Demonstration of Copper-Water Heat Pipes Embedded in High Conductivity (HiK™) Plates in the Advanced Passive Thermal eXperiment (APTx) on the International Space Station (ISS)

Mohammed T. Ababneh[1], Calin Tarau[2], and William G. Anderson[3]
Advanced Cooling Technologies, Inc. 1046 New Holland Ave. Lancaster, PA 17601, USA

Angel R. Alvarez-Hernandez[4] and Stephania Ortega[5]
NASA Johnson Space Center, Houston, TX 77058, USA

Jeffery T. Farmer[6] and and Robert Hawkins[7]
NASA Marshall Space Flight Center, Huntsville, AL 35808, USA

Copper-water heat pipes are commonly used for thermal management of electronics systems on earth and aircraft, but have not been used in spacecraft thermal control applications to date, due to the satellite industry's requirement that any device or system be successfully tested in a microgravity environment prior to adoption. Recently, Advanced Cooling Technologies Inc., (ACT), in coordination with engineers from NASA's Marshall Space Flight Center (MSFC) and Johnson Space Center (JSC) demonstrated successful flight operation of these heat pipes in low-Earth orbit. The testing was conducted aboard the International Space Station (ISS) under the Advanced Passive Thermal eXperiment (APTx) project, a project to test a suite of passive thermal control devices funded by the ISS Technology Demonstration Office at NASA JSC. The heat pipes were embedded in a high conductivity (HiK™) aluminum base plate and subject to a variety of thermal tests over a temperature range of -10 to 38 ºC for a ten-day period. Results showed excellent agreement with both predictions and ground tests. The HiK™ plate underwent 15 freeze-thaw cycles between -30 and 70 ºC during ground testing, and an additional 14 freeze-thaw cycles during the ISS testing. The following was demonstrated during 10 days of testing on the ISS:

1. **Successful operation of the copper-water heat pipes and HiK™ plate.**
2. **Ability of the copper-water heat pipes and HiK™ plate to survive multiple freeze/thaw cycles.**
3. **As-designed heat transport via copper-water heat pipes.**
4. **Reliable, repeatable start up of copper-water heat pipes and HiK™ plate from a frozen state.**

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
APTx	=	Advanced Passive Thermal experiment
CCHPs	=	Constant Conductance Heat Pipes
FEA	=	Finite Elelment Analysis
ISS	=	International Space Station
NASA	=	National Aeronautics and Space Administration
NCG	=	Non Condensable Gas
VCHP	=	Variable Conductance Heat Pipe
WEB	=	Warm Electronics Box

[1] R&D Engineer II, Defense/Aerospace Group, Mohammed.Ababneh@1-act.com
[2] Lead Engineer, Defense/Aerospace Group, Calin.Tarau@1-act.com
[3] Chief Engineer, Bill.Anderson@1-act.com
[4] Passive Thermal Technical Discipline Lead, NASA Johnson Space Center.
[5] Spacecraft Thermal Engineer, JSC-ES311, NASA Johnson Space Center.
[6] Project Manager, ES20, MSFC, AIAA Member.
[7] Aerospace Engineer,ES22,MSFC

I. Introduction

Typical electronics operating temperatures range from -45 to 85°C, and thermal management becomes a prime concern at the high end of the temperature range. Copper-water heat pipes as shown in Figure 1 are valuable for thermal management because they provide extremely low resistance thermal transport from 1 to 200°C. As electronics continue to push the envelope on performance, thermal management systems are becoming increasingly more important. Electronics in terrestrial applications frequently require copper-water heat pipes to move heat from discrete components to air heat sinks. Heat pipes are excellent for transporting heat to heat sink hardware.

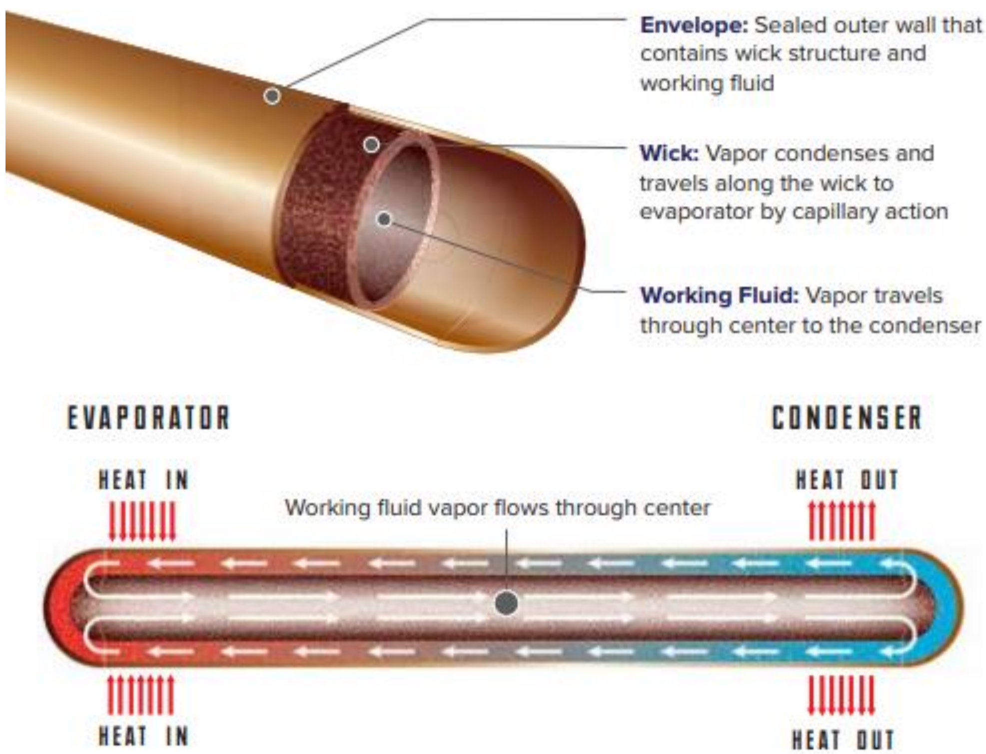


Figure 1. Copper–water heat pipe operation.

However, copper-water heat pipes have not been used in spacecraft thermal control applications to date, due to lack of testing in a microgravity environment. ACT, NASA Marshall Space Flight Center, and the International Space Station office at NASA's Johnson Space Center tested copper-water heat pipes in Low-Earth Orbit, aboard the International Space Station (ISS) under the Advanced Passive Thermal experiment (APTx) project.

The ISS as shown in Figure 2 is the only long-duration platform existing in the relevant space environment with an integrated space systems construction that can be used to validate operations concepts and advanced technologies. The ISS program offers an infrastructure capable of demonstrating and validating prototypes and systems that may advance spaceflight technology readiness. The space station, the in-orbit crew, the launch and return vehicles, and the operation control centers are all supporting the demonstration of advanced systems and operational concepts that will be needed for future exploration missions[1].

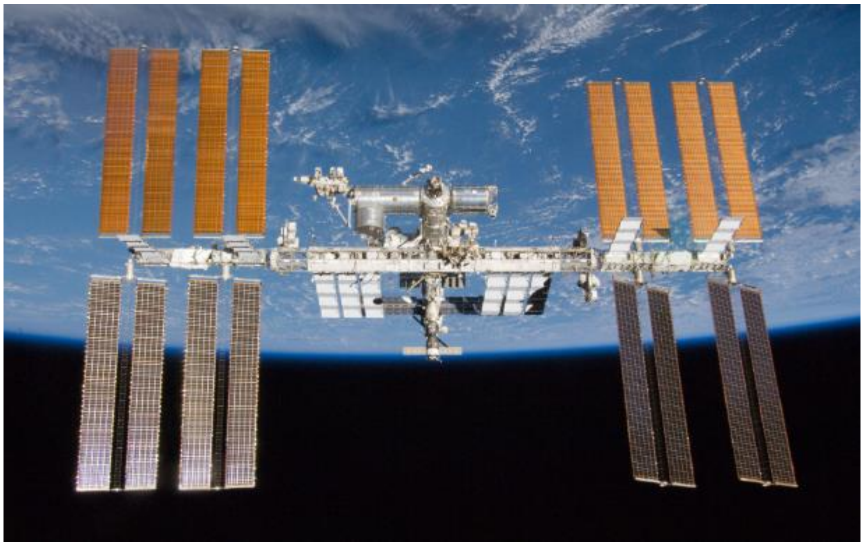


Figure 2. The International Space Station (Photo: NASA).

II. Heat Pipe Background

Copper-Water Heat Pipes

Heat pipes are fully passive, self-contained heat transfer devices. The liquid-vapor phase change of a saturated working fluid is used to achieve effective thermal conductivities from 10,000 to 200,000 W/m.K. This is hundreds to thousands of times higher than aluminum, which has a thermal conductivity between only 160 to 200 W/m.K. Two main factors are taken into consideration when designing heat pipe systems. These factors are the heat transport requirement (watts) and thermal resistance. Because heat pipes operate by fluid flow, the pressure balance and flow characteristics of the system are predicted. After a heat pipe or heat pipe array is designed that can carry the required power, the thermal resistance is calculated to predict the thermal performance. In most applications, copper-water heat pipes have a ΔT of between 2 and 5 °C.

Water is used as the working fluid because of its excellent thermophysical properties at electronics operating temperatures. The high latent heat of vaporization is a major driving force in heat pipe operation and is much greater than other fluids in this range. Not only that, but water's combination of viscosity and ability to generate high capillary pressures enable copper-water heat pipes to operate over long distances or against gravity.

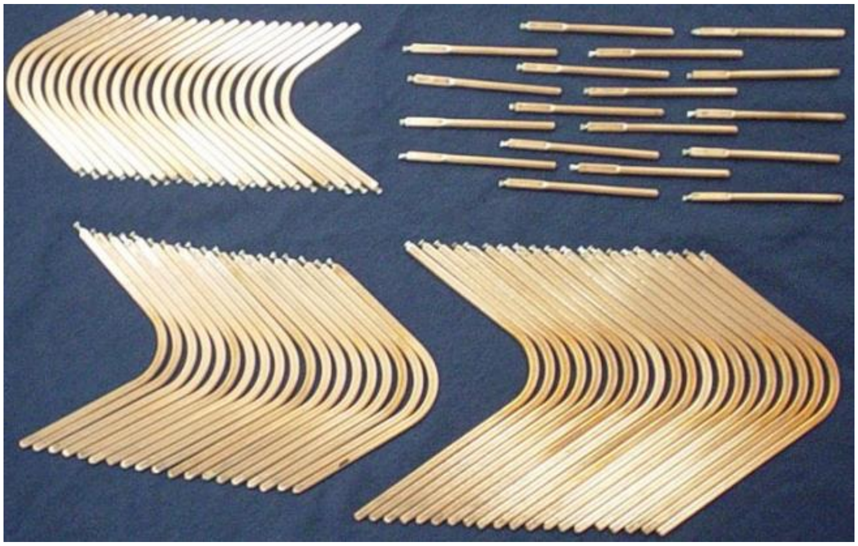


Figure 3. Examples of copper-water heat pipes (Photo: ACT, Inc.).

High Conductivity Plates (HiK™ Plates)

The HiK™ or high conductivity plate as shown in Figure 4 represents a technology developed at ACT (ACT Inc., 2013[2]) that consists of heat pipes embedded in a plate to transfer of heat from one location to another. The embedded heat pipes are soldered in place, and then the surface is fly-cut to provide a smooth surface. The weight of a HiK™ plate is roughly similar to its solid counterpart; however, effective thermal conductivities range from 500 to 1200 W/m.K (versus ~ 200 W/m.K for aluminum). In some spacecraft applications, the effective thermal conductivity can be as high as 2500 W/m.K, equivalent to diamond. For applications with large variations in heat load across a surface, such as electronics boards, the embedded heat pipes can be customized to provide controlled heat transfer across the plate. The addition of HiK™ plates to the electronics enclosure would further decrease the temperature gradient within this device by eliminating hot spots and improving overall heat transfer.

Analysis of a HiK™ Plate is shown in Figure 5 using finite element analysis (FEA) to compare the performance of a solid aluminum plate and potential improvements using an aluminum plate with embedded copper/water heat pipes. The conventional aluminum plate's highest temperature was 90.3° C whereas the HiK™ aluminum plate is 69.1°C. This is a considerable performance improvement. HiK™ plates can contain both copper/water and copper/methanol heat pipes. Note that the copper/water heat pipes drop in efficiency below about 20°C, due to the water properties. At 0°C, the water heat pipe will freeze and will make no contribution to the thermal conductivity until they thaw again. By controlling the water inventory so that no free liquid is available, HiK™ plates have been shown to withstand thousands of freeze/thaw cycles[3].

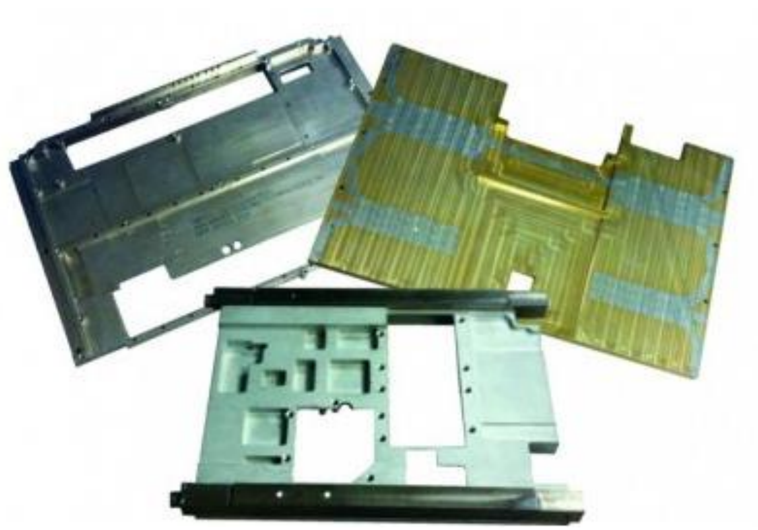
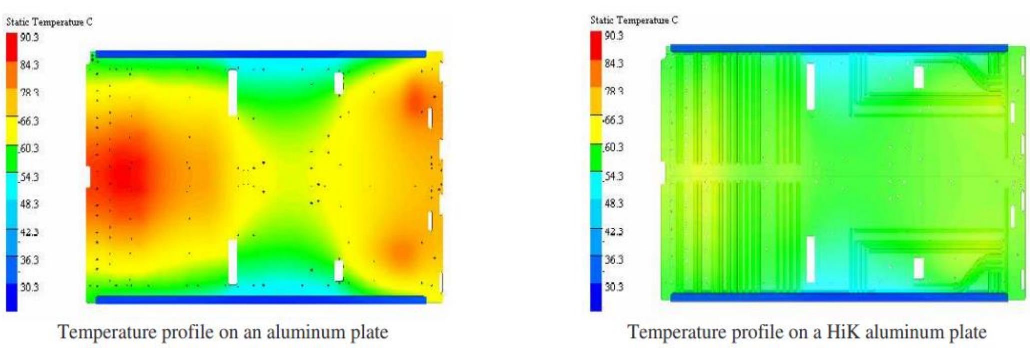


Figure 4. **Typical HiK™ Plates with embedded heat pipes to improve the effective thermal conductivity.**



(a) **(b)**

Figure 5. FEA for a particular application with multiple heat sources across the plate. For a) Temperature distribution on the standard aluminum plate b) Temperature distribution on the HiK™ plate. A reduction in peak temperature of 21°C can be observed.

III. ISS Flight Hardware

As NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architectures will be challenged with unprecedented thermal environments in deep space. In addition, there is a need to extend the duration of the missions in both cold and hot environments, including cis-lunar and planetary surface excursions. The heat rejection turn–down ratio of the increased thermal loads in the above mentioned conditions is crucial for minimizing vehicle resources (e.g. power). Therefore, future exploration activities will have the need of thermal management systems that can provide higher reliability and performance, and power and mass reduction. In an effort to start addressing the current technical gaps in thermal management systems, novel new passive thermal technologies were selected to be included as part of a suite of experiments to be tested on the board of the ISS, in 2017[4].

ACT Inc., together with NASA Marshall Space Flight Center and NASA Johnson Space Center, tested and validated HiK™ plates with embedded copper-water heat pipes on the ISS under the Advanced Passive Thermal experiment (APTx) project. The objectives for testing flight hardware on the ISS were to demonstrate the operation and flight worthiness of the HiK™ plate. The TRL of the high conductance plate (HiK™ plate) was TRL 9 for terrestrial applications and TRL 6 for space applications. The micro-gravity tests on this plate raise the TRL level of the plates to TRL 8 since the plate tested is very similar to those used actual applications.

The APTx consists of two separate payloads that will be tested sequentially:

- Payload 1 contains a VCHP/HiK™ plate assembly. (Payload 1 will be discussed in a separate paper)
- Payload 2 contains a HiK™ plate and the ElectroWetting Heat Pipe (EWHP) experiment, developed by the University of Texas at Austin.

<u>ACT Ground Testing of Payload 2:</u>

The first step in fabricating a HiK™ plate is to determine the location of the high power components on the aluminum board, as well as the location of the cooling areas. The second step is to design the heat pipe by selecting the working fluid and its amount and the wick structure. Water was selected as the working fluid and screen copper wick was selected as the heat pipe's wick structure. Two identical HiK™ plates were designed, fabricated, tested, and shipped to NASA. Each HiK™ plate had 9 copper/water heat pipes. Figure 6 shows the expected performance for each heat pipe at 1 inch against gravity. Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit[4].

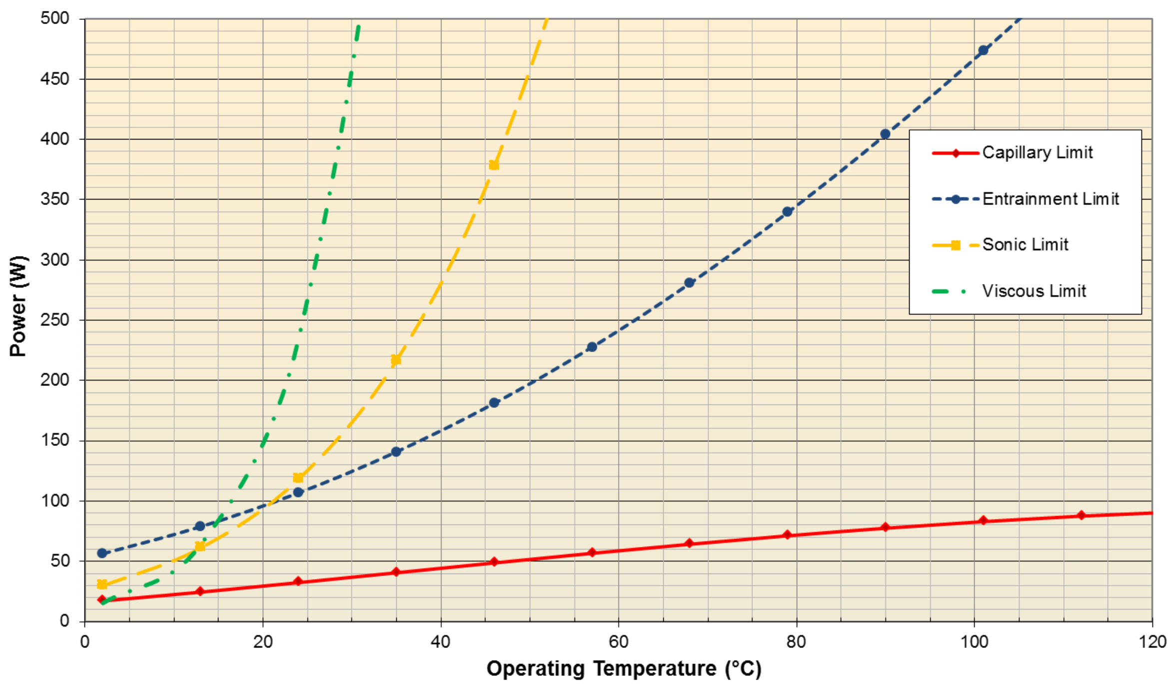
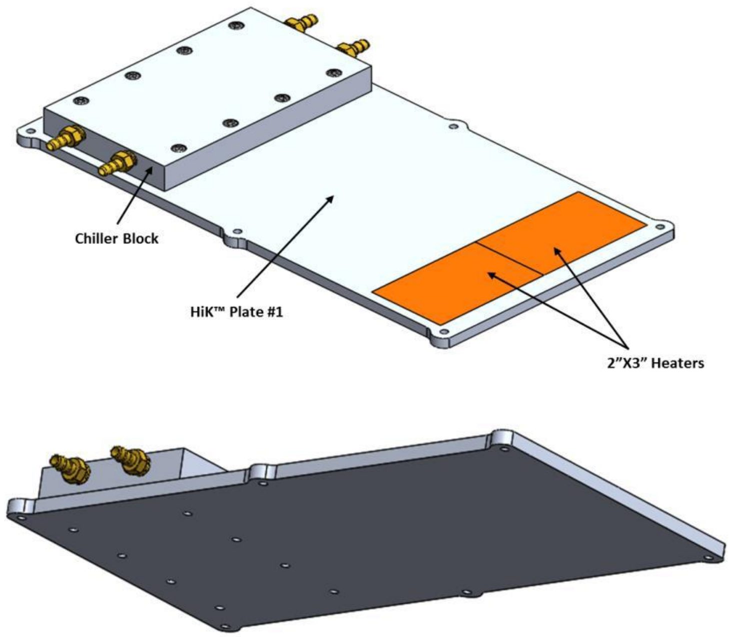


Figure 6. Heat pipe limit chart for the embedded copper/water heat pipes into the HiK™ plate for ISS APTx experiment.

Figure 7 shows the design of the HiK™ plate for the ISS experiment in payload 2. Two 53W (2”x3”) silicon heaters were used as a heat source on the top of the HiK™ plate; a chiller block was used to impose sink temperatures between -10 to 50°C and about 30 TCs were used to monitor the temperatures. Freeze/thaw testing was performed successfully for the HiK™ plates on ground as shown in Figure 8. The freeze/thaw tests were conducted horizontly with air temperature measured inside ACT’s environmental control unit for both HiK™ plates from temperature ranging from -30 to +70°C for 15 cycles.



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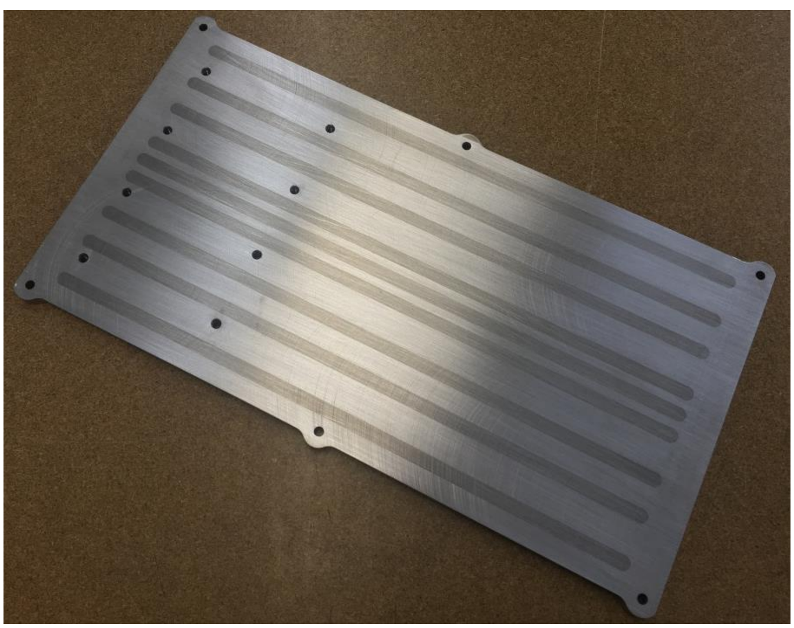


(b)

Figure 7. The HiK™ plate for the ISS experiment in payload 2: (a) The CAD model, (b) The fabricated HiK™ plate.

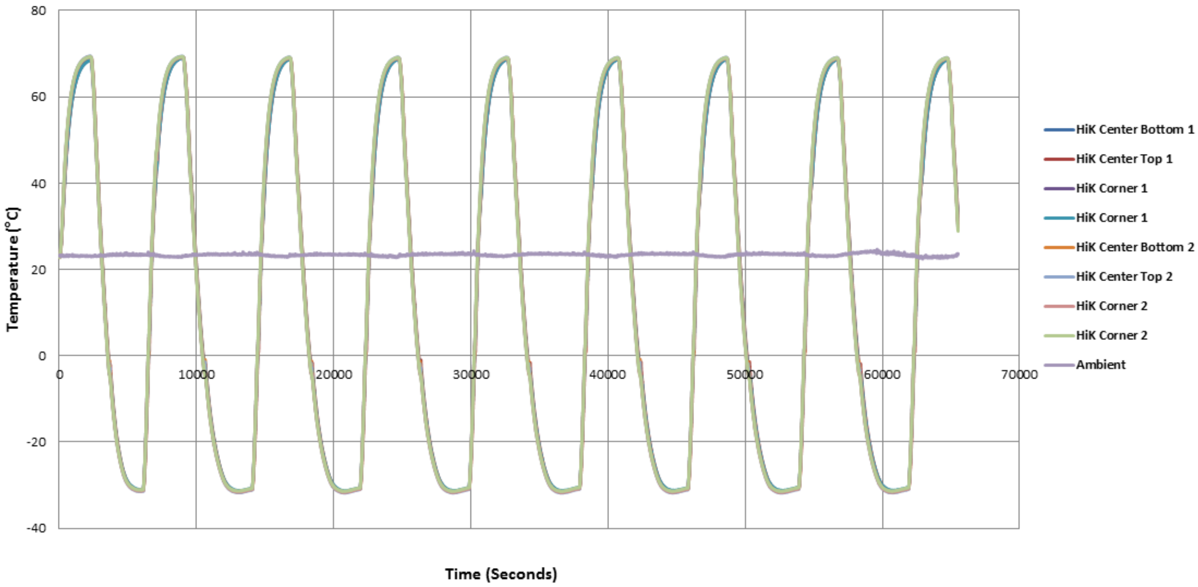
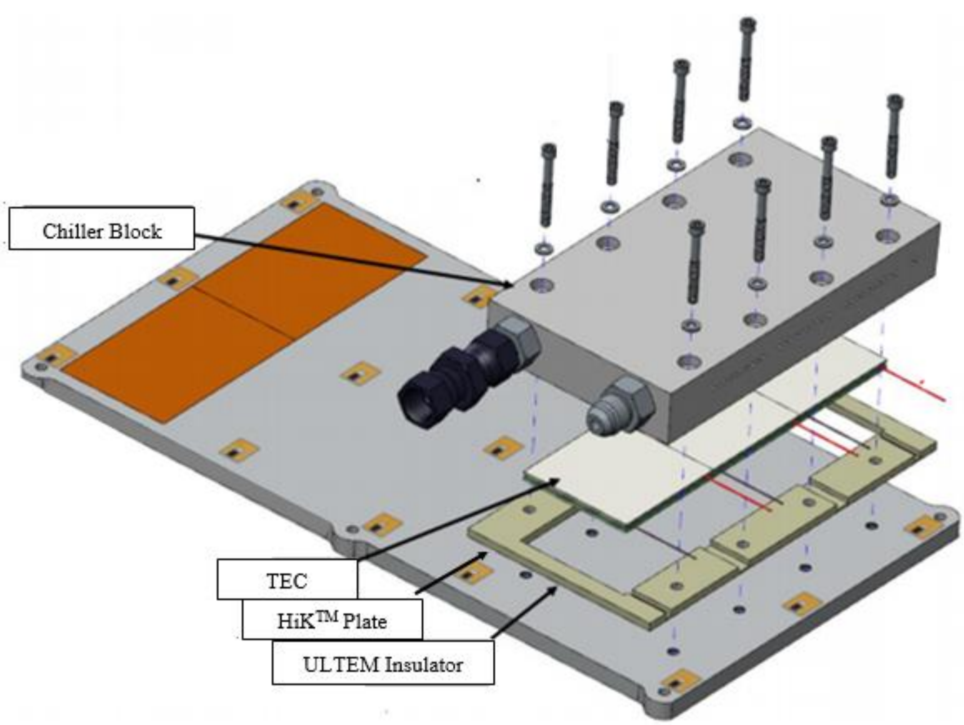


Figure 8. The temperature profile of HiK™ plates exposed to thermal cycling.

Microgravity Testing of Payload 2 on the ISS:

As shown in Figure 9, two 53W (2”x3”) silicon heaters were used as a heat source on the top of the HiK™ plate. A chiller block and Thermoelectric Coolers (TECs) were used to impose sink temperatures between -10 to 40°C, and 31 TCs were used to monitor the temperatures on the plate as shown in Figure 9.



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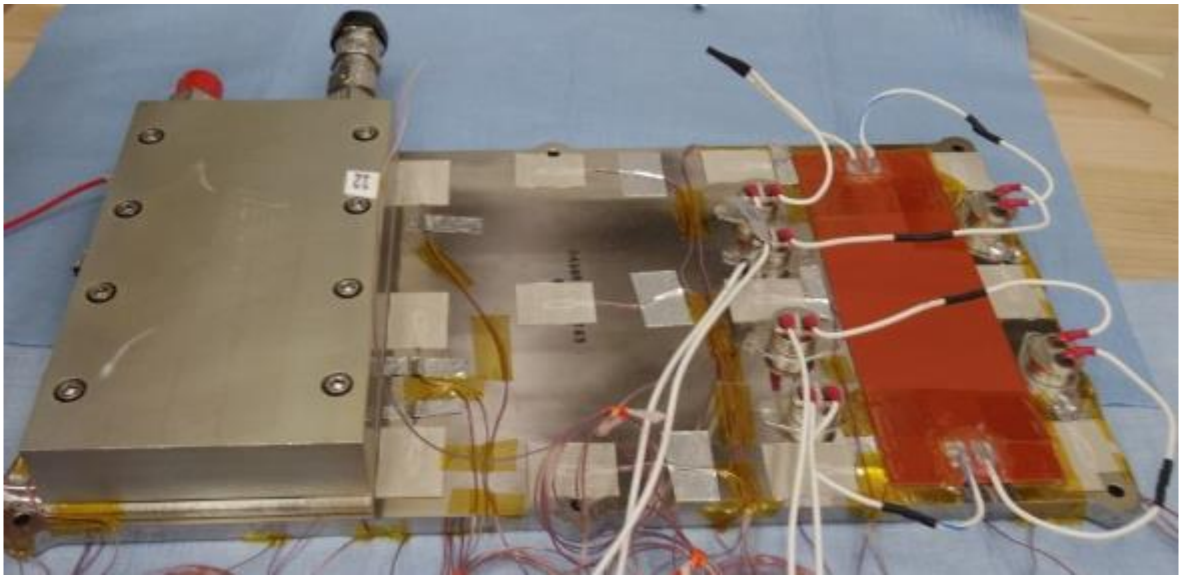

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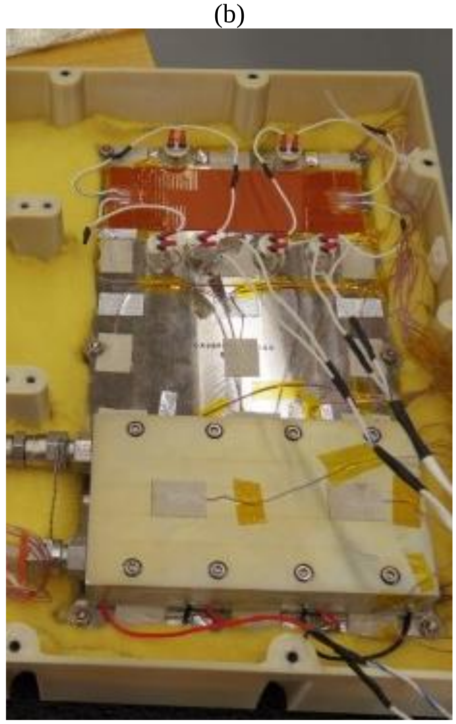

(c)

Figure 9. The HiK™ plate setup for ISS experiment in Payload 2: (a) The CAD model, (b) The assembled HiK™ plate, (c) The assembled HiK™ plate integrated in Payload 2.

Freeze/thaw testing was performed successfully for the HiK™ plate on orbit as shown in Figure 10. The freeze/thaw tests were conducted for the HiK™ plate from temperature ranging from -10°C to approximately 40°C. Fourteen cycles of freeze-thaw and freeze-startup-thaw cycles were performed on orbit. For the freeze-thaw cases, the TECs and heaters were operated independently; no heater power was supplied during TEC operation to freeze the plate and no TEC control was provided during heating operations to thaw the plate. The freeze-startup-thaw test cases used only TECs to freeze the plate. Once frozen, heater power was turned on while the TECs were maintained at freezing temperatures on one half of the plate, until the system reached equilibrium with a partially frozen plate. Once this startup condition was achieved, the TECs were turned off and the plate was subsequently heated to approximately 40°C.

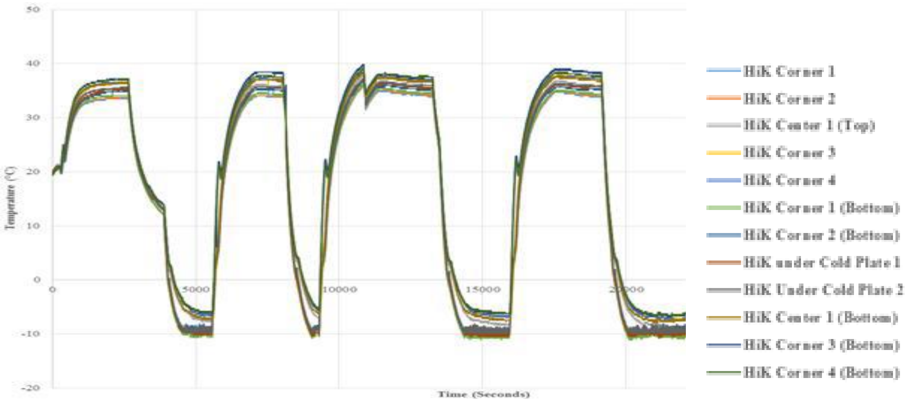

Figure 10. Snapshot of the temperature profile of HiK™ plate exposed to thermal cycling in orbit.

The maximum temperature difference (ΔT in °C) within the HiK™ plates on ground testing is less than 0.1 °C due to the heating and cooling methods for the HiK™ plates inside the environmental chamber (i.e. from -30 to +70°C). The reason for this test is to validate that the HiK™ plates withstand multiple freeze/thaw cycles without any problems. However, the heating method on orbit was performed using two silicon heaters which is more realistic. The resulting maximum temperature difference within the HiK™ plates is less than 5 °C.

IV. Conclusion

ACT Inc., NASA Marshall Space Flight Center and NASA Johnson Space Center, worked together to test HiK™ plates in the ISS microgravity environment. The flight test verified the operation of the HiK™ plates with the embedded copper/water heat pipes in micro-gravity environment. Two HiK™ aluminum base plates were designed, fabricated, and tested successfully on ground and on the ISS. Each HiK™ plate had 9 copper/water heat pipes. Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit in an unfavorable orientation (against gravity) of 1 inch. In the ISS test for payload 2, the copper-water heat pipes were embedded in a HiK™ plate, and subject to a variety of thermal tests over a temperature range of -10 to 40 ºC for a ten-day period. Results showed excellent agreement with both predictions and ground testing results. The HiK™ plate underwent 15 freeze-thaw cycles between -30 and 70 ºC during ground testing, and an additional 14 freeze-thaw cycles during the ISS test. This flight test onboard ISS is an important step toward qualifying copper/water heat pipes as a passive thermal management solution in support of future human and robotic space exploration missions by NASA.

Acknowledgments

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