High Temperature and High Heat Flux Thermal Management for Electronics

David B. Sarraf
Advanced Cooling Technologies, Inc.
1046 New Holland Ave.
Lancaster, PA 17601
717.295.6059 (v) 717.295.6064 (f)
Dave.Sarraf@1-act.com

William G. Anderson
Advanced Cooling Technologies, Inc.
1046 New Holland Ave.
Lancaster, PA 17601
717.295.6059 (v) 717.295.6064 (f)
Bill.Anderson@1-act.com

Key words: Heat Pipe, High Temperature, Water, Monel, Titanium, Halide

ABSTRACT

Four new cooling technologies are under development with applications in electronics cooling: 1. High *temperature water heat pipes*: Titanium/water and Monel/water heat pipes have been developed and life tested at temperatures up to 280°C, much higher than conventional copper/water heat pipes (150°C). The titanium heat pipes can also reduce the heat pipe mass. 2. *High temperature Water Loop Heat Pipes (LHPs)*: These titanium/water LHPs extend the operating temperature range for LHPs from the current 60°C to 200°C. 3. *Cold Plates with Oscillating Flow*: A cold plate uses the oscillating flow of a single phase fluid to spread the heat. Preliminary results show effective thermal conductivities of up to 240,000 W/m K (versus 1,200 W/m K for diamond and 90,000 W/m K for heat pipes), and the ability to remove heat fluxes as large as 1,200 W/cm^2. 4. *Hybrid pumped/wick system with multiple evaporators*: In a hybrid pumped/wick system, water flows through an artery in contact with a wick. Water evaporates from the wick, cooling the electronics. Capillary forces pull replacement water into the wick, passively adjusting the water flow rate. The use of a pump allows multiple evaporators to be used. Very high heat fluxes can be removed at very low thermal resistances (as low as 0.16 °C/W/cm^2).

INTRODUCTION

Conventional silicon-based semiconductors are limited to junction temperatures of about 150°C or less. Given a finite junction-to-case resistance, thermal management solutions for such devices are typically required to function between room temperature and about 120°C. In the case of phase change devices such as heat pipe and vapor chambers, the material system of choice is copper/water. In that temperature range water has the highest figure of merit, or the best combination of surface tension, latent heat, liquid viscosity, and liquid density. Copper has high thermal conductivity and reasonable strength at the required operating temperatures, which leads to thin walls and low temperature drops. Compatibility of the copper/water heat pipes is also well established, with some work going back nearly 40 years [Basiulis, 1975]. Finally, it is possible to produce a variety of useful wick structures in copper/water heat pipes, including sintered powder, extruded grooves, and circumferential screen wicks.

Copper/water heat pipes are a much less satisfactory solution for high temperature electronics, or those operating at temperatures of 200°C or higher. The major problems are mass, strength, and working fluid vapor pressure. Copper loses strength quickly with temperature, while the working fluid vapor pressure rises exponentially. At 200°C the yield strength of copper has fallen to 50% of its room temperature value while the working fluid vapor pressure has gone up almost 500-fold to 200 PSI. At 250°C the yield strength has fallen even more and the vapor pressure is over 500 PSI. This requires very thick, and consequently very heavy, heat pipe walls for sufficient strength. It also makes some structures, such as flat heat pipes or vapor chambers, impractical or expensive due to the very thick walls needed, or the need for elaborate and costly internal bracing to prevent bowing of the contact surfaces or rupture of the walls.

Aside from operating temperature, a second major problem with some high temperature electronics is the need to collect heat over large areas or at high fluxes, and to move it over long distances. High temperature electronics often consist of multiple power switches working in tandem. This requires collection of heat from multiple packages and often requires keeping them near the same operating temperature. Power switches also frequently produce high heat fluxes. As operating temperature increases, the surface tension of a two-phase working fluid falls. This reduces the transport distance capability and the heat flux capability of conventional passively-pumped two-phase heat transfer devices.

One solution to these problems is high-strength wall materials such as Monel and titanium. Life testing has shown long-term compatibility between those two materials and water working fluid. The production in these materials of all of the conventional wick structures including grooves, sintered powder, and screen, extends the useful range of water by providing a strong but light containment for the high vapor pressure with heat pipe performance and life equivalent to copper/water.

A second solution is alternative heat transfer devices. These include passive devices such as loop heat pipes as well as actively-pumped devices such as oscillating flow heat spreaders and hybrid capillary pumped loops. These can provide better performance than simple heat pipes, such as moving heat over large distances, handling very high heat fluxes, and the ability to use multiple heat input sources while maintaining isothermality.

The following sections contain a discussion of each of these solutions and their status as applied to high temperature electronics cooling.

HEAT PIPES

Heat pipes are passive devices that transfer heat by two-phase flow of a working fluid. Shown in Figure 1, a heat pipe is a vacuum tight device consisting of an envelope or container, a working fluid, and a wick structure. Heat enters at the evaporator and vaporizes the liquid working fluid inside the wick. The vapor,

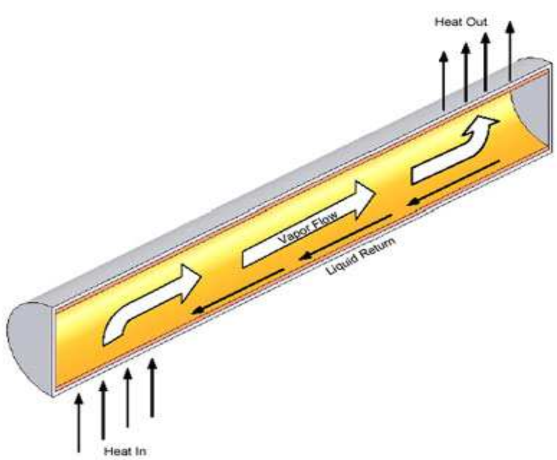

Figure 1. Conventional Heat Pipe.

carrying the latent heat of vaporization, flows towards the cooler condenser section. There, it 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.

High temperature heat pipes pose unique challenges, including strength, capillary pumping, and life. While water is still the best working fluid based on its figure of merit, its high vapor pressure makes containment more difficult. Copper, already a relatively weak material at room temperature, loses strength at high temperatures. Simply increasing the wall thickness to accommodate the high vapor pressure of water will make the heat pipe too heavy. Other materials such as titanium and monel are needed to yield a heat pipe having adequate strength with reasonable mass. Capillary pumping is a second challenge. Capillary pumping pressure, or the force that returns the working fluid to the evaporator region, is proportional to the liquid surface tension, and the surface tension of water is falls rapidly above 150°C. This makes any wick less effective at high operating temperatures. Fabrication of an adequate wick is yet another challenge. A variety of wick structures can readily be fabricated in copper, such as drawn grooves or threads, sintered powder metal, screen mesh, and metal felt. These are less easy to produce in other materials such as monel or titanium due to their reduced ductility and workability. A final challenge is heat pipe life. While water has long been shown to be compatible with copper, less data exists for monel or titanium. Moreover, the high operating temperature accelerates aging and makes a good life test more difficult to conduct.

ACT has produced several different heat pipes with a variety of useful wick structures in Monel and titanium. Some of them are shown in Figure 2, which are end views of 1-meter long titanium heat pipes with longitudinal axial grooves. They are some of several heat pipes fabricated in support of a high-temperature lunar radiator program. Those heat pipes were designed to operate at 220°C and carry up to 350 Watts of power. Candidate wick structures included axial grooves, screen, and conventional sintered powder metal. Heat pipes using these wick structures were eventually embedded in carbon-composite radiator panels. [Anderson, et.al., 2006] Proper operation of the panels and heat pipes was demonstrated in a thermal-vacuum chamber. Other high-temperature heat pipes have included a family of temperature calibration furnaces. Those were made of Monel with screen wicks and featured a re-entrant black-body cavity. They could operate at temperatures of up to 250°C. [ACT, 2008]

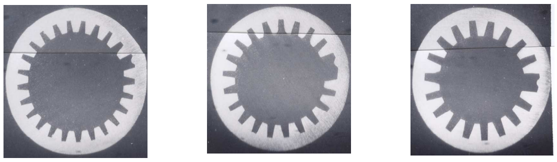

Figure 2. 1-meter long titanium heat pipes with longitudinal axial grooves: 23 grooves, 0.51 mm x 1.02 mm (0.020” x 0.040”), 19 grooves, 0.64 mm x 1.27 mm, and 17 grooves, 0.76 mm x 1.52 mm.

ACT has an ongoing life test program for titanium and monel heat pipes [Anderson, 2007]. This program is based on 8” long cylindrical heat pipes. They are electrically heated by cartridge heaters fastened to an aluminum heater block at the evaporator. They are cooled by natural convection. An array of thermocouples mounted along the axis of each heat pipe measures the temperature gradient. The heat pipes are mounted in a stainless steel box which is purged with argon. The heat pipes are operated at a nominal temperature of 280°C to accelerate aging. Periodically, their temperature is reduced to 70°C. This lowers the vapor pressure and allows any non-condensable gas to expand into the condenser region. That produces a temperature gradient which can be detected by the thermocouple array.

Materials currently under life test include Monel 400, Monel 500, cupronickel, and titanium. Monel 400 is an alloy consisting of 63% nickel and 30% copper. Monel 500 also contains titanium and aluminum and can be precipitation hardened. Cupronickel contains 70% copper and 30% nickel; it is the inverse of Monel 400 and is mainly useful for marine applications. All have been shown to be compatible with water at high temperatures. Figures 3 and 4 show representative data for titanium and monel, respectively. The titanium heat pipes started with a high initial temperature gradient and had to be vented soon after construction. After this initial passivation period those heat pipes ran well with no further sign of gas buildup. The Monel 400 life test pipes ran well from the start with only a slight buildup of non-condensable gas. The gradients shown in both charts are for operation at 70°C; the temperature gradient in either pipe was undetectable at the normal test temperature of 280°C.

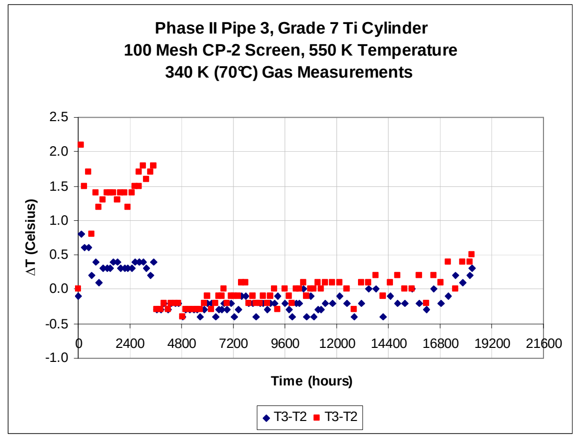

Figure 3. Life test results for titanium heat pipe with water working fluid. After initial period of passivation the heat pipe operated stably with minimal gas generation.

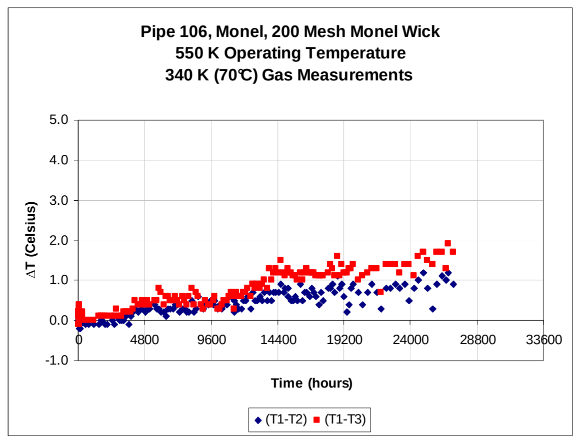

Figure 4. Life test results for Monel 400 heat pipe with water working fluid.

LOOP HEAT PIPE

The loop heat pipe (LHP) is a passive, capillary-driven device that solves the problem of moving heat over long distances against high gravity heads. Shown schematically in figure 5, the key components are the wick, body, compensation chamber, transport lines, and condenser. Working fluid evaporates from the wick at the wall/wick interface. The vapor travels down grooves machined in the wall of the wick, flows through the vapor transport lines and is delivered to the condenser. The condensed liquid travels back to the compensation chamber, which then delivers it to the interior of the wick. Figure 6 shows the details of the wick, including the longitudinal and circumferential grooves that carry vapor away from the wick.

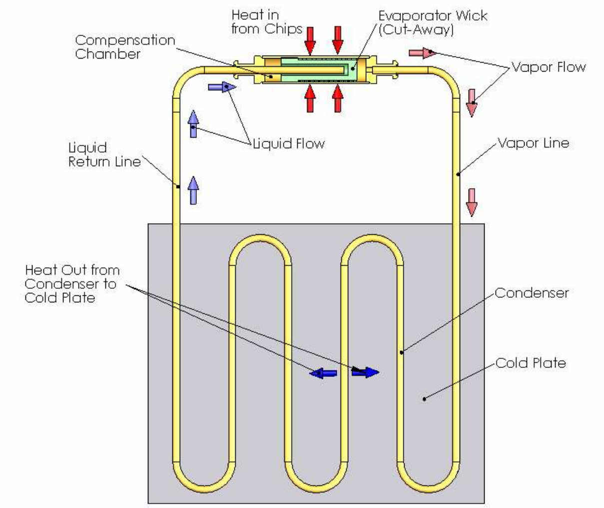

Figure 5. Schematic of Loop Heat Pipe, showing major components and fluid flow.

Figure 6. Detail of a LHP wick, showing the circumferential and axial grooves used to remove vapor from the heated surface.

Loop heat pipes have three major advantages over other passive heat transport devices. They can move heat over long distances, can overcome significant gravity heads, and use smooth-bore transport lines with no capillary lining. These advantages stem from the evaporator wick design. Since liquid flow through the wick is radial rather than axial, the path is short and the pressure drop is low. This allows the use of smaller pores than can be used with conventional heat pipes, and therefore allows higher capillary pumping pressure.

LHPs have typically been used in spacecraft for below-ambient temperature cooling. The long transport lines allow moving heat directly to a radiator panel, and the small transport lines can be coiled into springs that allow a radiator panel to be unfolded on orbit or allow the evaporator to be mounted on a flexible gimbal. The most popular working fluid is ammonia. Its high vapor pressure contributes to low mass flow rates and low temperature drops, and it works well at conventional electronic cooling temperatures (~25°C – 40°C). Lower-temperature working fluids used in LHPs include propylene, nitrogen, oxygen, neon, helium, and hydrogen [Hoang, 2002]. None are suitable for high-temperature electronics cooling because their critical temperatures are too low. Water has not previously been used because it is not compatible with the typical materials of construction, including stainless steel and aluminum.

ACT recently completed fabrication and test of high-temperature LHP which had a titanium envelope and wick and used water as the working fluid. [Hartenstine, 2008]. Shown in Figure 7, the evaporator portion was 8" long with an outer diameter of 1". The condenser was a 12 inch square plate. The liquid and vapor transport lines were 2 meters long. They were coiled into springs to make the test article more compact. This LHP carried up to 590 Watts at a vapor temperature of 140°C.

Figure 7. Titanium/water loop heat pipe that carried 590 Watts at vapor temperature of 140°C.

One application of high-temperature LHPs is the Full Authority Digital Engine Control (FADEC), which controls jet engine operation. It is historically mounted on the engine case to minimize the routing length of the sensor and actuator wiring. This also makes the electronics run very hot. The current design uses fuel to cool the FADEC, however, this often limits the allowable ground or flight idle time before the fuel is too hot to cool the FADEC. The operating temperature is in the 80 to 100°C range, which is too high for ammonia LHPs. A water LHP can transfer the FADEC heat load to an alternate sink, typically located several meters away. This eliminates the use of fuel for cooling the FADEC, isolating it from the fuel cooling system. In turn, the allowable fuel temperature is increased, increasing idle time

OSCILLATING FLOW HEAT SPREADERS

An Oscillating Flow Heat Spreader (OFHS) consists of a length of tubing that is filled with a working fluid. A mechanism at each end of the tube drives the fluid back and forth within the tube to create an oscillatory motion. The fluid has no net motion but simply oscillates back and forth. The heat transport mechanism is shown in Figure 8, which is a schematic cross section view of one tube wall and a volume of fluid in contact with the wall. Heat is transferred by conduction between the tube walls and the fluid. A given volume of fluid will absorb heat from the warm tube wall at t_0. Between t_0 and t_1 the fluid volume is advanced to a new position, where the wall is cooler. There, at t_1, the wall absorbs heat from the volume of fluid. The fluid volume then returns to its original position and repeats the process. Other adjacent volumes behave similarly, which results in macroscopic heat transport from the heat source to the heat sink.

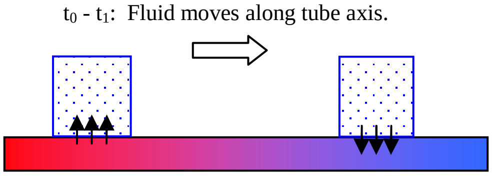

Figure 8. Schematic of OHFS Showing Operation.

The OFHS has several advantages over other means of heat transfer. Much like a conventional pumped system, the OFHS can move large amounts of heat over long distances. They both use smooth-bore tubing which can be readily bent to cover any arbitrary heat input and heat output areas. In contrast, the OFHS frequency and amplitude can be tuned to maximize either heat transport or heat flux capability. Unlike devices such as the LHP, the OFHS is independent of gravity and has no discrete heat input or output regions. Heat can enter or leave at any point on the OFHS tubing. Unlike other capillary-driven devices, the OFHS is not subject to dryout, where the rate of heat flow exceeds the wick's fluid pumping capability. The OFHS fill ratio exceeds 90%, so fluid will always be present at any reasonably-sized heat input region.

Several prototype OFHS systems were built and tested. An early system is shown in Figure 9. It was based on 1/8" (3.15mm) OD x 0.018" (0.46 mm) wall copper tubing. It had one discrete heat input region of 0.5 cm^2 and two discrete output regions, each covering 2" (5.1 cm) of tubing. The distance between the input and output was 14.5 inches (36.8 cm). Based on a matrix of tests which varied fill ratio and the amplitude and frequency of oscillation, this first prototype was shown to carry over 600 watts, or 1200 W/cm^2. The equivalent thermal conductivity of the tubing was 120,000 W/m*K. To contrast, a copper/water heat pipe of the same length and diameter would carry 10 watts or less and reliably handle heat fluxes of 40 $Watts/cm^2$ or less.

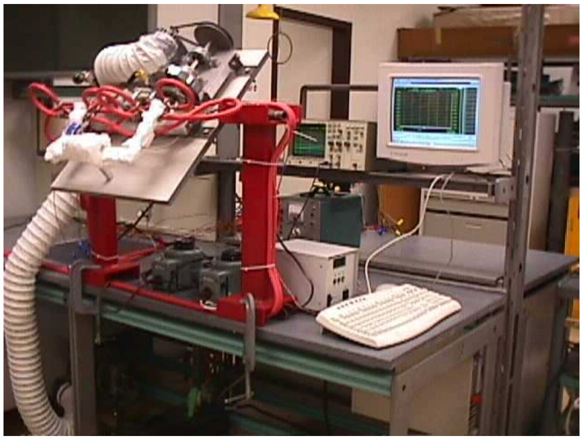

Figure 9. Oscillating Flow Heat Spreader Breadboard Demonstration Device that carried over 600 Watts with input flux of 1200 $Watts/cm^2$

A second prototype OFHS is under development. [Fan, 2008]. It is embedded in chill block used to cool an array of three IGBT modules. The OFHS increases the lateral conductivity of the chill block material and reduces local hot spots beneath the IGBT modules. Each module covers an area of 4.48" x 4.88" and dissipates 1000 Watts. The OFHS reduced local hot spots by 5°C or more.

Although the two prototype devices were run at relatively low temperatures, 100°C or less, they could be run hotter with little or no change in design. The working fluid, water, would stay the same. The copper tubing could be retained since the thick walls are a necessary part of the heat exchange process and the small tubing diameter would limit the hoop stress in the walls. If necessary, either Monel or titanium tubing could be used. Both have higher strength, although Monel would be more favorable due to its higher thermal conductivity and better resistance to oxidation.

HYBRID TWO-PHASE PUMPED LOOP

A hybrid two-phase pumped loop (HTPL) combines the high heat flux capability and robust operation of conventional pumped two-phase loops with the simplicity and reliability of capillary mechanisms. Shown below in Figure 10, the HTPL consists of a liquid reservoir, a small pump, a cold plate, and a condenser. The pump circulates liquid from the reservoir to a capillary feeder manifold in the cold plate. As heat enters the cold plate it draws liquid from the feeder manifold and vaporizes it. The vapor exits the cold plate and is sent to the condenser, where it gives up its absorbed latent heat. Any unused liquid remaining in the feeder manifold passages is returned to the reservoir by the pump.

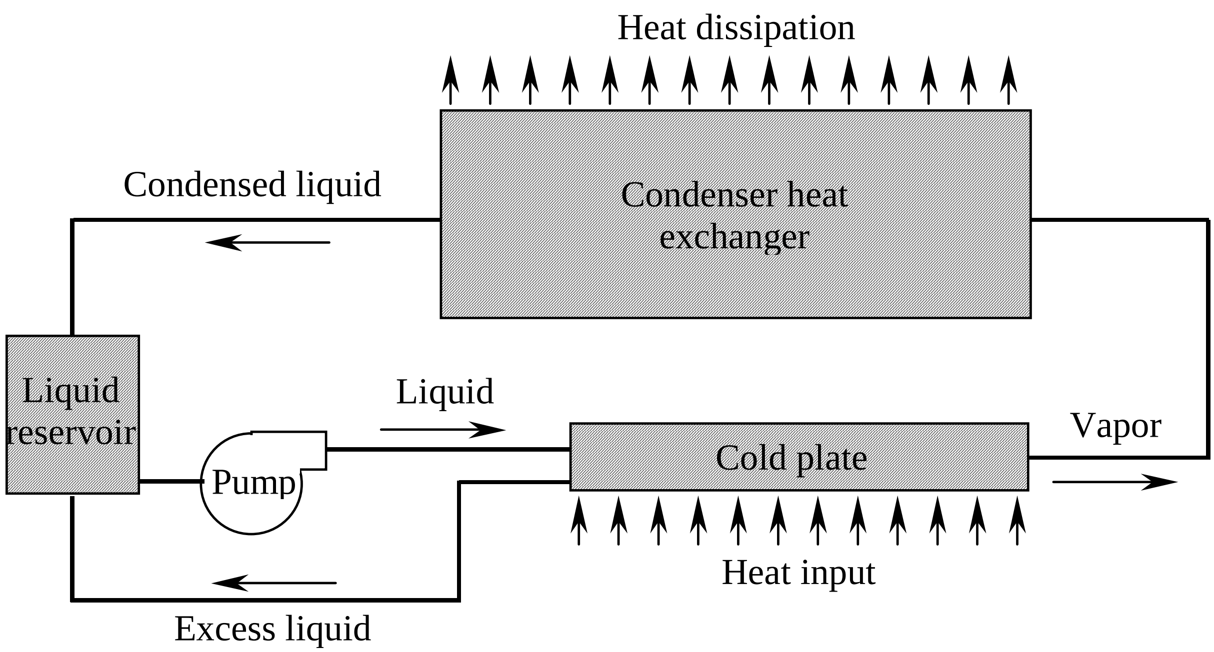

Figure 10. Schematic of Hybrid Two-Phase Pumped Loop (HTPL) System showing Major Components and Fluid Flow Path.

The feeder manifold is a capillary barrier that passively provides the proper amount of liquid to the evaporator. This makes the system self-regulating, and sidesteps the need to vary pump speed with heat load or have control valves to manage changes in flow rate as power or temperature change. It also assures that the wick remains wetted, which allows it to dissipate high heat fluxes and remain isothermal even over large heat input areas and multiple evaporators in parallel.

The features of the hybrid loop make it well-suited for cooling devices such as IGBT arrays in power converters. IGBTs dissipate large heat loads and generate high heat fluxes. Since their electrical properties vary with changes in operating temperature, it is desirable to keep all of the modules at the same temperature as well as remove their waste heat effectively.

Several different prototype HTPL systems have been fabricated and tested. Shown in Figure 11, one prototype was a vibration-hardened brassboard demonstration unit with four evaporators [Park, 2007]. Each evaporator measured 7.6 cm x 17.8 cm. It carried up to 10 kW, or 2.5 kW per evaporator, for a heat flux of 30W/cm² per evaporator. The measured evaporator thermal resistance was as low as 0.17°C-cm²/W and remained relatively constant over varying heat loads above 500W (or 3.7W/cm²). Moreover, the system was self-balancing. The heat load for each evaporator could vary within a wide range while the system continued to operate properly.

A second system was built to cool the IGBTs in a commercial power inverter module. That system had hree evaporators. The area of a single evaporator was 31.5 cm^2, and the heat load was 6.3 kW, or 2.1 kW per evaporator. The heat flux was 67 W/cm^2 and the thermal resistance of each evaporator was 0.031 K/Watt.

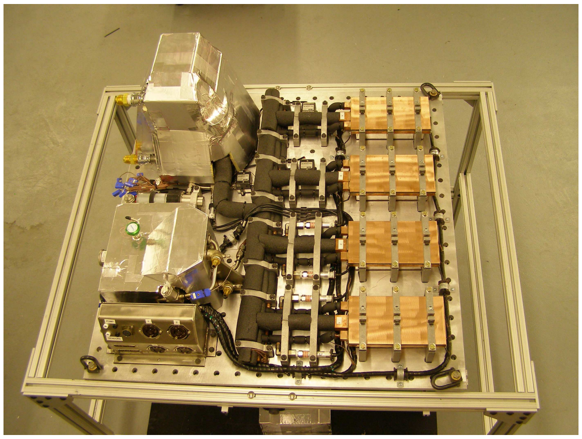

Figure 11. Hybrid Pumped Capillary Loop System that carried 10 kW with an input flux of 30W/cm².

As with the OFHS, the HTPL systems to date have been built in copper, however there is no technical reason they could not be extended to high-temperature materials such as titanium or Monel. The heat pipe and LHP work discussed previously have shown that the wick sintering and joining technologies are well established and will provide long life.

CONCLUSIONS

Four different heat transfer devices have been presented that are suitable for high-temperature electronics cooling. Heat pipes are the most mature, with a variety of viable construction methods that yield proven life and thermal performance at the temperatures of interest. Loop heat pipe technology has been demonstrated, with the construction of an all-titanium prototype that met its performance goals and conformed closely to the predictions of a mathematical model. One active device, the Oscillating Flow Heat Spreader, was demonstrated at lower temperatures. It has no technical hurdles to cross to reach higher operating temperatures. A second active device, the Hybrid Capillary Pumped Loop, has been demonstrated and well characterized at lower temperatures, removing heat fluxes up to 67 W/cm^2, but remains to be proven at high temperatures. It would bring significant benefit to high temperature electronics, however it would require a significant effort to construct and test at higher temperatures such as the 150°C to 200°C range.

ACKNOWLEDGMENTS

The high temperature heat pipe and LHP work was sponsored by NASA Glenn Research under contracts NNC04CA32C and NNC05TA36T (Duane Beach was the technical monitor), contract NNC07QB05P (David Ellis was the technical monitor), and contract NNC06CB38C (Eric Sunada, then Michael Paukin of JPL were the technical monitors). The oscillating flow heat spreader was sponsored by the U.S. Naval Surface Warfare Center under contract NNC04CA32C (Mark Zerby was the technical monitor). The hybrid loop system research was sponsored by U.S. Army TACOM under contract W56HZV-04-C-0704 (Jeffery Perez was the technical monitor).

REFERENCES

ACT, "Heat Pipe Blackbody Cavity," http://www.1-act.com/hpbcd.pdf, April 8, 2008.

Anderson, W. G., Bonner III, R. W., Dussinger, P. M., Hartenstine, J. R., Sarraf, D. B., and Locci, I. E., "Intermediate Temperature Fluids Life Tests – Experiments," Proceedings of the 2007 IECEC, AIAA, St. Louis, MO, June 25-27, 2007.

Anderson, W. G.., Dussinger, P. M., Bonner III, R. W., and Sarraf, D. B., "High Temperature Titanium-Water and Monel-Water Heat Pipes," Proceedings of the 2006 IECEC, AIAA, San Diego, CA, June 26-29, 2006.

Basiulis, A., and Prager, R. C., "Compatibility and Reliability of Heat Pipe Materials," AIAA 10th Thermophysics Conference, Denver, CO, May 27-29, 1975.

Fan, A, D. Fulmer and J. Hartenstine, "Experimental Study of Oscillating Flow Heat Transfer," Micro/Nanoscale Heat Transfer International Conference, Tainan, Taiwan, January 2008

Hartenstine, J. R., Anderson, W. G., and Bonner III, R. W.,, "Titanium Loop Heat Pipes for Space Nuclear Radiators," Proceeding of STAIF 2008, Albuquerque, NM, February 10-14, 2008.

Hoang, T.T, T. O'Connell, J. Ku , D. Butler, T. Swanson, "Large Area Cryocooling for Far Infrared Telescopes", SPIE 11th Cryogenic Optical Systems and Instruments, Jul-Aug 2003.

Park, C., Vallury, A., Zuo, A, Perez, J., and Rogers, P., "Electronics Thermal Management Using Advanced Hybrid Two-Phase Loop Technology", 2007 ASME-JSME Thermal Engineering Summer Heat Transfer Conference, Vancouver, Canada, July 2007