Advanced Two-Phase Cooling System for Modular Power Electronics

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Developing standardized electronics cooling system components is important to reduce system capital costs and reduce the operations and maintenance complexities. As such, it is important to develop components that can handle high heat loads with less temperature drop between the electronics and the heat sink. Two-phase thermal heat spreaders provide an excellent alternative to conventional conduction-based heat spreaders. Under a Small Business Innovation Research program, Advanced Cooling Technologies, Inc. (ACT) developed a pulsating heat pipe (PHP)-based heat spreader for advanced modular power electronics and compared with ACT's high conductivity (Hi-K™) plate. The features of the test components are in accordance with modular electronics standard for space power systems (MESSPS) and applicable across various space missions. Test results showed, that both heat spreaders (Hi-K™ plate and PHP) can reduce the thermal resistance by half compared to an aluminum plate. The unique feature of the PHP is that the capillary channels extend onto the sharp stepped interface, which is not feasible with Hi-K™ plate. This improves the thermal conductance across the stepped plane between the heat spreader and the card retainer. ACT's Isothermal Card Edge (ICE-Lok™) was used as the card retainer. Both PHP and Hi-K plates are able to operate against gravity orientation. Also, PHP was found to be up to 10.4% lighter than the conventional card by 16 grams.

Nomenclature

Q	=	Heat load
R	=	Thermal resistance
ΔT	=	Temperature difference

<u>Abbreviations</u>

ACT	=	Advanced Cooling Technologies, Inc.
AMPS	=	Advanced Modular Power systems
Hi-K™ plate	=	High conductivity card
ICE-Lok™	=	Isothermal Card Edge
PHP	=	Pulsating Heat Pipe
SBIR	=	Small Business Innovation Program
MESSPS	=	Modular Electronics Standard for Space Power Systems

I. Introduction

Standardizing electronics cooling system offers many advantages such as reducing the costs of component development and unique spare parts, easily repair and replace parts etc. The Advanced Exploration System Modular Power System (AMPS) project aims to construct future power control architecture of spacecraft with standardized, modularized and interchangeable components, including electronics and auxiliary thermal management

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components. As power electronics evolve, the standardized cooling system must handle high heat flux. Conventional cooling system with conduction only aluminum plate heat spreader is limited by the material thermal conductivity. Recent investigation by Colozza and Gardner showed an electronics module with the conventional heat spreader can only deliver up to 16 W per card at a maximum allowable operating temperature of 44 °C [1]. The thermal resistance was found to be around 1.5 °C/W, where the heat spreader thermal resistance contributed to about half the total thermal resistance. Replacing the conventional heat spreader with advanced two-phase heat spreaders can significantly improve the heat carrying capability by reducing the thermal resistance of the system.

Under SBIR Phase I Program for NASA, two different two-phase heat spreaders: ACT's Hi-K™ plate and pulsating heat pipe (PHP) were developed and tested as superior alternatives to a conduction only aluminum plate for electronics (3U card) cooling. ACT's Hi-K™ plate is essentially copper-water heat pipes embedded on to an aluminum plate [2]. Hi-K™ plate can have an effective thermal conductivity of 600 W/m-K to 1200 W/m-K, which is 3 to 6 times more than an aluminum plate. Hi-K™ plate can also handle up to a heat flux of 60-70 W/cm^2 [3]. Pulsating heat pipe (PHP) on the other hand, uses oscillation/ pulsation of the saturated working fluid within a serpentine capillary to transfer heat[4]. The heat transport capability is limited by the working fluid and geometry, but could be well in excess of 10 W/cm^2 up to 50 W/cm^2 [5,6]. In addition to the heat spreader, it was identified that Wedge-Lok is the standard solution to mechanically interface the electronic card enclosure with the chassis of the module. ACT's ICE-Lok™ can replace COTS Wedge-Lok as it provides an additional heat transfer path which in turn reduces the thermal resistance across the interface joint by more than 30% [7].

This manuscript describes the development, testing, and performance comparison of two-phase heat spreader components and conduction only aluminum plate heat spreader (baseline) for 3U card electronics cooling system. During the testing, ACT's ICE-Lok™ was used as the card retainer instead of COTS Wedge-Lok. The geometrical features of the fabricated components are in accordance with modular electronics standard for space power systems (MESSPS). The developed system components can directly benefit various missions such as *Gateway-Artemis, Lunar and Mars Habitats, Solar Electric Propulsions, Electrified Aircraft Propulsions*, and future ISS missions like *Orbiting Habitats, etc.*

II. Modular Power Electronics Cooling System

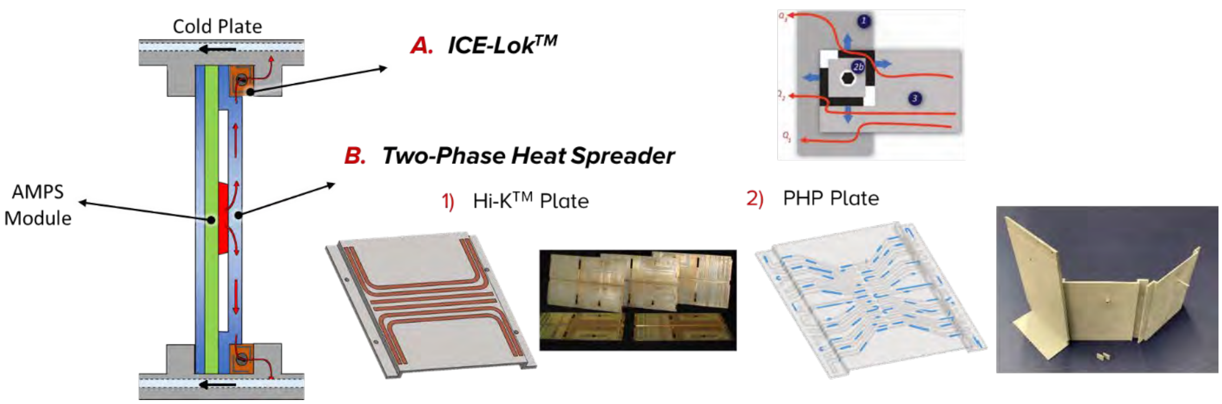

Figure 1. Advanced cooling system components for modular power electronics

Under an SBIR program, ACT developed an advanced cooling system for electronics card (3U size). Two-phase based heat spreaders based on two different heat pipe technologies, ACT's Hi-K™ plate and PHP were tested as part of the proposed cooling system for the modular power electronics. ACT's ICE-Lok™ was used as enhanced isothermal card edge retainer as it provides additional heat transfer path over COTS Wedge-Lok. The schematic of the system is shown in Figure 1. The heat transfer path from the electronics card source to the heat sink (coolant) is represented by red arrows.

A mock cooling system was constructed to test the proposed cooling system according to modular electronics standard for space power systems (MESSPS)[8]. The geometric details of the electronics cooling system are shown in Figure 2. The card is enclosed by the heat spreader, which provides primary heat transfer path, and with a back plane on the backside of the card. The backplane was a standard 1/8” (3.2 mm) thick solid aluminum plate. The heat spreader and the back plane interface with the chassis rails (or teeth) by means of an ICE-Lok™. A cold plate (aluminum plate with embedded copper tubes) was attached on the top and the bottom side of the chassis to provide a uniform heat sink temperature. Water at standard 22 °C was used as the heat transfer fluid. A 2-inch x 2-inch polyimide film heater was used to simulate heat generation in the electronics cards.

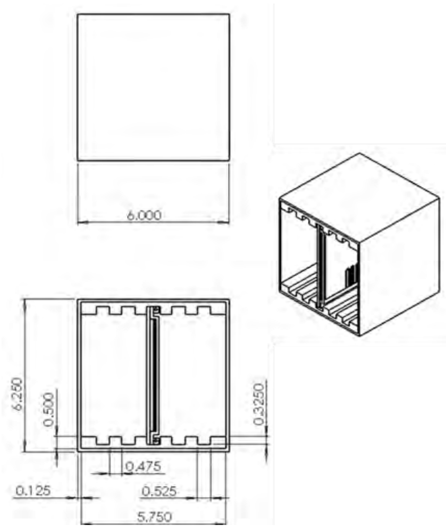

Figure 2. Geometric details of the modular power electronics cooling system (dimensions in inches)

III. Design and Development of Hi-K™ plate and PHP

Based on the chosen film heater configuration, a Hi-K™ plate with heat pipes was designed and fabricated according to ACT’s standard fabrication procedure. There were six copper water heat pipes symmetrically embedded onto the aluminum base plate.

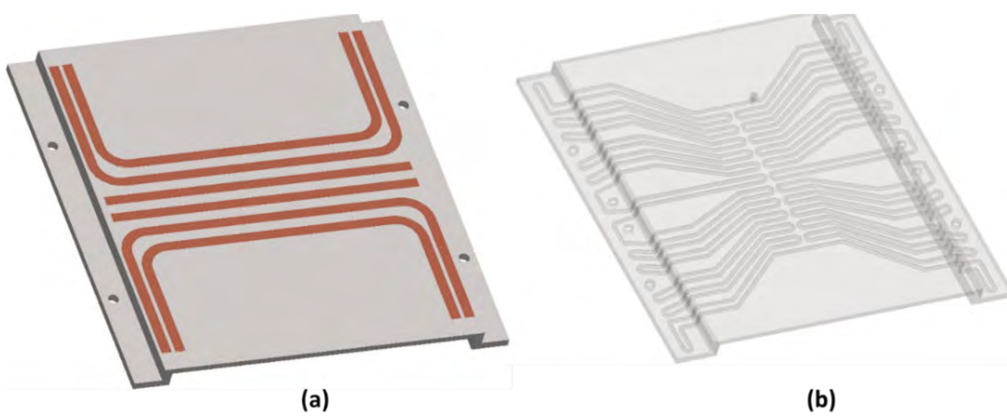

Figure 3. Schematic of (a) Hi-K™ plate and (b) PHP for electronics cooling

The schematic of the Hi-K™ plate heat spreader is shown in Figure 3 (a). The heat pipe condensers only extend until the edge of the heat source plane as it is difficult to incorporate sharp turns onto the stepped plane. The PHP design on the other hand, allowed for incorporating working fluid channels onto the stepped plane. The schematic of the PHP is shown in Figure 3 (b). A total of 24 PHP channels of size 1/16” (1.6 mm) were symmetrically spread out along the heat spreader. A common fluid charging port was provided to charge the PHP working fluid. ethanol. Propylene was selected as the working fluid based on the merit number calculation [9], size applicability based on Bond number and ease of handling.

A. Heat transfer operating limit of the proposed heat spreaders

Before fabricating the two-phase heat spreaders, heat transfer operating limits were calculated for both Hi-K™ plate (from in-house codes) and PHP [10] to assess the feasibility of using the proposed concept for modular electronics cooling.

The operating limits for one half of one heat pipe was determined from established in-house codes, and the results are shown in Figure 4 (a). The maximum Hi-K™ plate heat transfer capability is limited by the capillary limit, which has an increasing trend with operating temperature. At 40 °C operating temperature, the heat transfer capability of the overall Hi-K™ plate is 180 W. On the other hand, the swept length limit imposes a maximum heat transfer limit on the operation of the PHP. The swept length limit decreases with increasing operating temperature. Propylene was chosen as the working fluid, as it has a Bond number limit at over 54 °C, while, the same for R134a, is only 36 °C. At 40 °C operating temperature, PHP heat transport limit is 80 W.

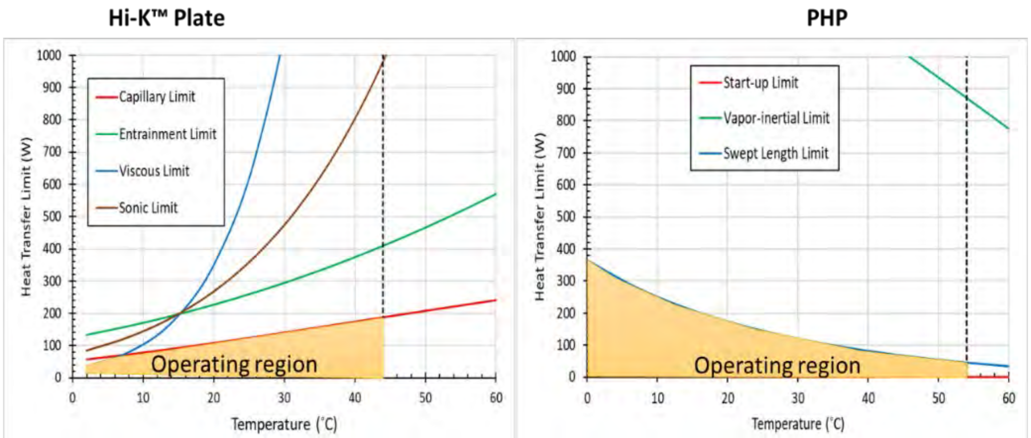

Figure 4. Heat transfer operating limits of (a) Hi-K™ plate and (b) PHP

B. Fabrication of the heat spreaders

Along with the proposed heat spreader solutions, a standard aluminum base plate of thickness 0.1" was fabricated by conventional methods. The solid aluminum plate weighed 153 grams. The Hi-K™ plate was fabricated as per ACT's standardized fabrication procedure. The heat pipe and the base plate production can start simultaneously at tandem. The heat pipes are soldered onto the base plate slots and standard surface treatment was applied. The prototype Hi-K™ plate for the testing in the SBIR program is shown in Figure 5. In the post processing step, slots for securing the back plane and the ICE-Lok™ were provided on the stepped interfaces. Tentative heater location for simulating heat generation on the Hi-K™ plate is represented by the red square region at the center of the heat spreader. The Hi-K™ plate is now ready to be tested as the heat spreader. The total mass of the Hi-K™ plate was found to be 173 grams, which was 13% higher than solid aluminum plate. Note that the mass of Hi-K™ can be further optimized by removing excessive base material. The optimized mass should be comparable to aluminum plate.

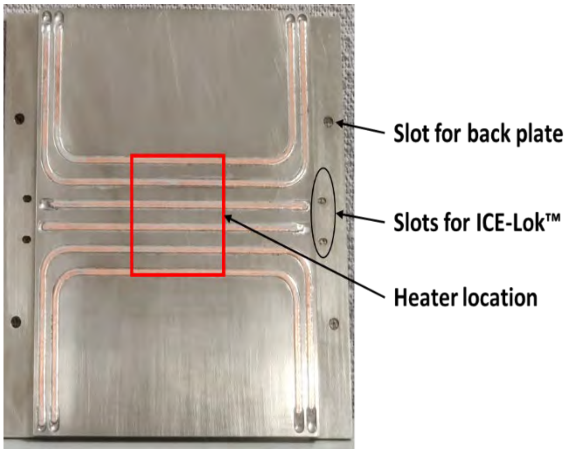

Figure 5. Hi-K™ plate for electronics card cooling

A PHP, on the other hand, was 3D printed due to the complexity of incorporating working fluid channels. The base material was standard aluminum alloy for additive manufacturing ($AlSi_{10}Mg$). Figure 6 shows the fabricated PHP. Post fabrication, a number of post-production steps were carried to charge and test the PHP as heat spreader, including metal power removal, x-ray inspection, de-powdering port closing, fill tube welding. Helium leak check was performed to ensure that the PHP was leak tight. The PHP was then charged with working fluid up to 50% of the available channel volume. The PHP is now

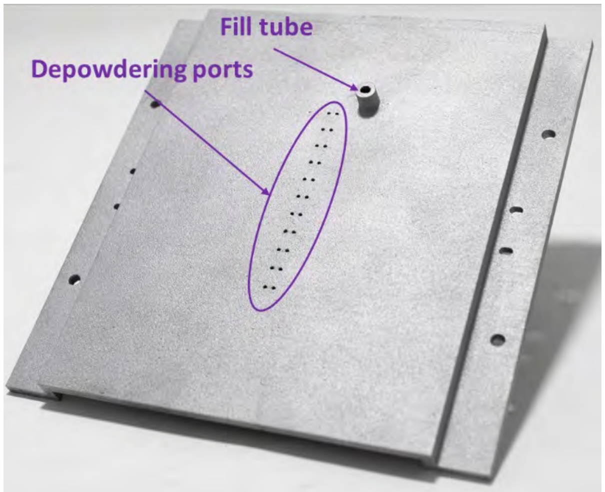

Figure 6. 3D printed PHP for electronics card cooling

ready to be tested as the heat spreader. It was observed that the PHP weighted 137 grams, and was about 10.4% lighter than the aluminum standard base plate.

IV. IR Characterization of PHP Prototype

Before thermal performance testing, another prototype PHP with separate channels was first charged with acetone and placed under an IR camera to characterize and visualize PHP's operating mechanism. A PHP prototype containing two separate channels as shown in Figure 7. was constructed for IR characterization. A 2" by 2" film heater was attached to the center of the test piece and the top surface was cooled by fans. For this characterization testing, only the left half PHP channel was filled with acetone up to 60% of volume. The right half was kept empty and used as aluminum conduction only test piece. This allows for direct comparison of heat transfer performance between the PHP and conduction plate within the same test piece.

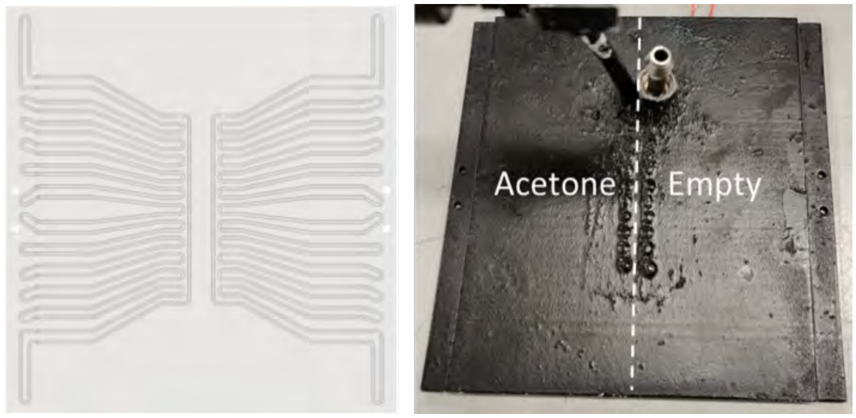

Figure 7. PHP prototype for IR characterization testing

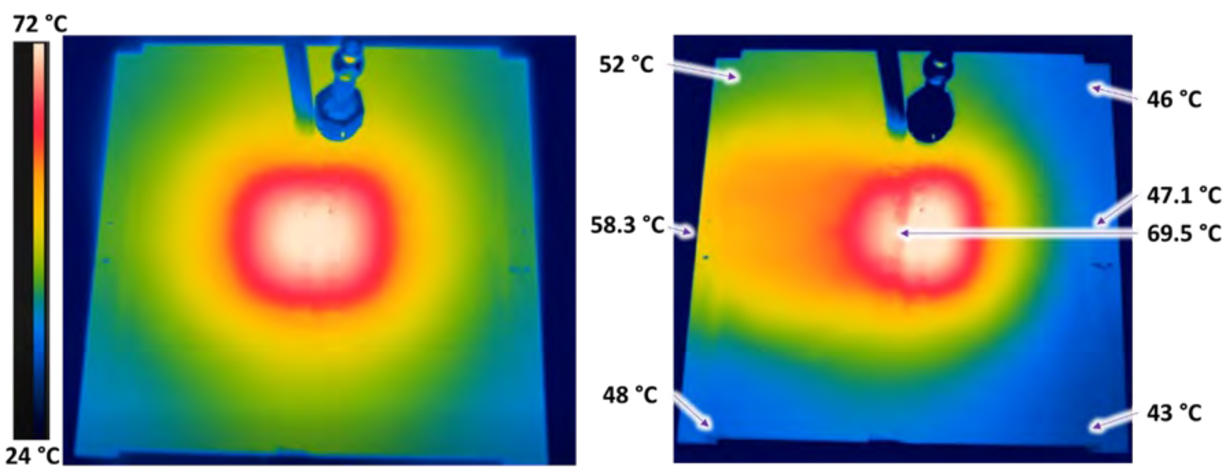

Figure 8. Left - Test piece temperature before PHP start-up; Right - Test piece temperatures when PHP is operating

The IR camera test results are shown in Figure 8. The figure of the left shows the increasing test piece temperature before the PHP start-up. At this time, the temperature is uniformly distributed throughout the entire test piece. Once, the PHP starts pulsating, the center temperature drops immediately from above 76 °C to below 70 °C. The temperature measurements at different locations of the test piece is shown above. Performance calculation showed that the conductance of the PHP was ~3.7 times higher than the conduction-only plate. The video file for the test characterization can be accessed at: https://www.youtube.com/watch?v=08AnO60Cw7k&feature=youtu.be

V. Testing of heat spreaders for electronics cooling

The three heat spreaders: aluminum plate (baseline), Hi-K™ plate and the PHP were tested with the electronics chassis cooling setup shown in Figure 9. The setup consisted of two cold plate channels at the top and the bottom of the electronics system chassis for uniform heat distribution. The 2-inch x 2-inch film heater was attached to the underside of the heat spreader. The coolant (water) temperature was set at 22 °C with a total flow rate of 0.9 gallon per minute. The heat transfer from the heat spreader to the sink was through the chassis by means of an ICE-Lok™. Steady state temperature measurements of the components were recorded at varying heater levels until the maximum temperature of 44 °C according to the MESSPS standards. In the case of the PHP, propylene at 50% charge ratio (volume basis) was charged in to the channels. During the testing, the system was insulated to mitigate heat losses to the environment.

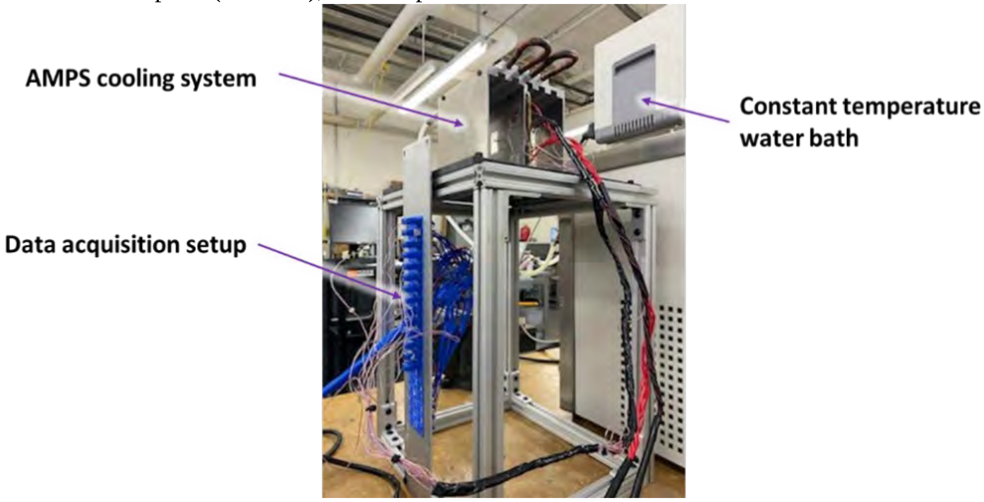

Figure 9. Experimental test setup for testing heat spreaders

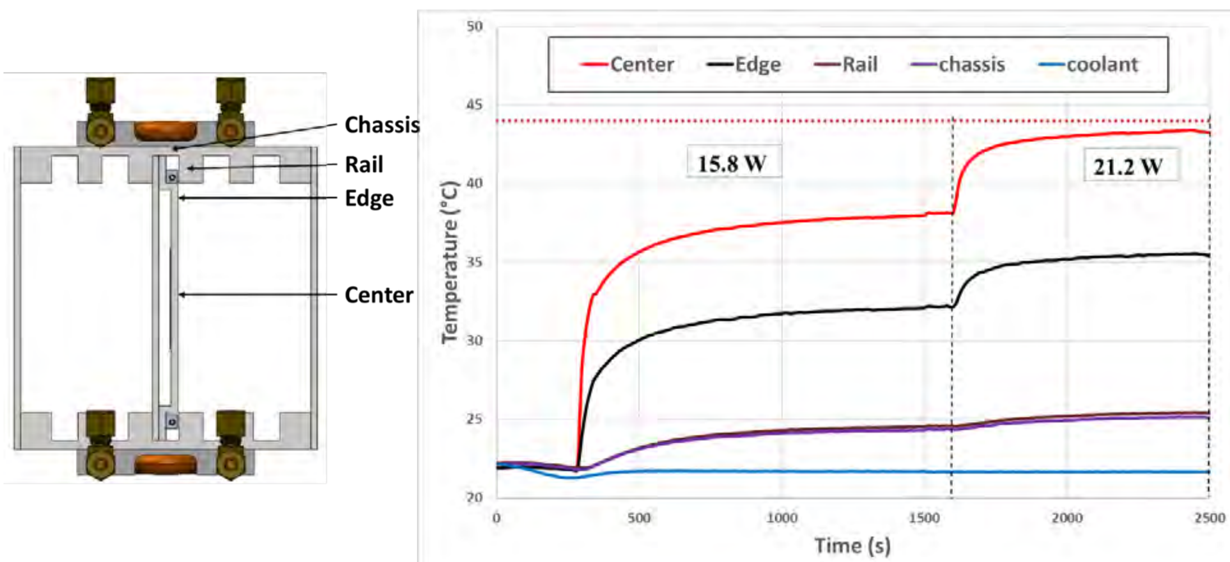

Figure 10. Cooling system component temperatures with aluminum plate heat spreader

The experiments were first performed with aluminum plate as the baseline. The temperature measurements of the different components are shown in Figure 10. The dotted red line is the maximum allowable temperature of 44 °C. The steady temperature difference between the center to the edge of the heat spreader was proportional to the heat applied. It was observed that the aluminum plate can transport up to 21.2 W heat (flux: 0.8 W/cm^2) with an overall system thermal resistance of 2 °C/W. The heat spreader thermal resistance was 0.75 °C/W.

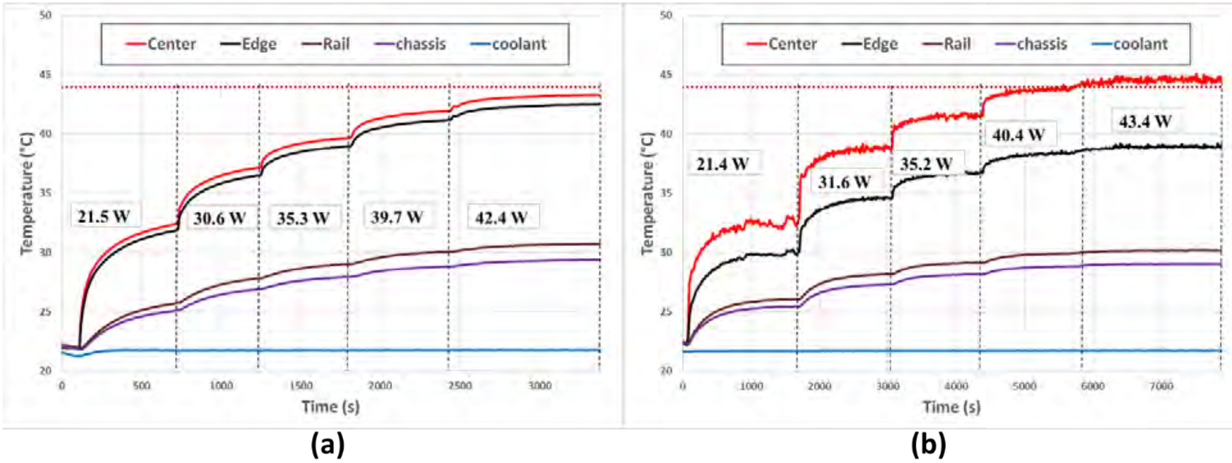

Figure 11. Cooling system component temperatures with (a) Hi-K™ plate and (b) PHP as heat spreader

Figure 11 shows cooling system component temperatures with Hi-K™ plate and PHP as heat spreaders in the cooling system. In the case of Hi-K™ plate as heat spreader, the maximum recorded temperature at 42.4 W heat input was 43 °C. While, the temperature drop between the center and the edge was small, the temperature drop from the heat spreader edge to the chassis rail was large. On the other hand, with PHP as the heat spreader, the mean oscillation temperature was closer to 44 °C at around 43.4 W. The temperature drop between the center to the edge was higher than the Hi-K™ plate. However, the temperature drop between the edge and the chassis was smaller than the Hi-K™ plate. In this test, no noticeable flow-induced vibration of PHP was observed. Potential reasons for unnoticeable vibration could be (1) the mass ratio between the fluid and solid is small enough so that the oscillation of slugs in the mini-channels will not induce overall device vibration (2) the channel are symmetrically distributed in the plate[11].

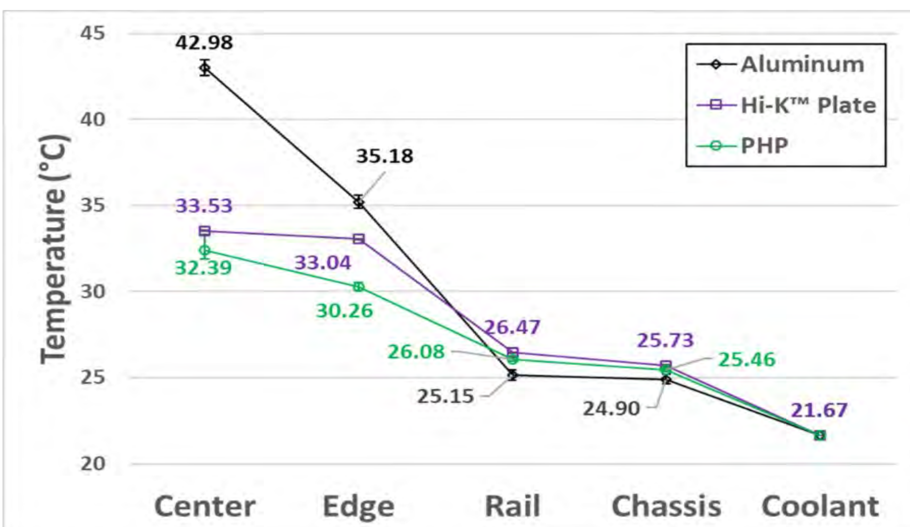

Figure 12. Instantaneous temperature profile of electronics cooling system

The cooling system with all three heat spreaders was compared with instantaneous temperature plots at 21 W of heat input at the film heater. The results are shown in Figure 12. The aluminum plate heat spreader had the steepest temperature gradient from the center to edge at about 7.8 °C. This is the component thermal resistance which is limited by the thermal conductivity of the material. The component thermal resistance was the highest of the three heat spreaders at 0.75 °C/W. On the other hand, the temperature drop from the center to the edge of the Hi-K™ plate was the lowest at only 0.5 °C, while for PHP, it was around 2.1 °C. The isothermal profile comparison from the heat spreader center to the edge is shown in Figure 13.

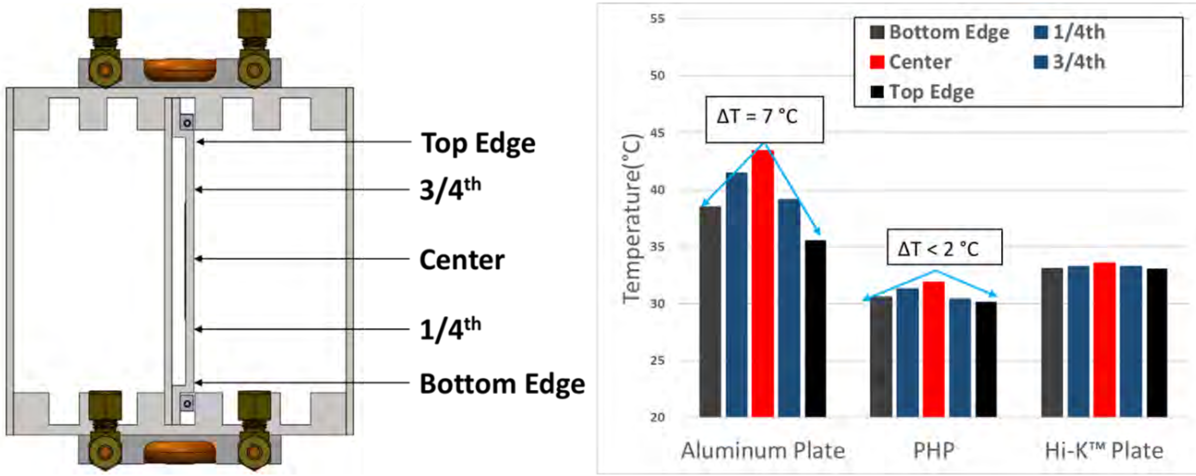

Figure 13. Heat spreader temperature distribution during testing

However, it is interesting to note that the edge to the chassis rail temperature drop for the PHP was the lowest of all the three heat spreaders. For both aluminum plate and the Hi-K™ plate, the temperature drop was 8.7 °C and 6.6 °C, respectively, while, for the PHP, it was only 4.2 °C.

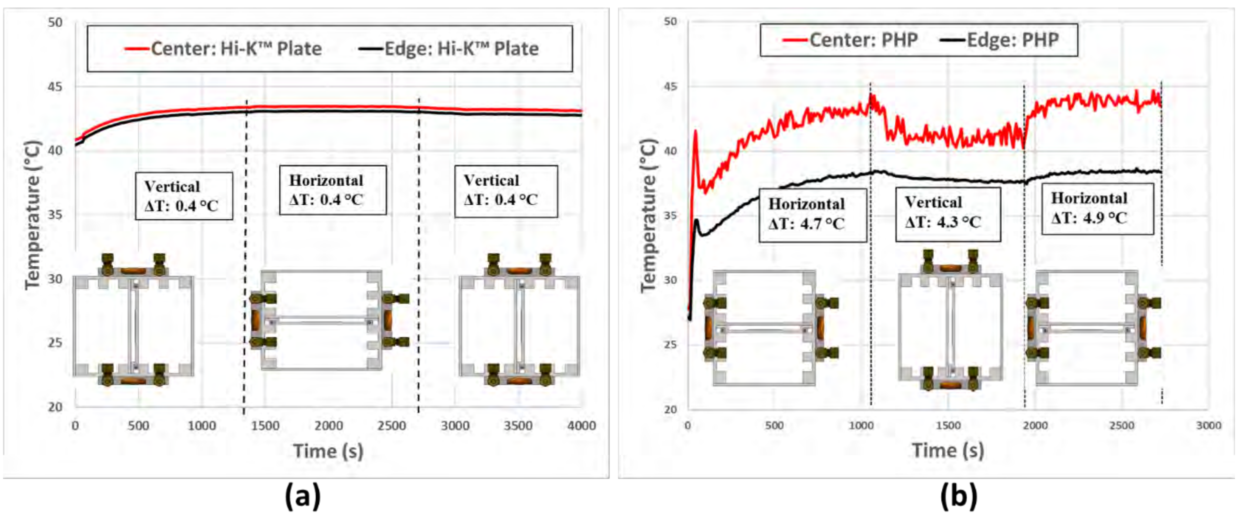

Figure 14. Gravity independence test of (a) Hi-K™ plate; and (b) PHP

A set of tests with horizontal and vertical orientation was performed to determine the influence of gravity on the performance of the Hi-K™ plate cooling system and the PHP cooling system. The test results are shown in Figure 14 at about 40 W heater power. At the start of the test, the Hi-K™ plate was first placed in the usual vertical configuration. The temperature drop from the center to the plane edge (same plane) was 0.4 °C. Then, the system was placed in horizontal configuration. No change in temperature drop from the center to the edge was observed. After this, the system was returned to vertical orientation. Hi-K™ plate heat spreading performance was found to be independent of gravity. PHP heat spreader system on the other hand, was first tested in horizontal configuration. The temperature drop from the center to the edge was 4.7 °C. Then the system was switched to vertical orientation, in which case, the temperature drop mildly changed to 4.3 °C. The system then was returned to horizontal orientation. The temperature drop from center to the edge was again about 4.9 °C. The change in PHP component thermal resistance was negligible, so it can be surmised that the PHP performance was also unaffected by gravity. The performance of both, Hi-K™ plate and PHP heat spreader cooling system is thus independent of gravity.

VI. Finite Element Analysis

FEA was performed to analyze the heat transfer paths of the three heat spreaders from center to the card edges, where ICE-Lok™ interface with a chassis. The results are shown in Figure 15. In this FEA, the applied heater power was 21 W at the center of the heat spreaders, and the convective heat transfer coefficient of 500 W/m^2-K at 20 °C reference temperature was applied at the card stepped edges. The temperature drop across the heat spreader edge to the stepped plane was highest in the case of aluminum plate, followed by heat spreader and lowest in the case of PHP.

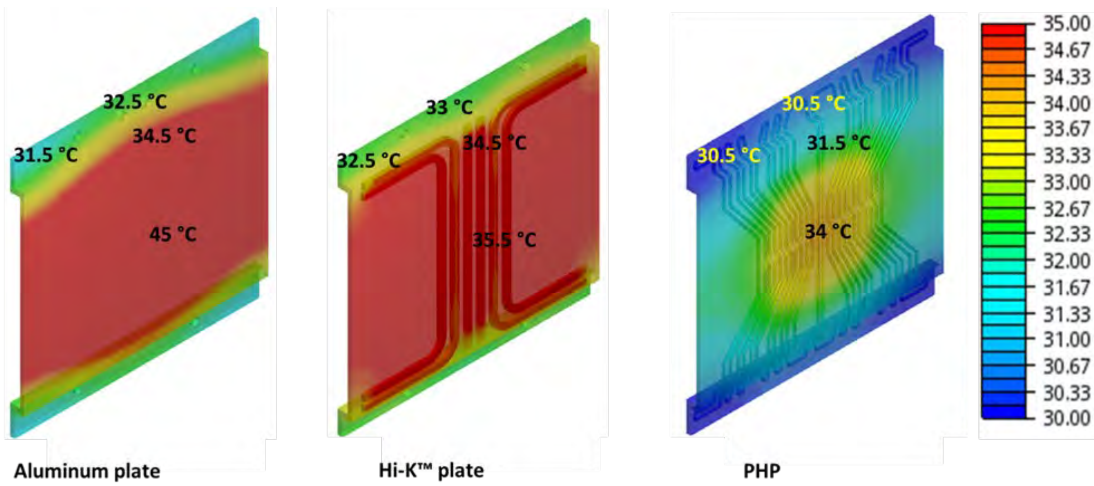

Figure 15. Temperature profile of heat spreaders to analyze temperature distribution from the edge to the stepped plane

This reason can be explained as follows:

- As the CAD model shows (Figure 3), the two-phase PHP channels extend all the way to the stepped edge of the heat spreader where the ICE-Lok™ interfaces with the chassis. The two-phase channels have higher thermal conductance compared to the solid conduction. The heat pipes of the Hi-K™ plate only extend until the edge of the heat source plane, and not on the stepped edge. As a result, the heat transfer along the stepped plane is by base plate conduction in the case of the Hi-K™ plate.
- Comparing the aluminum plate and the Hi-K™ plate: the two-dimensional conduction plane heat transfer originates near the stepped edge for the Hi-K™ plate, while for the baseline, heat transfer is by conduction only from the center to the stepped edge.

So, it is evident that two-phase channels of the PHP reduce the thermal resistance across the stepped edge plane to the chassis rails. The system thermal resistances with aluminum plate, Hi-K™ plate and PHP as heat spreaders were 2 °C/W, 1.1 °C/W, and 1 °C/W, respectively.

VII. Conclusions

ACT developed and tested two-phase based Hi-K™ plate and PHP as advanced heat spreaders for 3U card electronics cooling. Hi-K™ plate is copper-water heat pipe embedded aluminum plate. In the PHP, propylene was used as the working fluid due to its suitability in working temperature and higher merit number over other common working fluids. The unique feature of the PHP is that the capillary channels can accommodate the sharp edges like that of the ICE-Lok™ interface plane. Trade study of both Hi-K™ plate and the PHP showed heat handling capability up to 80 W and higher. Experimental results showed that both Hi-K™ plate and PHP can reduce the system thermal resistance by up to 50% from over 2 °C/W to around 1 °C/W in comparison to the aluminum plate (baseline). This can be attributed to the superior heat transfer characteristics of the two-phase working fluid in both the Hi-K™ plate (water) and the PHP. . Table 1 summarizes the performance of the two heat spreaders.

Table 1. Summary of performance of heat spreaders for 3U electronics cooling

Heat spreader	Overall system thermal resistance (°C/W)	Maximum heat load at 44 °C maximum temperature (W)	Weight (g)*
Aluminum plate (baseline)	2.07	21.3	153.8
Hi-K™ plate	1.1	42.4 (+98%)	170.4
PHP plate	1.02	43 (> 100%)	137.8

* Weight is based on the same thickness. The Hi-K™ plate weight can be further reduced by optimizing the number of heat pipes and removing excessive base plate material. Also, reducing heat spreader thickness can further reduce the component weight for all three solutions.

The performance of the PHP heat spreader developed in this program is similar to that of the Hi-K™ plate, but is lighter than the other two options. This is because the milled out solid materials that form the channels is replaced by saturated two-phase working fluid, which is less dense. The advantage of the PHP over aluminum plate is that the two-phase channels extend onto the stepped edges, which improves the thermal conductance across the heat spreader-ICE-Lok™ interface.

Acknowledgments

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