reactors for future space transportation and surface power applications. The Kilopower system will use a nuclear reactor to supply energy to Stirling convertors to produce electricity. Titanium/water heat pipes will be used to carry the waste heat from the Stirling to a radiator, where the heat is rejected. Most current water heat pipe radiator designs are for surface fission power, and use gravity aided heat pipes (thermosyphons). The Kilopower system will be designed to operate in space, which will require a different heat pipe design than the thermosyphons used in surface applications. The heat pipe design needs to support the Kilopower system through four different operating conditions: operation in space, with zero gravity; operation on earth, with a slight adverse orientation, to estimate performance in space; ground testing, with the heat pipes operating gravity aided; and launch, with the evaporator elevated above the condenser. During the last two conditions, vertical ground testing and launch, the heat pipe wick will deprime and will need to re-prime for operation in space after launch. Two heat pipe wick designs were identified as potential candidates: grooved wick heat pipes and self-venting arterial heat pipes. In the grooved wick design a screen or sintered wick is required in the evaporator during start-up. This hybrid-wick design is necessary to supply liquid to the evaporator during vertical operation. The purpose of the self-venting arterial wick is to provide high performance in a zero gravity environment without de-priming. Grooved wick will not de-prime by nature. Two heat pipes were designed, fabricated and tested: one with self-venting arterial wick and one with a hybrid groove-screen wick. Both heat pipes successfully carried more than the 125 W required power at adverse elevation of 2.5 mm and 5 mm (to simulate operation in space). Repriming after operating as vertical thermosyphons was demonstrated, as was the ability to withstand a single freeze/thaw cycle.

Nomenclature

CCHP	=	Constant Conduction Heat Pipes
FSPS	=	Fission Surface Power System
RPS	=	Radioisotope Power System
VCHP	=	Variable Conductance Heat Pipe

I. Introduction

NASA is examining small fission reactors for future space transportation and surface power applications[2]. The Fission Surface Power System (FSPS) is designed to operate from 10 to 100 kWe while current Radioisotope Power Systems (RPS) operate below 500 We. The Kilopower system would address the power gap between current RPS and FSPS. A nominal Kilopower design is shown in Figure 1[1]. The nuclear reactor supplies energy to Stirling (or Brayton) convertors to produce electricity. Titanium/water heat pipes carry the waste heat to a radiator, where the heat is rejected.

Previous spacecraft heat pipe designs have neglected ground testability, and assumed a grooved wick. The Kilopower heat pipes must accommodate four different operating conditions:

1. Operation in space, with zero gravity. Liquid is returned from the condenser to the evaporator by capillary forces in the wick.

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2. Operation on earth, with a slight adverse orientation, to estimate performance in space. The heat pipe is operated with the evaporator slightly oriented above the condenser. The adverse orientations are typically 0.1, 0.2, and 0.3 inches.
3. Ground testing, with the heat pipes gravity aided. The heat pipes will deprime in this orientation. Liquid is returned to the evaporator by gravity; see Figure 2b.
4. Launch, with the evaporator elevated above the condenser. The heat pipes will deprime in this condition; see Figure 2a.

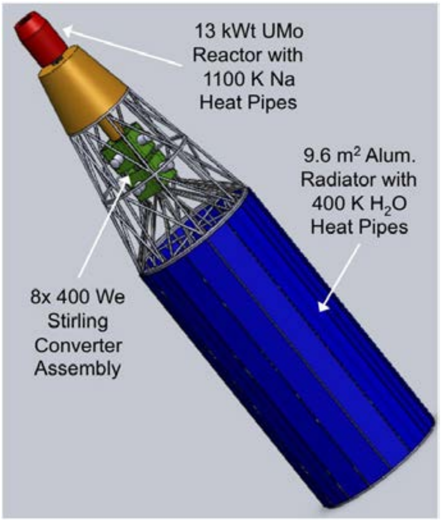

Figure 1. Kilopower system[1]

The orientation of the heat pipes during ground testing is shown in Figure 2b. The reactor (not shown) is located below the Stirling convertors. The pipes are orientated with the evaporator (by the Stirling engines) below the condenser (radiator). Water vapor travels from the evaporator to the condenser, releasing heat. The liquid condensate returns to the evaporator by gravity. During these tests, the grooves and self-venting arteries will deprime, as discussed below. A wick in the evaporator is required during start-up, to supply liquid to the evaporator during startup, before liquid drips back down from the condenser.

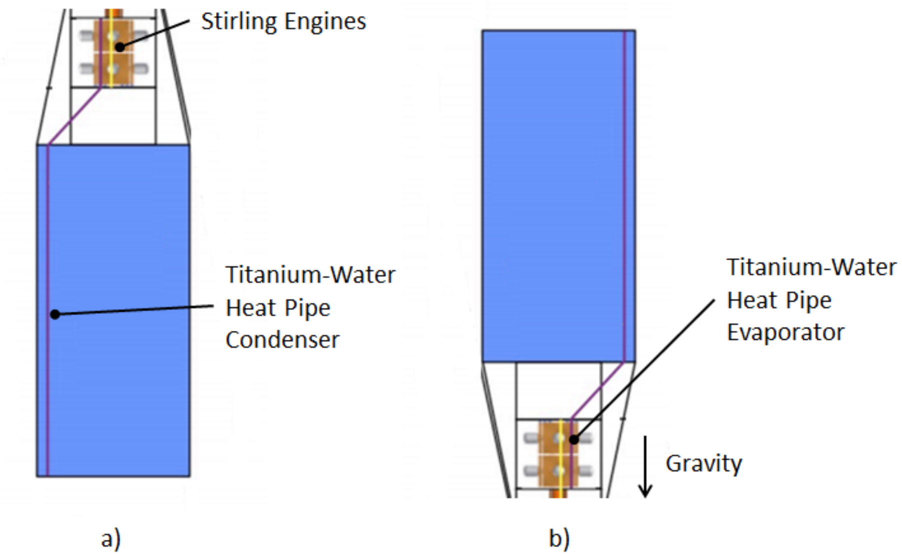

Figure 2. Two operating conditions for the Kilopower radiator: a) The pipe is oriented opposite gravity, during launch, causing the wick to deprime, b) the pipe operates gravity aided during testing.[2]

When the Kilopower system is prepared for launch, the system will be oriented such that the evaporator will be above the condenser (Figure 2a), causing the pipe to deprime. Once in space the pipe will need to reprime and begin working. The hybrid-wick heat pipe is known to reprime spontaneously. ACT performed repriming tests to verify that the self-venting arterial heat pipe will operate normally after depriming.

A. Heat Pipe Wicks

Heat pipes transport heat by two-phase flow of a working fluid as shown in Figure 3. A heat pipe is a vacuum tight device consisting of a working fluid and a wick structure. The heat input vaporizes the liquid working fluid inside the wick in the evaporator section. The saturated vapor, carrying the latent heat of vaporization, flows towards the colder condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The phase change processes and two-phase flow circulation continue as long as the temperature gradient between the evaporator and condenser are maintained.

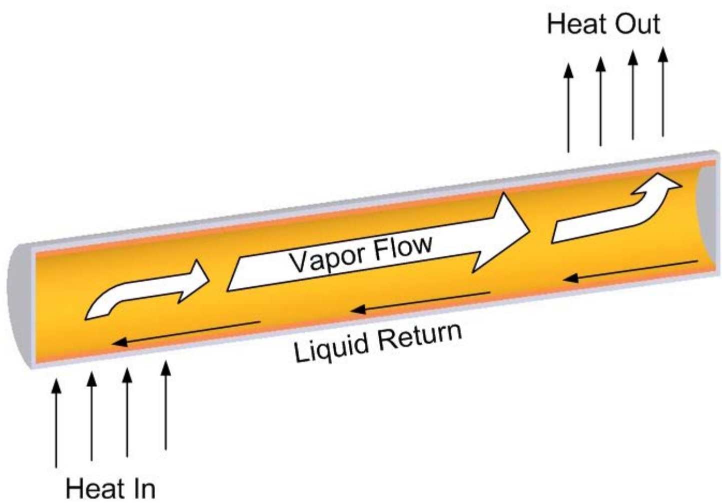

Figure 3. Illustration of heat pipe operation

The length of the Kilopower titanium/water 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.

Arterial and grooved pipes are not suitable for this application. The arterial pipes will de-prime during testing and during launch and it is not possible to reliably re-prime arterial pipes. 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 grooved/screen wick, and the self-venting arterial heat pipe.

Grooved wicks are the standard wick used in spacecraft Constant Conductance Heat Pipes (CCHPs) and Variable Conductance Heat Pipes (VCHPs). The benefit of the grooved wick is that it cannot be deprimed by vapor bubbles, since the bubbles can vent into the vapor space. These extruded grooves also have a very high permeability, allowing very long heat pipes for operation in zero-g, typically several meters long. Their only flaw is that they are unsuitable for the evaporator when the heat pipe is tested vertically on the ground. Instead, a hybrid wick is used, with grooved adiabatic and condenser sections, and a screen evaporator wick. The screened evaporator section is necessary for startup after the pipe has been deprimed or frozen.

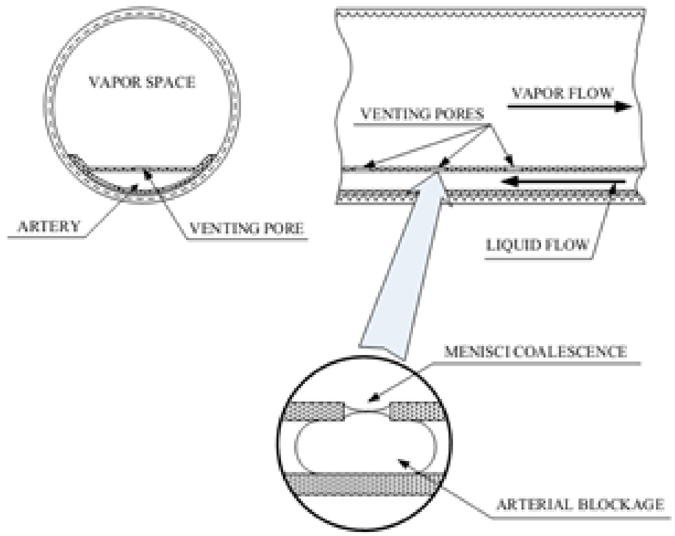

Figure 4. Russian developed self-venting arterial heat pipe with a screen wick.[3]

The second wick design ACT investigated was a self-venting arterial heat pipe developed by Goncharov et al. at Lavochkin in Russia[3]; see Figure 4. Standard arterial heat pipes utilize a single artery as well as a screen or sintered wick for liquid return. During operation, liquid condensing in the condenser flows circumferentially in the condenser to the artery. The liquid then flows through the artery to the evaporator, where the sintered (or screen) wick distributes the liquid. 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, since the arteries will definitely deprime during launch. To eliminate the de-priming problems seen in standard arterial heat pipes, self-venting arterial heat pipes use small venting pores that are located in the evaporator section of the heat pipe. If vapor or non-condensable gas (NCG) is introduced into the single artery the typical de-priming that would be experienced in a standard arterial heat pipe can be avoided due to the venting pores. The vapor blockage will travel through the artery and into the evaporator where the venting pores are located. The design eliminates the single point failure nature of previous arterial heat pipes.

B. Wick Depriming

During ground testing the Kilopower system will be oriented so that the proposed heat pipes will be operating vertically as thermosyphons; see Figure 2b. In this orientation ACT expects the wick in the self-venting pipe to deprime due to the variation in liquid pressure along the length of the heat pipe due to gravity; see Figure 8. Assume that the heat pipe is in a vertical orientation and not operating. In this case, the vapor pressure and liquid pressure at the bottom of the heat pipe are identical. As the height increases, the liquid pressure drop decreases, due to the hydrostatic head. Figure 5 shows the location along the length of the heat pipe where the ΔP between the liquid and vapor is equal:

$$\Delta P = \frac{2\sigma}{r_c}$$

where:
σ surface tension
r wick pore size

At higher elevations, vapor will be sucked into the artery, depriming it. The minimum pore thickness to avoid this depriming on earth is roughly 5 µm, much smaller than the minimum pore radius of titanium screen, roughly 110 µm. The required pore size is even smaller during launch.

One way to visualize the problem is to consider the old time water cooler, where a bottle of water is upended above a dispenser. The pressure in the water is lower than atmospheric. If a small hole was drilled into the top of the plastic, air would rush in, and water would drain out.

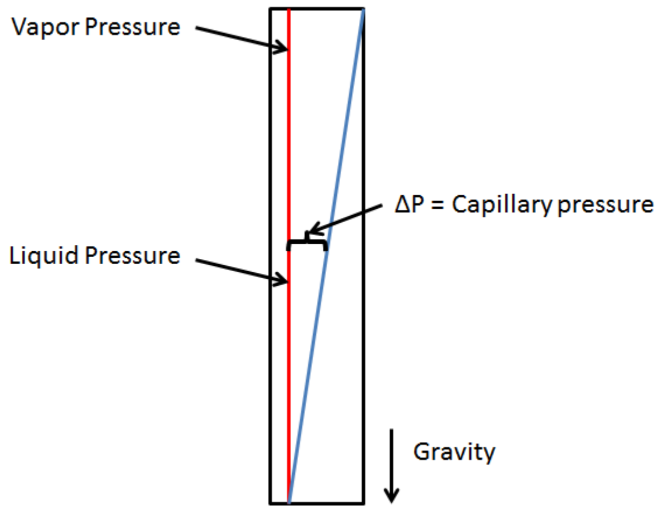

Figure 5. Vapor pressure v. liquid pressure comparison in a long, vertical heat pipe.

II. Heat Pipe Design and Fabrication

Two heat pipe configurations were designed: a self-venting arterial wick, with a screen artery and vent holes and a hybrid wick design, with a screened evaporator and grooved condenser. Both heat pipes also incorporated a reservoir (sump) at the end of the evaporator which stored any excess fluid charge during vertical operation to prevent the water from blocking the evaporator during startup.

A. Hybrid Screen – Grooved Wick Design and Fabrication

The hybrid heat pipe design used 1.27 cm outside diameter titanium tube with 0.089 cm walls. Capillary, entrainment, sonic and flooding limits were calculated for the 1.27cm OD hybrid wick heat pipe design. The heat pipe needed to function 0.508 cm against gravity for ground testing, which was accounted for in the performance calculations. The performance predictions for the 1.27 cm OD, 0.99 m long hybrid wick heat pipe can be seen in Figure 6. The designed heat pipe can theoretically carry a maximum power of 375W at the target temperature of 400K.

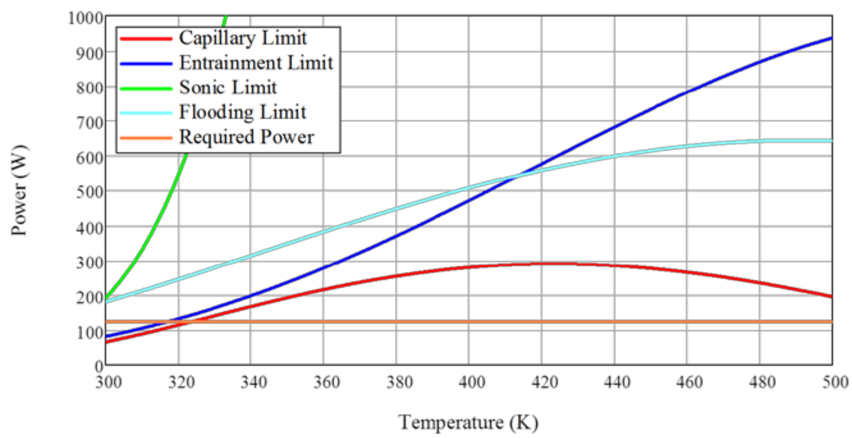

Figure 6. Performance predictions for a 1.27 cm OD, 0.99 m hybrid wick heat pipe

The hybrid heat pipe was fabricated from four grooved sections and one screened tube section. The evaporator section of the heat pipe was screened and the condenser section of the heat pipe was grooved. The groove geometry that resulted from the hybrid heat pipe design is shown in Figure 7.

Figure 7. Hybrid heat pipe groove geometry

B. Self-Venting Arterial Wick Design and Fabrication

The design for the self-venting arterial pipe used a 1.27 cm outside diameter titanium tube with 0.089 cm walls, the same dimensions as the hybrid wick heat pipe. The capillary, entrainment, sonic and flooding limits were also calculated for the 1.27cm OD self-venting arterial heat pipe design. The self-venting arterial heat pipe will need to function at 0.508 cm against gravity for ground testing, which was accounted for in the performance calculations. The performance predictions for the 1.27cm OD, 0.99 m long self-venting arterial heat pipe can be seen in Figure 8. The designed heat pipe can carry theoretically carry a maximum power of 390 W at the target temperature of 400K.

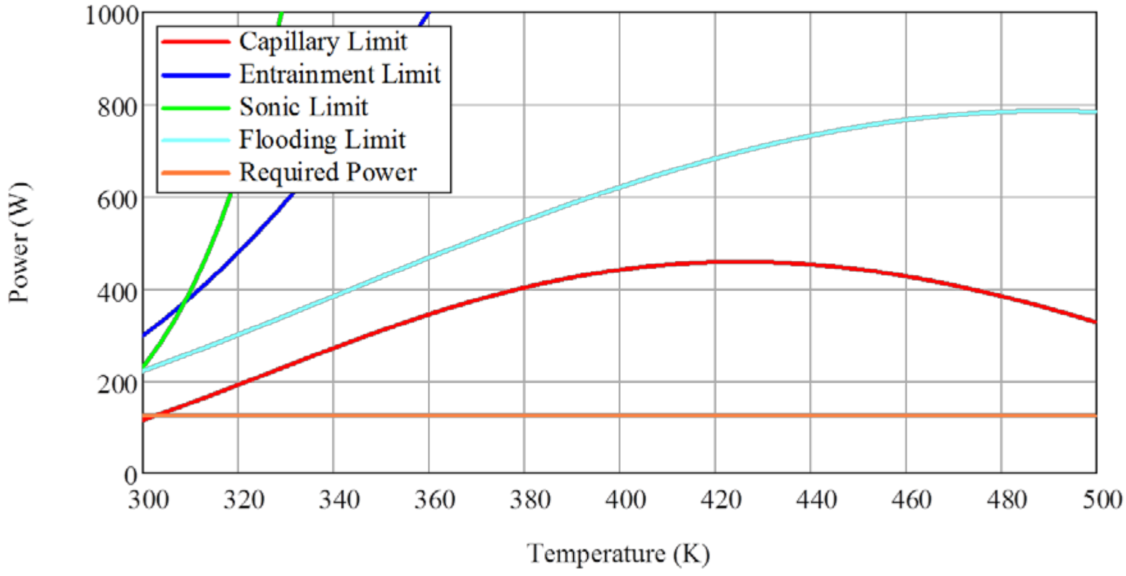

Figure 8. Performance predictions for a 1.27 cm OD, 0.99 m hybrid wick heat pipe

The self-venting arterial heat pipe was fabricated from a single 0.99 m tube with 0.089 cm walls. Included in the design is a small reservoir (sump) below the evaporator. The reservoir is used to hold the working fluid during vertical operation and freezing.

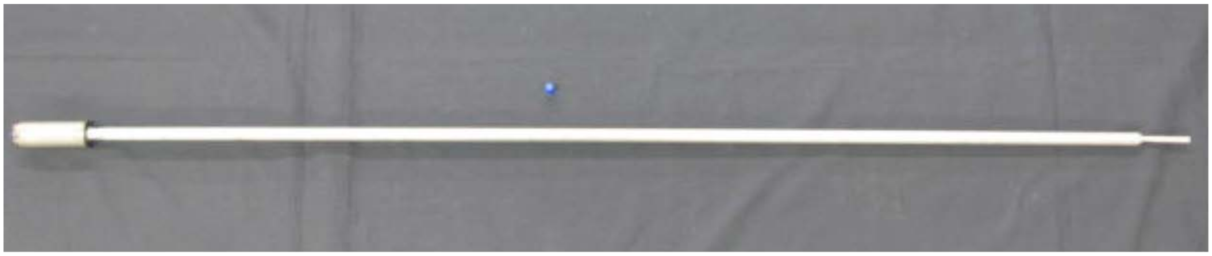

Figure 9. Fabricated self-venting arterial pipe. The exterior of the hybrid grooved/screen wick pipe is similar.

III. Test Results

The test set up was designed so that all tests could be performed with little or no modifications during testing. The heat pipe was mounted to a tilt table which allowed for testing at any angle. Power was applied to the evaporator using an aluminum heater block with four cartridge heaters. The heat pipe condenser was cooled using compressed air forced through a tube around the pipe. Both assembled heat pipes were instrumented according to the thermocouple map shown in Figure 10. Two thermocouples measured the reservoir temperature. The temperature along the heat pipe was measured every 12.7 cm, with two thermocouples at each location for redundancy. An additional thermocouple was located on the outside of the heater block, which is labeled evaporator in the results.

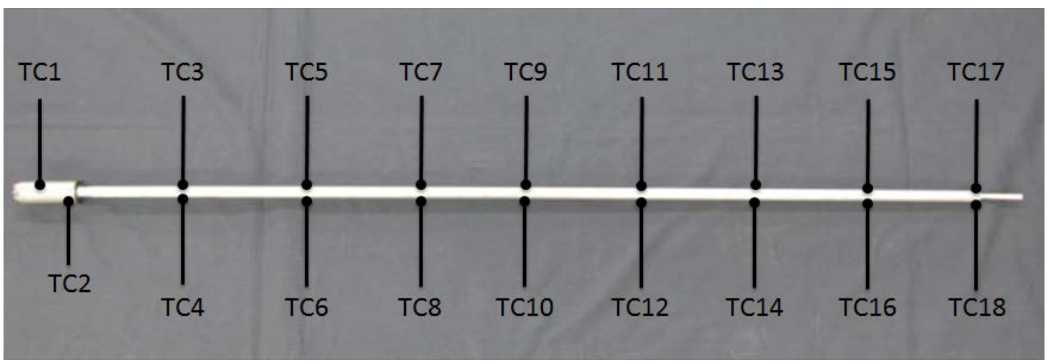

Figure 10. Thermocouple map for the self-venting arterial heat pipe

A. Self-Venting Arterial Pipe Power Test Results

To evaluate the operation of the heat pipe in space, the self-venting arterial heat pipe was tested at 0.25 cm and 0.5 cm against gravity, with the results from the 0.5 cm test presented in Figure 11. The self-venting heat pipe dried out at 225 W, which was about half of the predicted 425 W but 100 W more than the required power. The heater block temperature was also offset from the pipe temperature for most of the testing. This can be attributed to thermal resistance between the heater block and the heat pipe evaporator, which increased with temperature due to the coefficient of thermal expansion (CTE) mismatch between the aluminum block and titanium heat pipe.

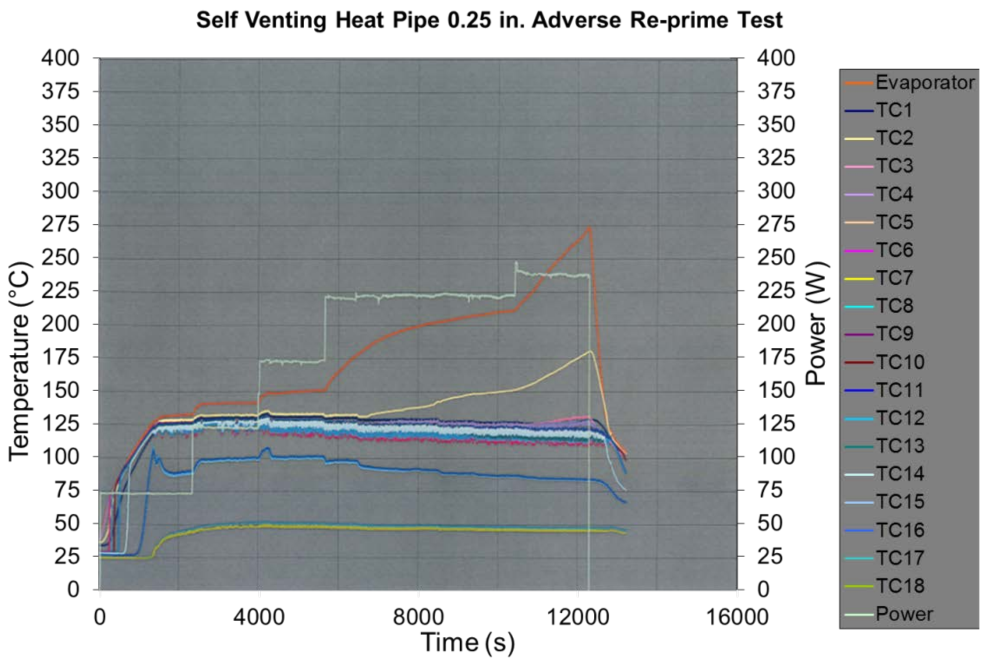

Figure 11. Test results for the self- venting arterial heat pipe at 0.5 cm adverse elevation.

B. Hybrid Screen-Groove Heat Pipe Power Test Results

The hybrid heat pipe was also tested at 0.25 cm and 0.5 cm against gravity to evaluate space performance. The results for the 0.5 cm. adverse test of the hybrid heat pipe are shown in Figure 12. At 0.5 cm adverse elevation, the hybrid heat pipe started up and reached steady state at each power increment until 150 W, when the heater block temperature became unstable. The heat pipe temperatures also started to fluctuate more than it had been seen in previous tests, with the fluctuations matching those seen in the heater block temperature. At this point the vapor temperature was reduced from 125°C to 90°C, which produced stable results. This is shown at the beginning of the data set in Figure 12. After the temperatures reached steady state, the temperature was increased while maintaining a constant power until the vapor temperature was again at 125°C. At this point the temperatures continued to be unstable for about 4000 seconds before reaching steady state, which continued until dry out at 475 W. ACT suspects this behavior is due to the pipe being undercharged, which in this case seems to be caused by fluid being trapped in the reservoir. The hybrid heat pipe carried 475 W of power, which was higher than both the predicted 375 W and the required 125 W.

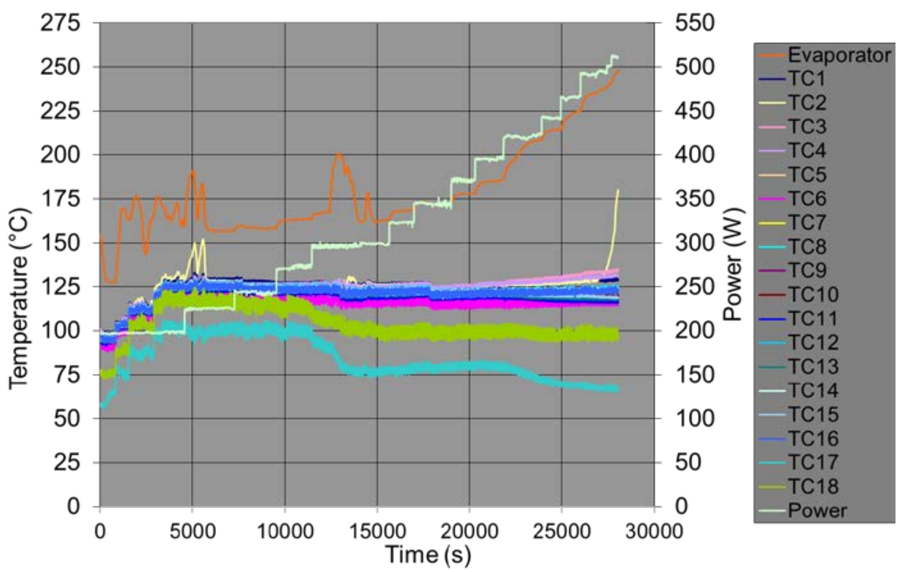

Figure 12. Test results for the hybrid groove-screen heat pipe at 0.5 cm adverse elevation.

C. Vertical Orientation and Re-priming Tests

Both heat pipe designs must operate as thermosyphons and re-prime. To test re-priming of the self-venting artery the pipe was first tested vertical and allowed to de-prime. The heat pipe was then be turned horizontal and tested to demonstrate re-priming. The hybrid heat pipe was also tested as a thermosyphon to validate the reservoir and evaporator design. The screen in the evaporator was necessary to ensure that there was a fluid supply during start up in the evaporator while the reservoir held the excess fluid inventory to prevent pool boiling.

1. Self-Venting Arterial Heat Pipe Vertical Orientation and Re-priming Tests

The self-venting heat pipe will need to operate as a thermosyphon for ground testing. Figure 13 shows the test results from the vertical orientation test. The heat pipe showed no pool boiling or dry-out in the evaporator, indicating that the reservoir and evaporator were operating as expected. The power test went up to 500 W, which was the limit for cooling with the current air cooled test set up. Throughout the testing, the temperature of the evaporator block spiked with increases in power. Again, this was due to the increase of thermal resistance between the heater block and the heat pipe.

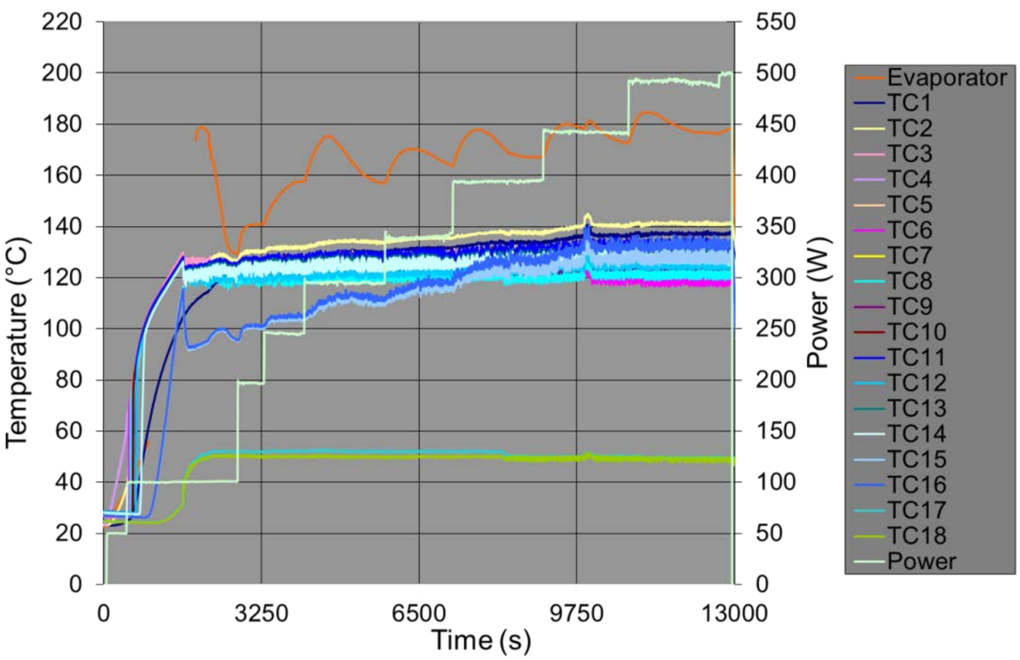

Figure 13. Self-venting arterial heat pipe thermosyphon mode test results.

After the self-venting arterial heat pipe thermosyphon mode test, the heat pipe was left in a vertical orientation overnight. For the re-priming test the heat pipe was turned to 0.5 cm against gravity orientation and power was immediately applied. The results of this re-prime test are shown in Figure 14. The heat pipe had no noticeable problems with startup and the performance matched the power test conducted before de-priming. The re-primed heat pipe dried out at 225 W, which was the same performance seen before de-priming.

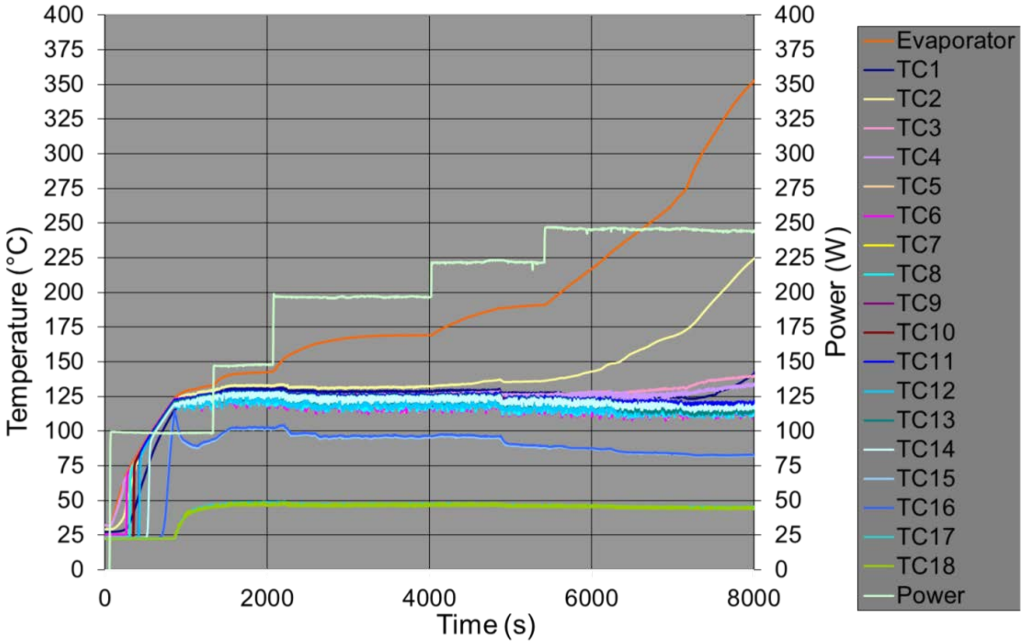

Figure 14. Self-venting heat pipe re-prime test at 0.5 cm adverse elevation.

2. Hybrid Screen-Groove Thermosyphon Test

The hybrid screen-groove heat pipe was tested as a thermosyphon to evaluate the screened evaporator during start up and normal operation. The results from the hybrid heat pipe thermosyphon test are shown in Figure 15. As in all the other tests, the heater block temperature is higher than the heat pipe temperature, due to the thermal resistance between the two. While operating as a thermosyphon the hybrid heat pipe showed no evidence of start-up issues or pool boiling during operation. The heat pipe was able to carry 500 W, at which point the cooling was becoming inadequate so the test was stopped.

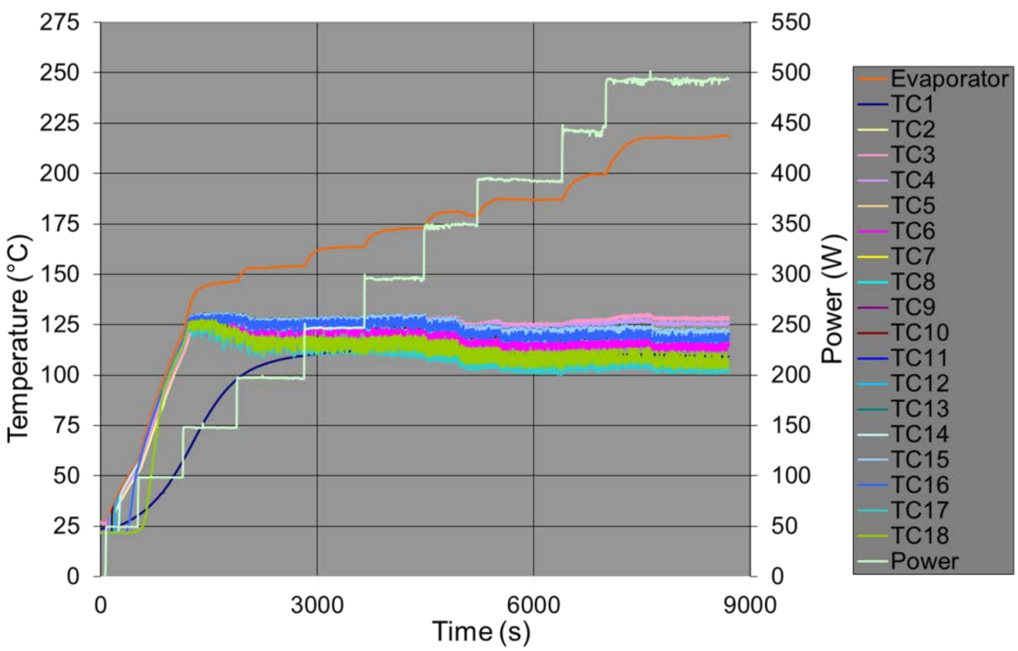

Figure 15. Test results for the hybrid heat pipe thermosyphon.

D. Freeze-Thaw Testing

ACT conducted freeze-thaw testing on both heat pipe designs. This testing was used to evaluate the response of the two wick designs to a freeze-thaw cycle. The freeze-thaw testing included short term freezing vertically with thawing at a slight adverse elevation, to demonstrate that the heat pipe can restart in space.

3. Hybrid Groove-Screen Heat Pipe Freeze-Thaw Test

The hybrid heat pipe was subjected to one freeze-thaw cycle. The heat pipe was placed in a freezer overnight in a vertical orientation so the fluid would freeze in the evaporator and reservoir. The heat pipe was then placed in the test stand at 0.25 cm adverse elevation and heat was applied. The power was ramped up just like the previous power tests and stopped at the nominal power of 125 W. During start up the heat pipe showed no problems with the liquid supply to the evaporator and showed the expected behavior as the pipe came up to the nominal temperature of 125°C. The results of the freeze-thaw test are shown in Figure 16.

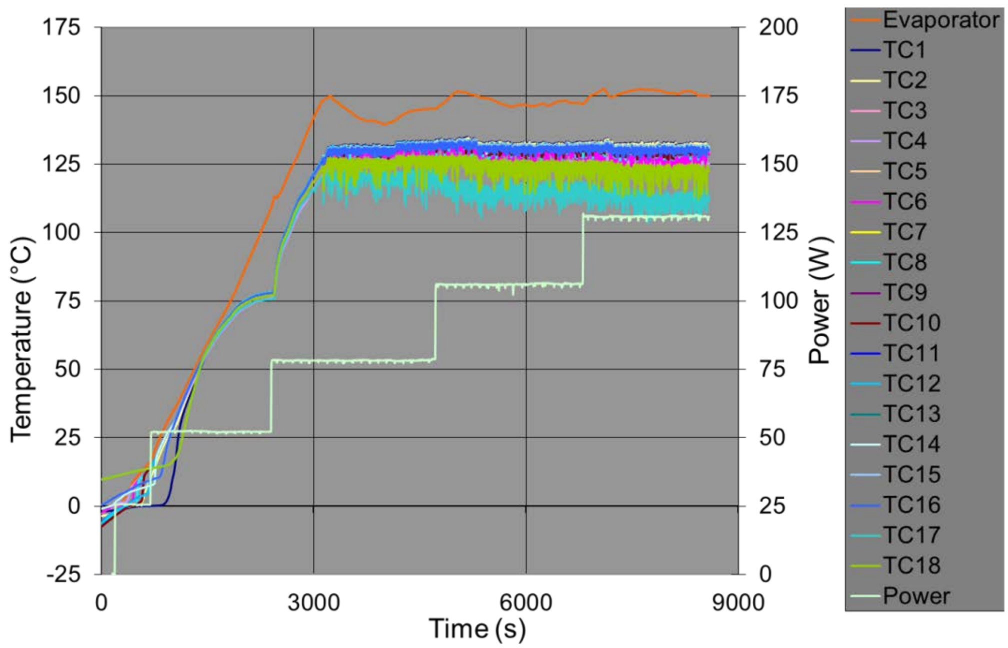

Figure 16. Test results for the hybrid grooved-screen heat pipe freeze-thaw.

4. Self-Venting Arterial Heat Pipe Freeze-Thaw Test

The self-venting arterial heat pipe was also subjected to a freeze-thaw cycle. Like the hybrid heat pipe, the self-venting arterial heat pipe was placed in a freezer overnight in a vertical orientation so the fluid would freeze in the evaporator and reservoir. The heat pipe was then placed in the test stand at 0.25 cm adverse elevation and heat was applied. The power was ramped up just like the previous power tests and stopped at the nominal power of 125 W. The test results are shown in Figure 17. During start up the heat pipe showed no problems with the liquid supply to the evaporator and showed the expected behavior as the pipe came up to the nominal temperature of 125°C. Each thermocouple was initially at 0°C and, as the pipe thawed, the temperature increased rapidly in order from the evaporator to the end of the condenser. Once the pipe was completely thawed and the operating temperature reached of 125°C, the pipe showed the same behavior seen during the initial power tests.

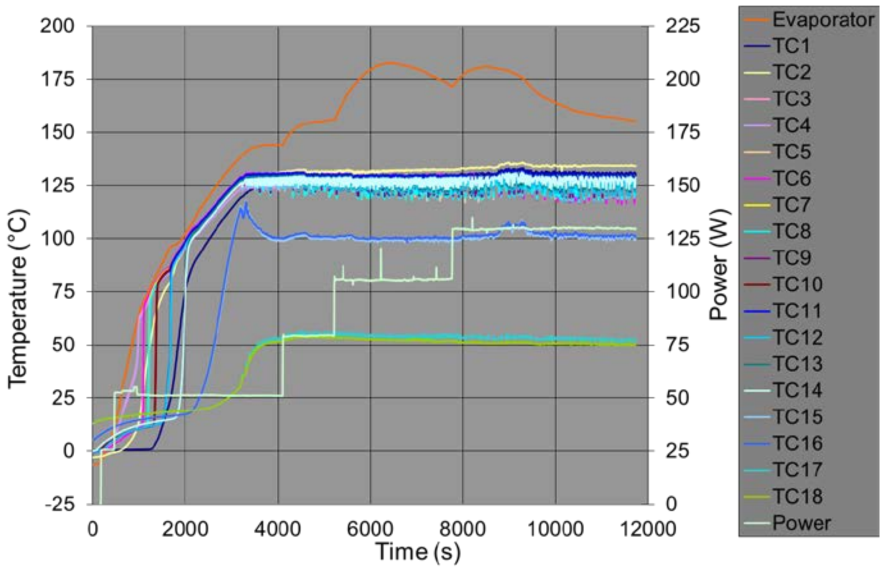

Figure 17. Test results for the self-venting arterial heat pipe freeze-thaw.

IV. Conclusion

The two heat pipe designs were successfully tested in all modes of operation: against gravity tests, vertical and re-priming tests and freeze-thaw tests. While the self-venting arterial heat pipe successfully carried more than the required 125 W at both adverse elevations, the heat pipe only carried about half of the predicted power. The hybrid heat pipe successfully carried the required 125 W at both adverse elevations and carried more power than the model predicted. During the test at 2.5 mm adverse elevation the heat pipe operated very smoothly, quickly reaching steady state and displaying a clear dry out at about 490 W. At 5 mm adverse elevation, the heat pipe did eventually operate smoothly after displaying unstable temperatures, especially in the heater block temperature. Based on the performance difference between the 2.5 mm and 5 mm adverse cases, ACT believes that at 5 mm adverse elevation the pipe may be undercharged due to fluid becoming trapped in the corners of the reservoir. The vertical and re-priming tests showed that both wick designs are suitable for Kilopower, successfully operating as a thermosyphon for ground testing and in the self-venting case, able to re-prime with no change in performance. Both pipes also underwent freeze-thaw cycle testing with no change in performance. Further research and testing is needed for both heat pipe designs to address the issues seen during the adverse testing.

The self-venting arterial heat pipe carried about half of the predicted power. The next step will be to investigate the reason for this low performance, starting with the hypothesis that the heat pipe was undercharged. This will be followed by a redesign of the heat pipe evaporators to remove heat from the Kilopower Stirling convertors. Following this, full-length heat pipes will be designed, fabricated, and tested.

Acknowledgments

This research was sponsored by NASA Glenn Research Center under Contract No. NNX14CC27P. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration. We would like to thank Maxwell Briggs who was the contract technical monitor. Tim Wagner was the technician for this project.

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]M. Gibson, L. Mason, C. Bowman, D. Poston, P. McClure, J. Creasy, and C. Robinson, "Development of NASA's Small Fission Power System for Science and Human Exploration," 12^{th} International Energy Conversion Engineering Conference (IECEC), Cleveland, OH, July 28-30, 2014.

[3]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.