High Temperature Water Heat Pipes for Kilopower System

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NASA Glenn Research Center is examining small fission power systems that address the gap between Radioisotope Power Systems (RPS) and Fission Surface Power Systems (FPS) for future spacecraft applications and Lunar and Martian surface missions. The Kilopower system, operating in the 1 to 10 kWe range, uses alkali metal heat pipes to supply heat to Stirling convertors to produce electricity and titanium water heat pipes to remove the waste heat and transport it to the radiators where it is rejected to space. The design of the heat pipes must allow for testing of the Kilopower system on earth, operation in space, survival during launch, and adverse orientations (evaporator above condenser). Advanced Cooling Technologies, Inc. (ACT) is designing and fabricating hybrid screen-groove titanium water heat pipes as solely grooved wicks are insufficient for the varied operating environments. This paper reports on the fabrication and test results for the titanium water heat pipes and radiators and future development efforts. A screened annular evaporator which interfaces to the cold end of the Stirling convertor was designed, fabricated, and welded to the grooved heat pipe previously developed. The hybrid heat pipe was then tested for heat transport capability. Heat pipe radiators were fabricated by joining solid aluminum facesheets to titanium heat pipes using S-Bond. The heat pipe radiators were cycle tested under vacuum for bond integrity and performance tested in ambient conditions for radiator effectiveness.

Nomenclature

CCHP	=	Constant Conductance Heat Pipe
FSPS	=	Fission Surface Power System
RPS	=	Radioisotope Power System
VCHP	=	Variable Conductance Heat Pipe
ACT	=	Advanced Cooling Technologies, Inc.
CTE	=	Coefficient of Thermal Expansion
NCG	=	Non-Condensable Gas

I. Introduction

NASA Glenn Research Center is examining small fission power systems, such as Kilopower, for future spacecraft applications and Lunar and Martian surface missions. These systems are designed for operation from 1 to 10 kWe 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, example shown in Figure 1, utilizes alkali metal heat pipes to transfer thermal energy from the fission reactor to the Stirling convertors for electrical generation and titanium water heat pipes to transfer waste heat to radiators for rejection to space. The Kilopower titanium water heat pipes must accommodate four different operation conditions and orientations:

1. Operation in space under zero-gravity. Liquid returns 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 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.
3. Operation on ground in an aided orientation, for system testing. Liquid returns from the condenser to the evaporator by gravitional forces.
4. Restart after launch orientation – significant adverse orientation. The wick deprimes during launch, and must reprime in space for operation.

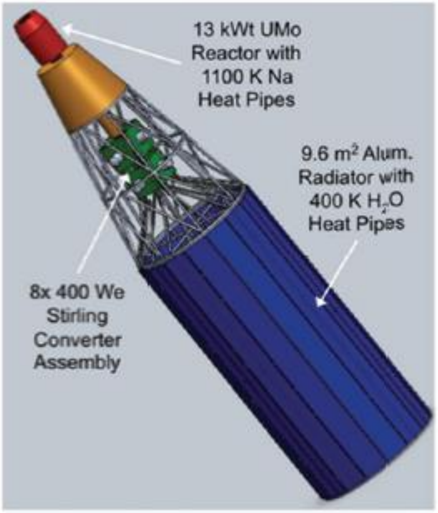

Figure 1. Kilopower 1 kWe Design.[1]

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.

A. Heat Pipes

A Heat pipe is a device with a hermetic envelope that contains a working fluid and an optional wick structure. Incoming heat in the evaporator vaporizes the working fluid which expands towards the condenser carrying latent heat. Once there, the vapor condenses to liquid, rejecting the latent heat. Finally, the liquid returns to the evaporator by gravity (thermosyphons) or a wick structure by capillary forces in a wick (heat pipes). The fluid circuit continues while a temperature gradient persists between the evaporator and condenser. Since the working fluid within the heat pipe is at saturated conditions, the temperature gradient within the heat pipe from end to end is generally less than 2°C.

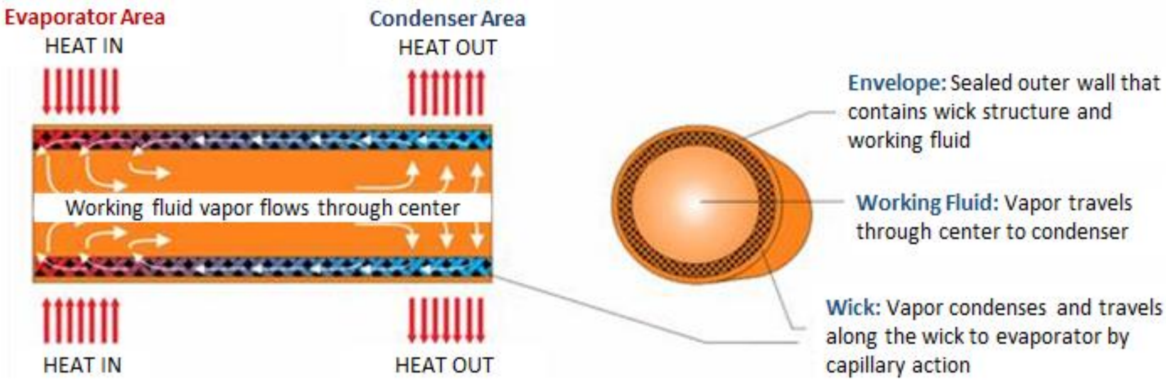

Figure 2. Illustration of Heat Pipe Operation.

B. Downselection of Kilopower Heat Pipe Wicks

In previously reported research[2], Advanced Cooling Technologies, Inc. (ACT) identified and demonstrated two suitable wicks for Kilopower: a self-venting arterial wick and a hybrid screen-groove wick (shown in Figure 3). Test results indicate both designs met requirements in all modes of operation: against gravity, vertical and re-priming, and freeze-thaw. While the self-venting arterial heat pipe successfully carried more than the required 125 W at both slight-adverse elevations, it significantly fell short of predictions, indicating a problem with the manufacturing of the heat pipe or the original model. The hybrid screen-groove heat pipe successfully carried the required 125 W at adverse elevations and more power than predicted. In response to these results, the hybrid screen-grove wick was selected for further development for the Kilopower system.

a) Hybrid Screen-Groove **b) Self-Venting Arterial**

Figure 3. Heat Pipe Wick Structures Evaluated for the Kilopower Program.

II. Heat Pipe Development and Fabrication

The hybrid screen-groove heat pipe removes heat from the Stirling convertor and the rejects it to the radiator panel and is made up of four major components: the evaporator, accumulator, grooved pipe, and a Non-Condensable Gas (NCG) reservoir. The evaporator is a semi-annular screened envelope that mounts to and removes heat from the Stirling convertor. The accumulator is located within the evaporator envelope, but in an adiabatic region, and is sized to store all of the working fluid in the grooved section. The grooved pipe is routes from the evaporator to and along the radiator panel where the heat is rejected to space. In addition, the grooved pipe extends past the radiator to make a reservoir for Non-Condensable Gas (NCG) which is used to prevent vapor from freezing in the grooves during extreme startup or shutdown.

A. Groove Design

The grooved section of the heat pipe previously demonstrated was further refined for mass reduction and higher transport capability during this research period. Toward this end, a parametric model was developed to determine the optimal screen-groove wick structure regarding heat transport capability, temperature gradient, mass, and cost. After selection of the optimal design, a 48 in sample was fabricated and tested to validate the model. This was accomplished by a series of transport tests, varied by temperature and elevation against gravity. The heat pipe was instrumented and tested at 100, 120, and 140°C vapor temperature and at 0.1, 0.2, and 0.3 in against gravity orientation. The test results in Figure 4 show agreement with the model within 20%.

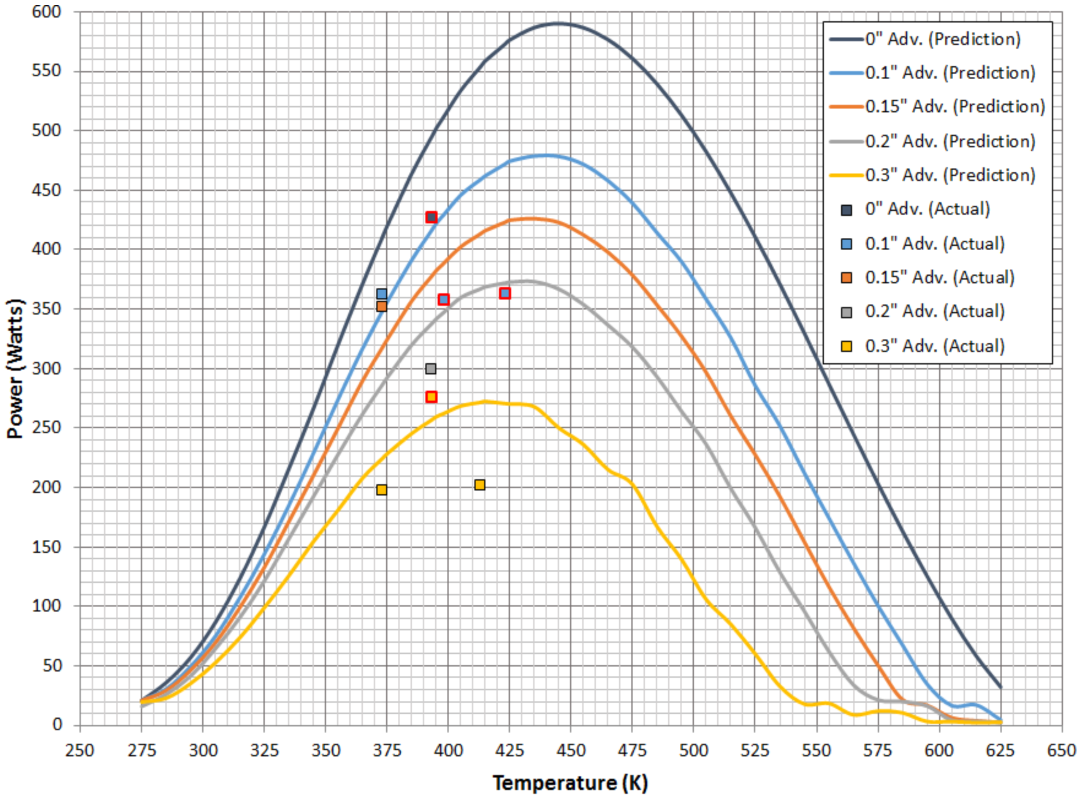

Figure 4. Test Results vs. Predictions for Downselected Grooved Heat Pipe Design.

B. Groove Bending

The Kilopower heat pipe was bent in order to interface with the Stirling convertor and radiator, since they are not in the same plane. Bending introduces local stresses that can lead to unattractive deformations or weakening or failure of the envelope. The success of the bend is mainly determined by the bending process and pipe geometry (such as the outer diameter, wall thickness, and wick structure). A more robust geometry usually requires trades with mass and transport capability while an improved bending process can allow for smaller mass and higher heat transport. In certain heat pipe applications, the pressure vessel determines the limiting geometry instead of the bending process, but not here because of the relatively low saturation pressure of water and the high yield strength of titanium.

a) Novel Bending Process **b) Traditional Bending Process**

Figure 5. Comparsion of Bending Processes for Titanium Tubing

During this research, a novel bending process was developed that provides a 41% mass reduction while maintaining the integrity of the envelope. Figure 5 compares two 0.625 in diameter samples of titanium tubing with 0.020 in wall thickness by bending process. Figure 5a shows the novel bend process sample has a smooth bend with little change in cross-sectional geometry, contrasted with the traditional bend sample, Figure 5b, that has a crumpled envelope throughout the bend.

C. Hybrid Screen-groove Fabrication

The hybrid screen-groove heat pipe design is constructed from four 12 in sections of grooved 0.625 in outside diameter titanium tube with 0.02 in walls that are joined together and the screened semi-annular evaporator for the Stirling convertor. The evaporator is cylindrical with two internal wicks: a fine screen for pumping liquid to the heat transfer surface and a coarse screen for liquid storage when the heat pipe is not operating, called the accumulator. Therefore, the hybrid screen-groove heat pipe has three wick structures in total: grooves, fine screen in evaporator, and an accumulator within evaporator; these are shown in Figure 6. The accumulator's purpose is twofold: (1) store liquid when the sink temperature drops below the freezing temperature of water in order to prevent damage to the grooves from liquid to solid expansion, and (2) ensure sufficient liquid in the evaporator during startup. The accumulator is sized to hold the entire liquid volume in the grooves.

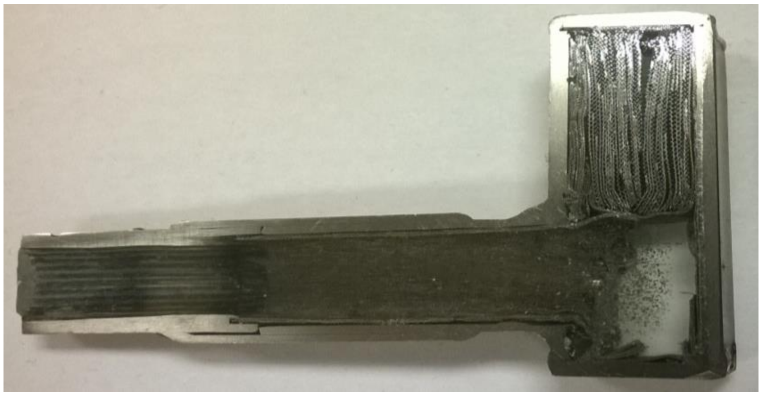

Figure 6. Cross-section of Evaporator, Accumulator, and Groove Components.

III. Heat Pipe Test Results

The test setup for the hybrid heat pipe was designed so that little to no changes were required between the tests. The hybrid heat pipe was mounted to a tilt table and instrumented with type T thermocouples. Power was applied to the heat pipe by an aluminum heater block with four cartridge heaters. Aluminum blocks with coolant passages for nitrogen were used to remove heat from the heat pipe in place of radiators. The heat pipe was instrumented according to Figure 7.

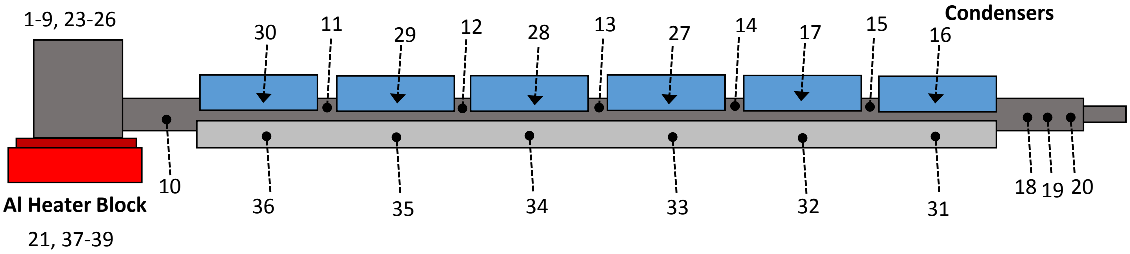

Figure 7. Thermocouple Layout for Hybrid Screen-Groove Heat Pipe.

A. Power Test Results

In order to evaluate the performance in space, the heat pipe was tested at an adverse inclination of 0.1 in and 0.2 in, with the results from the 0.1 in shown in Figure 8. The hybrid screen-groove heat pipe showed signs of parital dryout at 450 W (at about 1050 sec) with the divergence of thermocouple 9; however, this is well above the nominal design power of 125 W and the required power of 250 W for adequate margin.

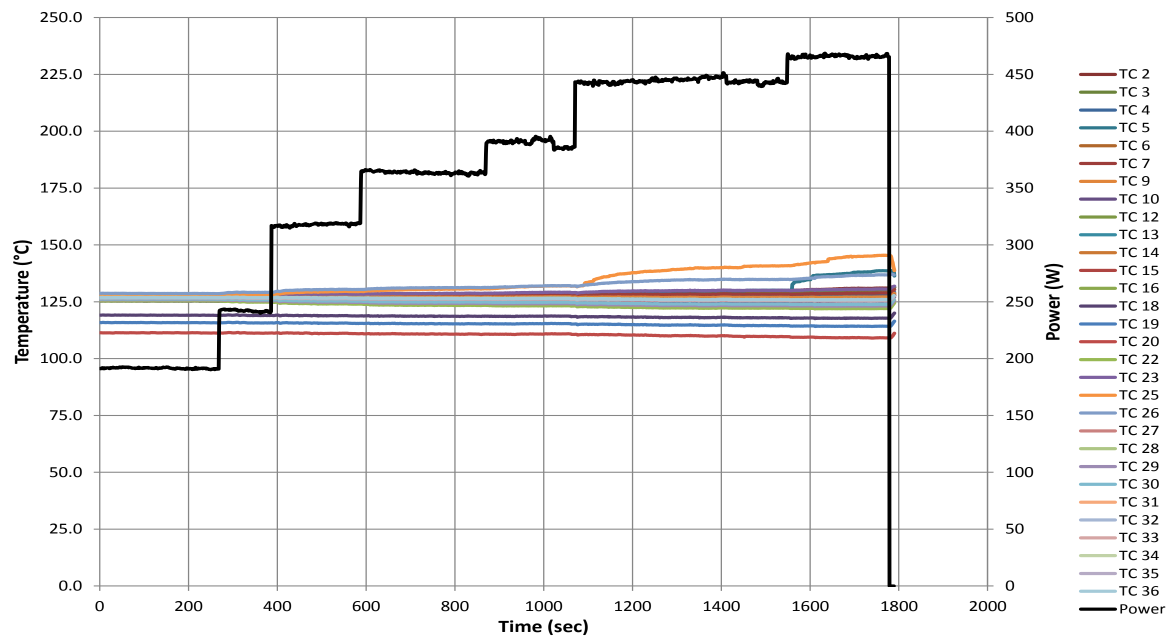

Figure 8. Performance Test of Hybrid Screen-Groove Heat Pipe.

B. Vertical Orientation and Re-priming Tests

The heat pipe was oriented vertically, with the condenser above the evaporator, in order to simulate the ground testing of the Kilopower system. In this orientation, the heat pipe is acting as a thermosyphon, where gravity is driving the liquid return from the condenser to the evaporator; however, before operation begins, the grooves deprime since their wicking potential is unable to overcome the gravity head and the liquid coalesces into a puddle at the bottom of the heat pipe. This puddle can lead to pool boiling or flooding when the thermosyphons begin operating, causing a high temperature gradient or heat transport limitations. The accumulator prevents these phenomena by storing the puddle as seen in Figure 9.

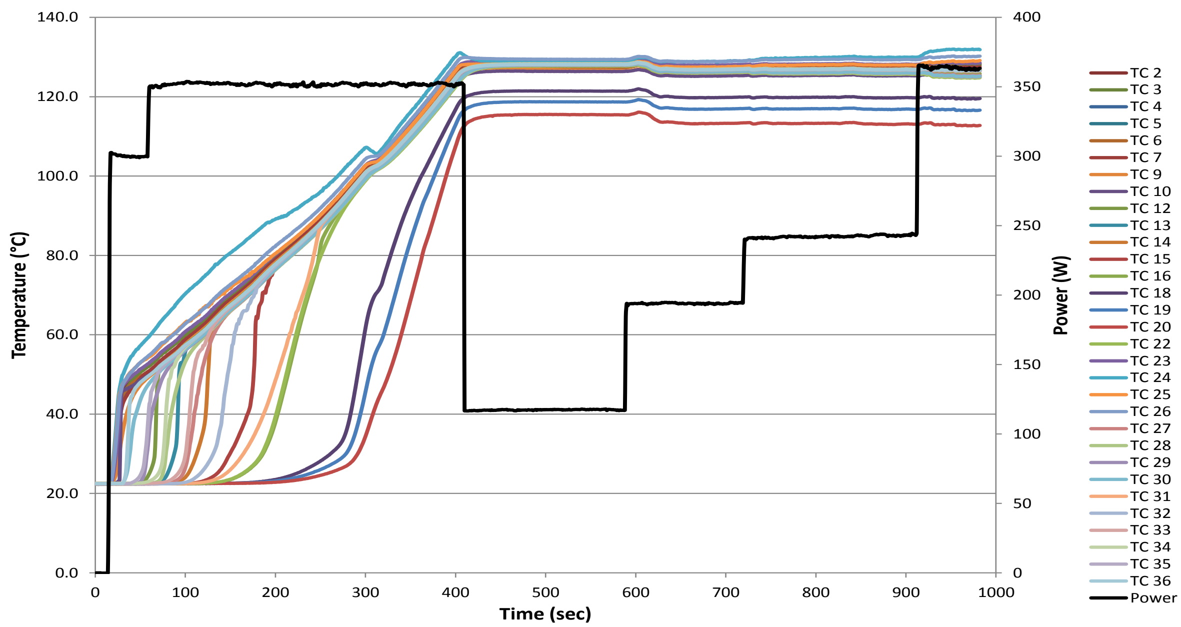

Figure 9. Vertical Orientation Test of Hybrid Screen-Groove Heat Pipe.

C. Freeze-Thaw Testing

In order to simulate the conditions of an extended shutdown and restart of the Striling convertors in space, the hybrid screen-groove heat pipe was chilled to -50°C and then heated with the nominal design power of 125 W to the operational temperature of 125°C. The test results in Figure 10 show a smooth startup from frozen condtions and stable performance at operational temperature.

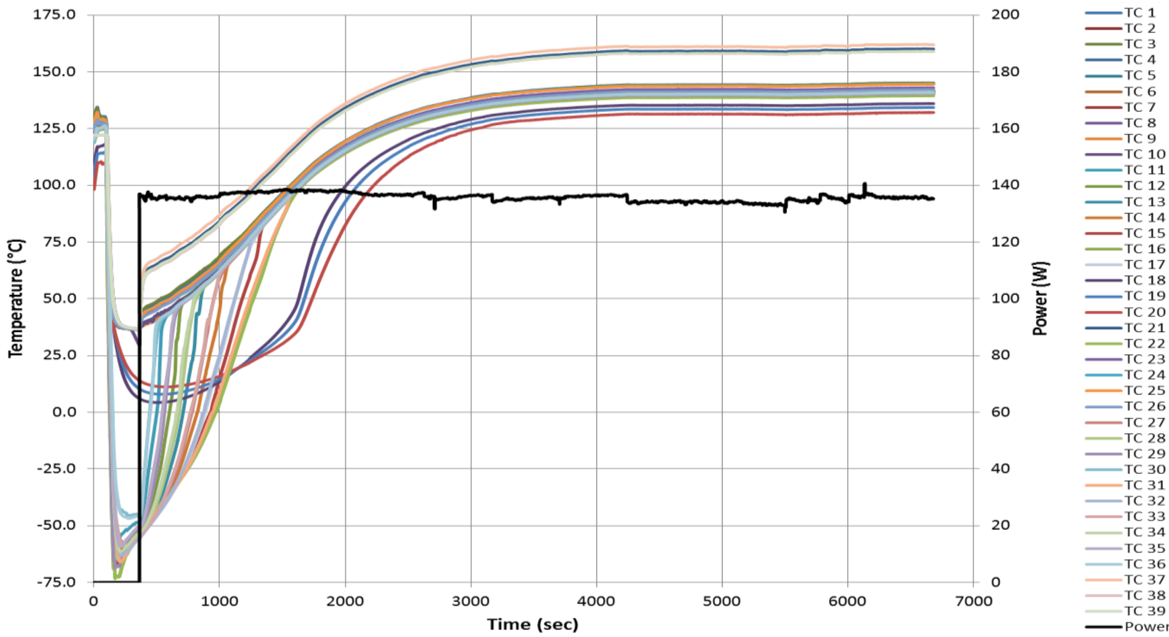

Figure 10. Freeze-Thaw Test of Hybrid Screen-Groove Heat Pipe.

IV. Radiator Development and Fabrication

The hybrid heat pipe interfaces to a radiator that rejects the waste heat from the Stirling convertor to space. Since traditional radiator designs were cost-prohibitive for this research, ACT investigated directly bonding aluminum facesheets to the titanium heat pipe via a high temperature solder called S-Bond. S-Bond Technologies, LLC performed the joining process on sample heat pipes and radiators. These samples were tested to determine the integrity and thermal characteristics of the bond. A picture of a S-Bonded heat pipe radiator is shown in Figure 11. The large Coefficient of Thermal Expansion (CTE) mismatch between titanium and aluminum causes warping of the components, most readily visible on the aluminum.

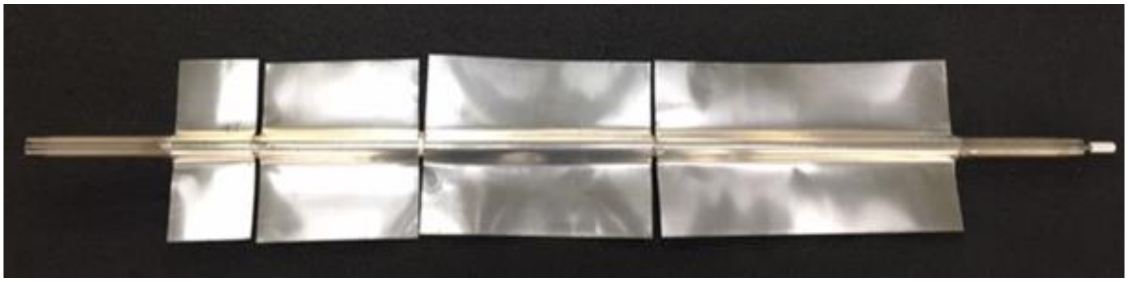

Figure 11. S-Bonded Titanium Heat Pipe to Aluminum Facesheet.

V. Radiator Test Results

A 0.75 in outer diameter titanium tube was bonded to an 0.040 in thick aluminum sheet for testing. This article was mounted to a tilt table, charged with water, and instrumented with type T thermocouples as shown in Figure 12. An aluminum heater block with a single cartridge heater was used as the evaporator. The article was then tested in ambient and vacuum environments.

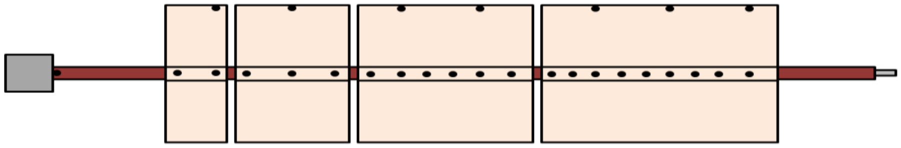

Figure 12. Thermocouple Layout on S-Bonded Titanium - Aluminum Heat Pipe Radiator.

A. Thermal Cycle Testing

Since the heat pipe and radiator are rigidly connected, the large CTE mismatch between the titanium heat pipe and the aluminum radiator induces significant shear stress in the bond, which could cause it to fail. In order to investigate bond strength, the test article was thermally cycled from 40 to 140°C under vacuum. The article was cycled continuously 19 times. Figure 13 shows the temperature evolution during the cycling testing.

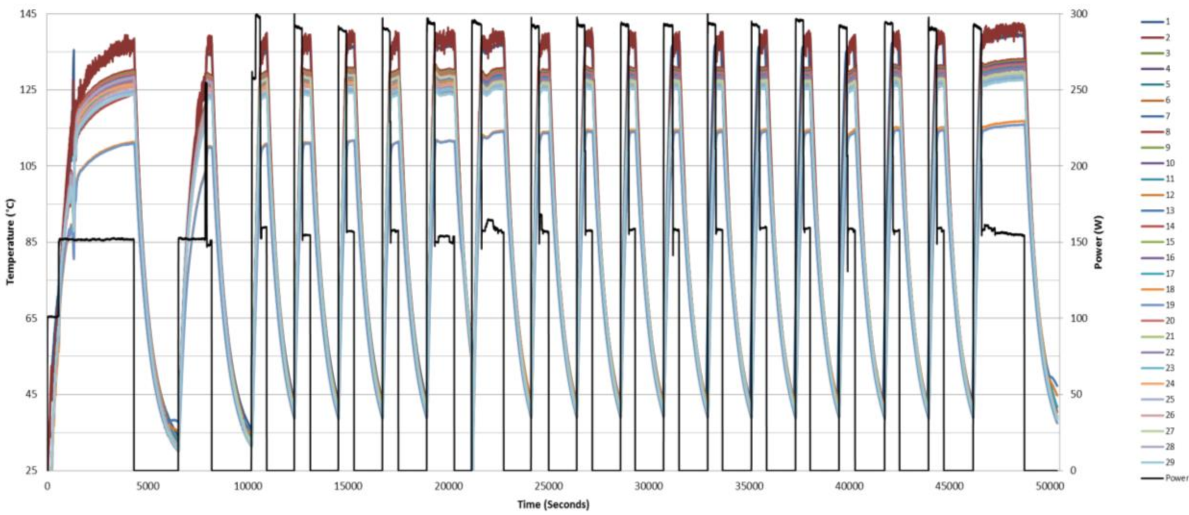

Figure 13. Temperature Evolution of Thermal Cycle Testing of S-Bonded Heat Pipe Radiator.

Average thermal resistance across the bond joint was determined during the steady state for each cycle of the test and plotted for comparsion, as shown in Figure 14. The data shows that the thermal resistance is relatively consistent throughout each cycle. Noise in the thermal resistance is attributed to noise in the power. Based on the results above and visual inspection, it was determined the quality of the bond was not altered by the exposure to thermal cycling.

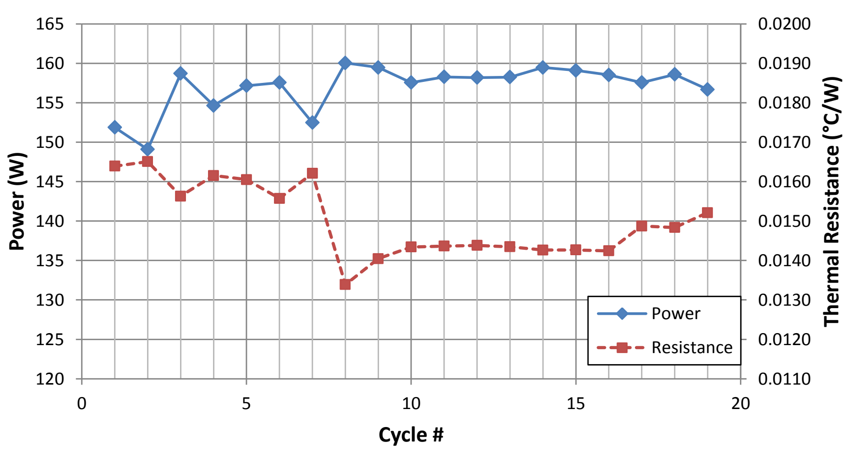

Figure 14. Thermal Resistance History of Cycled S-Bond Heat Pipe Radiator.

B. Thermal Imaging Testing

The article was tested in ambient in order to determine the uniformity of the bond by thermal imaging. Constant power was applied to the evaporator until the article reached steady-state by cooling from natural convection. Figure 15 below shows the temperature evolution of the test and a thermal image corresponding to 4500 sec into the test. The thermal image shows the root of the fin is isothermal and temperatures at corresponding locations on the fins are within 5°C. A few outliing cold spots are shown on the fins, predominately at the tips and bottoms of the fins. These effects can be attributed to local irregularities in the natural convection boundary layer. Overall, results show an acceptable thermal bond between the hybrid screen-groove heat pipe and radiator.

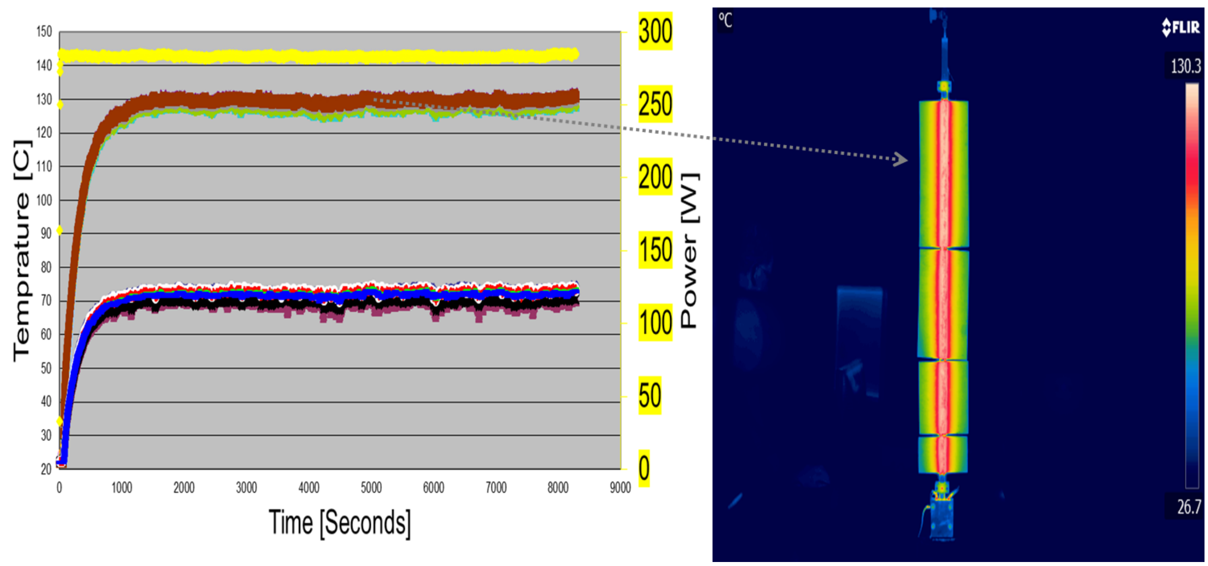

Figure 15. Thermal Image of S-Bonded Heat Pipe Radiator.

VI. Conclusion

The hybrid screen-groove heat pipe was successfully tested in all modes of operation: against gravity, gravity aided in vertical orientation, and freeze-thaw. During the against gravity test, the heat pipe carried 390 W before partial dryout, and 450 W with partial dryout, which is significantly greater than the 125 W nominal power and the 250 W requirement. The vertical orientation test demonstrated the capability of the accumulator to store the liquid from the grooves that deprimed. During the test, the startup from room to operating temperature was smooth and the steady-state data was stable. The heat pipe also showed a smooth startup from frozen conditions to operating temperature and stable performance at steady state. Based on the test results, the hybrid screen-groove heat pipe issuitable for Kilopower, successfully operating as a thermosiphon for ground testing and slightly inclined against gravity for space operation.

The radiator directly bonded to the hybrid screen-groove heat pipe with S-Bond was tested for thermal performance and bond strength by thermal cycle testing. After thermal cycle testing, the bondline showed no signs of damage and thermal imaging during a steady-state test revealed uniformity throughout the bond. While the large CTE mismatch between the heat pipe and radiator caused warping, there was no negative effect on the thermal performance; however, structural and assembly issues are envisioned. Through this testing, S-Bond proved to be a viable low-cost alternative to standard radiator constructions with the exception of significant warping of the components.

Acknowledgments

This research was sponsored by NASA Glenn Research Center under Contract No. NNX15CC06C. 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. Phil Texter was the technician for this project.

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