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Electronics Cooling Using High Temperature Loop Heat Pipes With Multiple Condensers

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ABSTRACT

In military aircraft, electronics are often subjected to operating environments well beyond their survival temperatures and with limited heat sinks. The current approach is to use a Liquid Cooling System (LCS) with either vehicle fuel or Polyalphaolephin (PAO) to cool electronics. However, advanced military platforms have found this approach limits their operational effectiveness. A thermal management system for electronics cooling in high temperature avionics environments is under development using Loop Heat Pipe (LHP) and heat pipe based technology. The system reduces thermal energy transport inefficiencies within electronics enclosures, identifies potential sinks to provide continuous heat rejection over the operating envelope of the platform, and provides passive thermal energy transport from the electronics enclosure to selected sinks.

The system developed to accomplish these tasks is divided into two subsystems. The first subsystem is responsible for improving thermal transport within the electronics enclosure and consists primarily of heat pipe assemblies. Model results of the first subsystem show considerable improvements over the current implementation. The overall temperature gradient within a generic electronics box decreased from 42.7°C (76.9 °F) to 17.8 °C (32.0 °F), increasing the allowable sink temperature from 66.7 °C (152.1 °F) to 91.7 °C (197.1 °F). This increase allows for more freedom in sink selection, which is typically limited aboard military platforms. The second subsystem transports thermal energy from the external surface of the enclosure to appropriate sinks and consists primarily of a LHP. At this stage, several sinks have been identified and evaluated. Final sink selection is underway. Depending on sink temperature and capacity throughout the operating envelope of the platform, multiple sinks may be used. During operation, the LHP will passively select the appropriate sink.

INTRODUCTION

In military aircraft, electronics are often subjected to operating environments well beyond their survival temperatures and with limited heat sinks. While this alone presents a thermal management challenge, the recent trend towards more compact electronics assemblies and integrated subsystems compounds this problem. The current approach is to use a Liquid Cooling System (LCS) with either vehicle fuel or Polyalphaolephin (PAO) to cool electronics. However, advanced military platforms have found this approach limits their operational effectiveness. In some cases, these platforms have been rendered inoperable due to overheated electronics. A more effective thermal management approach is needed to overcome this shortcoming, which will allow improved performance of current military vehicles and future designs.

ACT is working with AFRL and industry partners to address this issue and provide a robust thermal management approach for electronics required to operate in high temperature environments. The first step was to review current thermal management practices. Three areas for improvement were identified. First, current electronics boxes are robust, but often have large internal temperature gradients. Second, some electronics are in high temperature boxes, but are not insulated, so that the majority of the thermal energy removed by the LCS was generated outside the electronics enclosure. Finally, sink availability is often limited for these assemblies due to their location in a high temperature environment. The current thermal management system has two primary goals: internal temperature gradient reduction and passive thermal energy transport to improve sink availability.

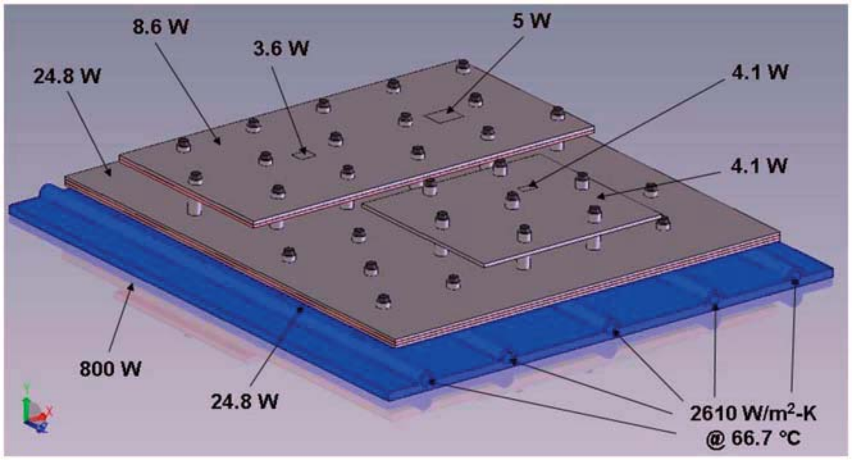


Figure 1. Lower half of the Representative Electronics Box Assembly.

In cooperation with AFRL and industry partners, a thermal model for a Representative Electronics Assembly (REA) was developed. The lower half of the REA is shown in Figure 1. The half-REA has three circuit boards, one lower and two upper. The circuit boards are mounted to aluminum plates, and the plates are mounted to the liquid cooled box with a series of aluminum posts. In Figure 1, the powers in small squares represent high power chips, the rest of the power is assumed to be distributed uniformly. The thermal results for the baseline REA were checked by industry partners to ensure that the temperature distribution was similar to actual systems.

INTERNAL TEMPERATURE GRADIENT REDUCTION

There are two primary shortcomings with the REA. First, the enclosure was not insulated from the high temperature environment. This allowed for over a kilowatt of ambient heat gains compared to the actual waste heat generated by the electronics of approximately 100 W. To maintain electronics temperatures, this additional heat must be removed by the LCS, and increases the overall ΔT in the box. Second, high thermal resistances exist between the electronics and LCS. This produces a high temperature gradient between the LCS and electronics. This gradient requires the LCS to operate with a lower required inlet temperature and places constraints on the operating conditions of the platform. In addition, a lower inlet temperature results in a lower outlet temperature and further constrains the already limited sink selection.

As shown in Figure 2, one reason for the large temperature gradients is the relatively tortuous path for heat removal from the chips on the inner circuit boards:

1. Chip to the Circuit Board.

2. Inner circuit Board to inner heat sink (if installed, this is an aluminum plate).

3. Inner Heat Sink to aluminum post.

4. Aluminum post to outer circuit board heat sink.

5. Outer circuit board heat sink to aluminum post.

6. Aluminum post to case.

7. Case to liquid.

To address these problems and reduce the internal thermal gradients, a multi-pronged approach was proposed (ACT, 2010):

1. Adding insulation to reduce the heat that must be removed by the liquid cooling system.

2. Using heat pipes to directly cool critical components.

3. Replacing the solid aluminum posts with heat pipes.

4. Replacing the solid aluminum plates with HiK plates.

A schematic of the proposed scheme is shown in Figure 3. HiK plates consist of heat pipes embedded in a plate as shown in Figure 4a below (ACT, 2009). This figure shows the HiK plate prior to sealing and finishing. The heat pipes are soldered in place. Finishing provides a smooth surface and produces the final product as shown in Figure 4b. In general, a HiK plate has a thermal conductivity comparable to high performance composite materials but can be manufactured at a reduced cost. HiK Plates weigh less than their solid counterpart, have been fabricated to thicknesses of 4 mm (0.16″), and have shown thermal conductivities of 500 to 800 W/m K (versus 180 W/m K for Aluminum). In addition, the embedded heat pipes eliminate hot spots and enable a nearly isothermal surface. For applications with high variation 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 FADEC enclosure and internal heat sink

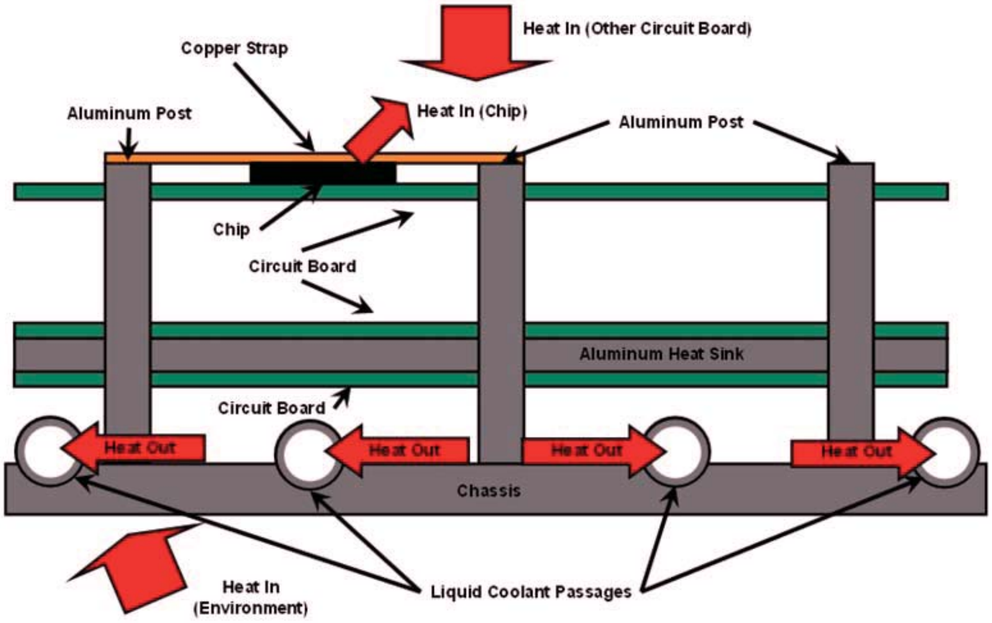


Figure 2. Thermal Schematic of electronics box Internal Components.

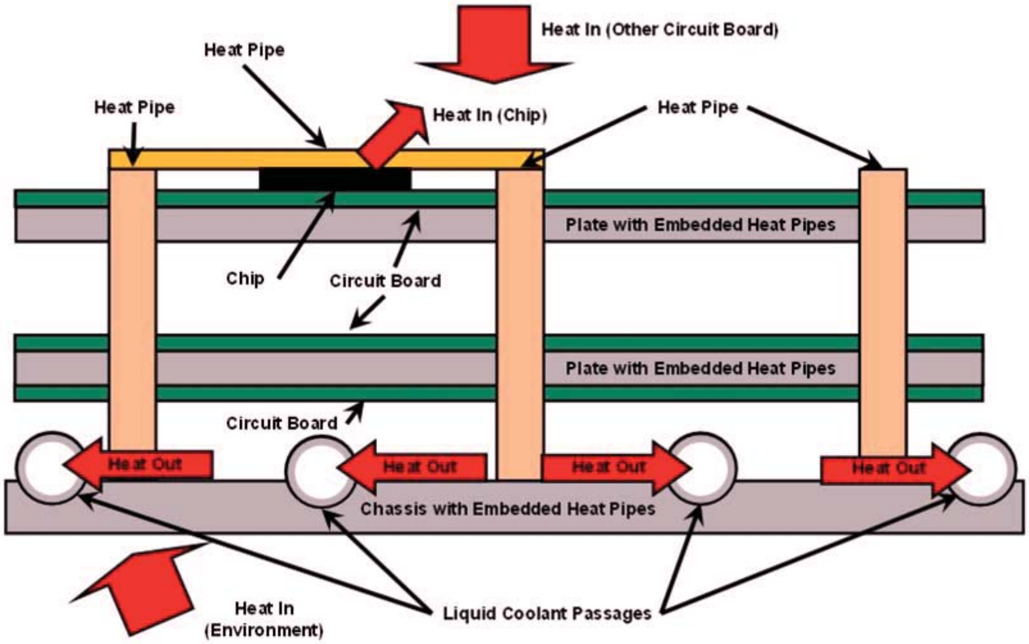


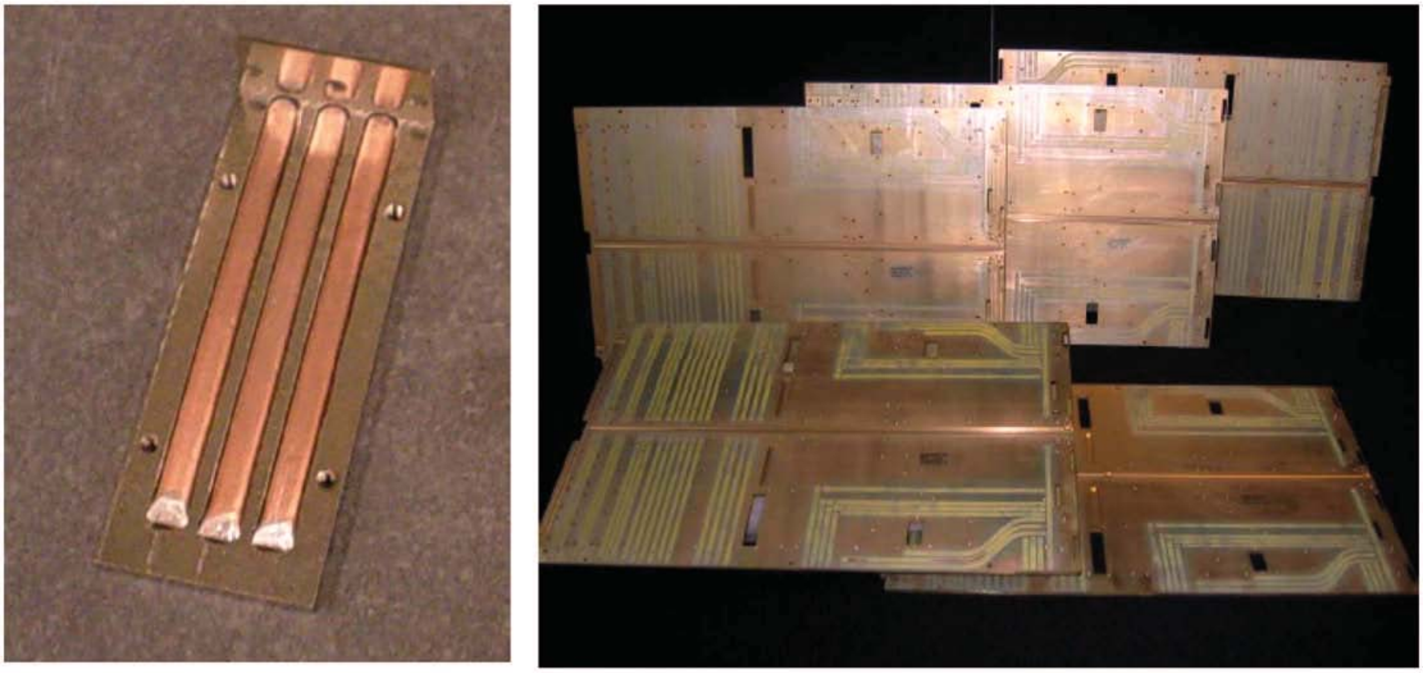
Figure 3. A series of heat pipes are used to reduce the internal ΔT in the Electronics box. This includes a heat pipe directly cooling problem chips, heat pipes replacing the posts, and using plates with embedded heat pipes next to the circuit boards, and in the chassis of the box, to conduct heat to the cooling passages.

improves the temperature gradient within this device by eliminating hot spots and improving overall heat transfer.

INTERNAL BOX PREDICTED PERFORMANCE

The following combinations of changes to the baseline REA were examined using CFDesign:

1. Unmodified (Baseline)
2. Insulation



a) b)

Figure 4. a) Sample HiK Bracket Prior to Sealing and Finishing, b) Finished HiK Plates.

Table 1. Internal Thermal Management Model Results.

	Thermal Management Solution					
Temperature	Unmodified	Insulation	HiK Plates	Heat Pipes	Insulation & HiK Plates	Insulation, HiK Plates & Heat Pipes
Board Min. (°C)	71.1	67.9	71.9	71.2	68.2	68.2
Board Max. (°C)	100.9	94.6	94.5	88.0	89.5	75.9
Junction Max. (°C)	109.4	103.2	103.1	96.5	98.0	84.5
Allowable LCS Max. (°C)	66.7	73.0	73.1	79.6	78.1	91.7
Junction ΔT Notes: Texas Instruments 320c6203 DSP: 1.7 °C/W × 5 W = 8.5 °C Arctic Silver 5 Thermal Compound: 0.0045 °C-in^2/W × (0.52 in^2)$^{-1}$ × 5 W = 0.043 °C						

3. HiK plates replacing the aluminum heat sinks and enclosure

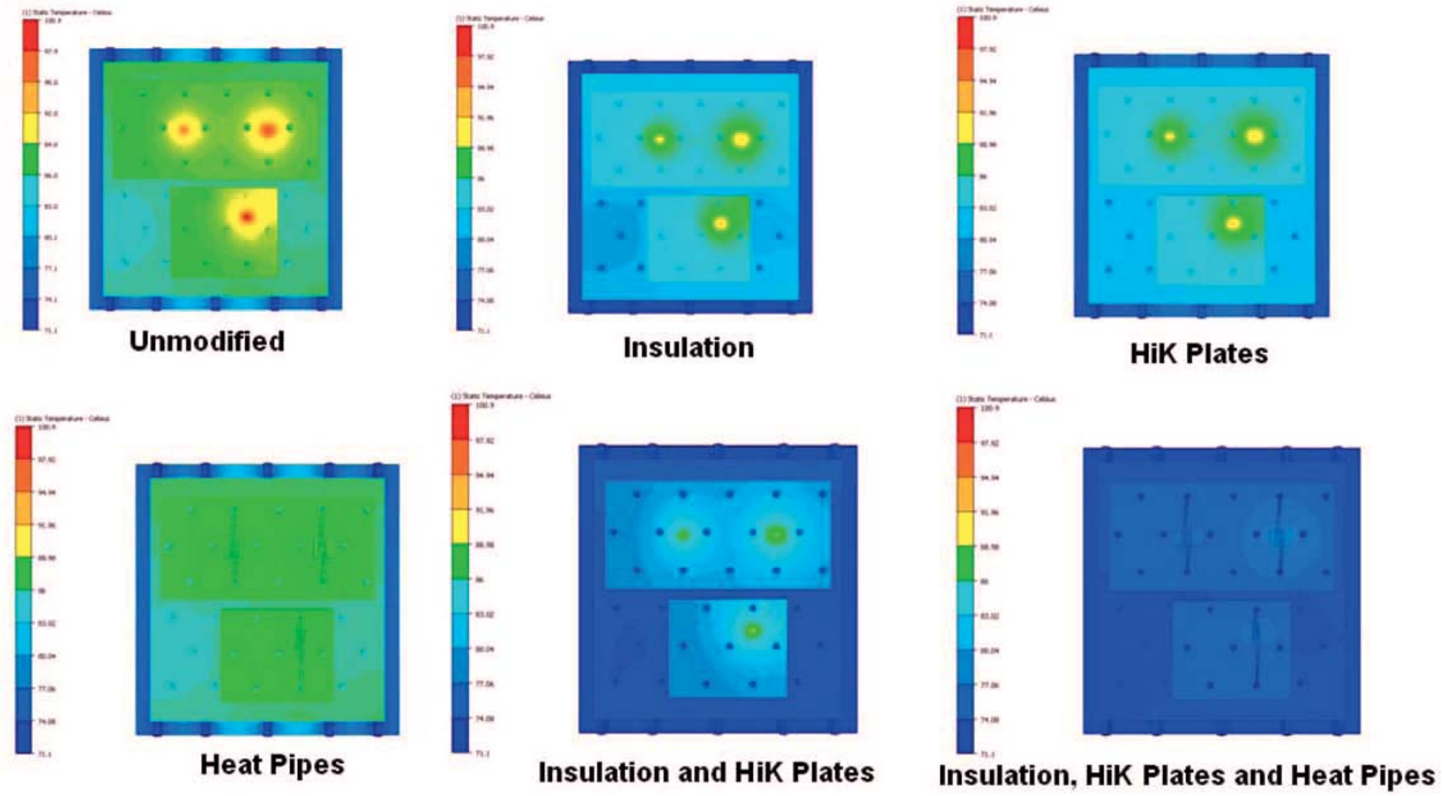
4. Heat Pipes to directly cool problem chips

5. Insulation and HiK plates

6. Insulation, HiK plates, and heat pipes

The cases assumed the baseline liquid cooling temperature of 66.7°C. Model results are shown in Table 1 and Figure 5.

For each analysis, the temperature color mapping was scaled to that of the unmodified case (red: 100.9 °C, blue: 71.1 °C); see Figure 5. Each of the thermal management solutions decreased the maximum board temperature. Out of the three single solution designs, the one that employs heat pipes improves the temperature gradient by the greatest amount. Comparing all the cases, the best thermal performance is achieved when all solutions are implemented (insulation, HiK plates and heat pipes).



Unmodified

Insulation

HiK Plates

Heat Pipes

Insulation and HiK Plates

Insulation, HiK Plates and Heat Pipes

Figure 5. Internal Thermal Management Model Results.

The board minimum and maximum temperature were the temperatures discussed in the previous sections and the temperatures shown in the color mapped pictures. The junction temperature is the expected die temperature of the hottest chip, back calculated by adding 8.5 °C to the maximum board temperature. The temperature difference between the board and the junction (junction ΔT) was based upon commercially available specifications for the thermal resistances of a heat sink and thermal grease. The heat flux was assumed to be 5 W through an area of 0.52 in^2.

The results shown in Table 1 and Figure 5 assume a constant liquid cooling temperature of 66.7°C. For the best case, the overall temperature gradient within a generic electronics box decreased from 42.7 °C (76.9 °F) to 17.8 °C (32.0 °F) with maximum electronics temperature decreasing from 109.4 °C (228.9 °F) to 84.5 °C (184.1 °F).

Alternatively, if electronics temperature limits are maintained at their current maximum, the required sink temperature can be increased. The maximum allowable LCS temperature is calculated by first finding the difference between the maximum temperature of a particular case and the maximum temperature of the unmodified case (100.9 °C). This difference is then added to the fuel temperature of the unmodified case (66.7 °C) to yield the estimated maximum allowable inlet LCS temperature. The allowable sink temperature increases from 66.7 °C (152.1 °F) to 91.7 °C (197.1 °F). This increase allows for more freedom in sink selection, which is typically limited aboard military platforms.

PASSIVE THERMAL ENERGY TRANSPORT

The second subsystem transports thermal energy from the external surface of the enclosure to appropriate sinks and consists primarily of a LHP. Loop heat pipes are very high thermal conductivity, self-contained, passive devices. A schematic of a loop heat pipe is shown in Figure 6. Note that the figure is not to scale; the vapor and liquid lines can be made much longer. Heat enters the evaporator as shown and vaporizes working fluid at the outside surface of the wick. The vapor is collected by a system of grooves and headers and flows down the vapor line to the condenser. In this section, vapor condenses as heat is removed by the cold plate. In general, most of the condenser is filled with a two-phase mixture. A small section at the end of the condenser provides a small amount of sub-cooling.

The compensation chamber at the end of the evaporator is designed to operate at a lower temperature than the evaporator (and the condenser). Since the temperature is lower, the pressure of the saturated fluid in the compensation

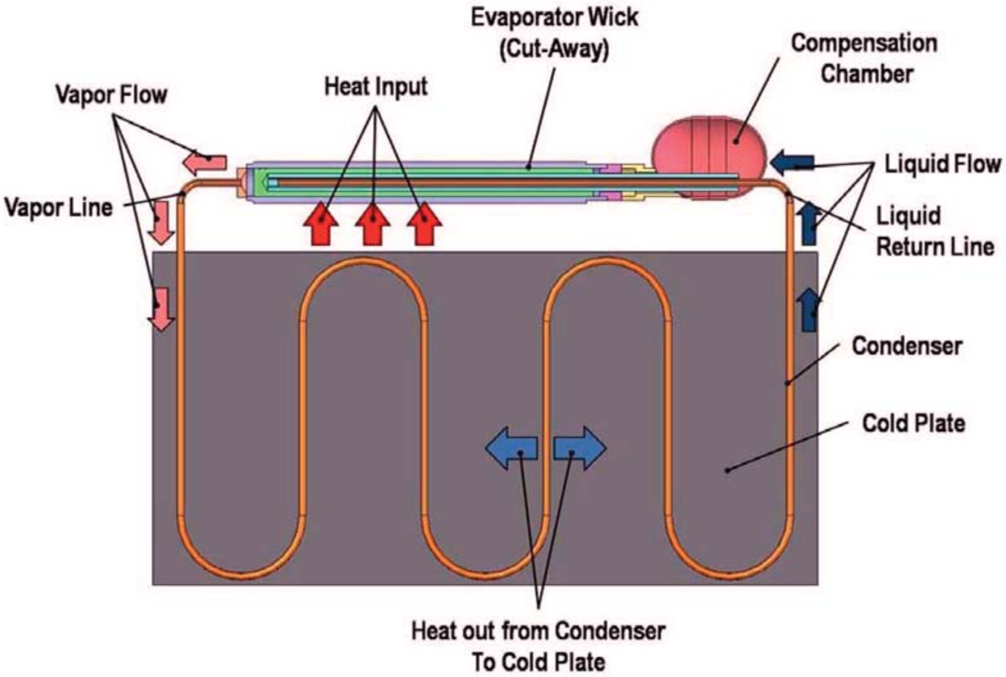


Figure 6. Loop Heat Pipe Schematic (Not to scale). For example, the vapor and liquid return lines can be much longer.

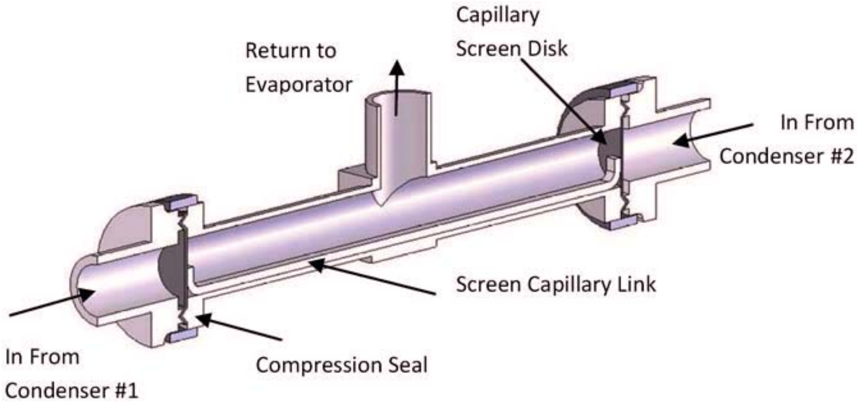


Figure 7. LHP Parallel Condenser Flow Balancer.

chamber is also lower. This lower pressure forces the condensate through the condenser and liquid return line. The fluid then flows into a central pipe where it feeds the wick. Excess fluid drains into the compensation chamber. A secondary wick in the compensation chamber (not shown for clarity) allows the compensation chamber liquid to feed the evaporator wick. The liquid in the compensation chamber and the interior of the wick must be returned to the exterior surface of the wick to close the cycle. Capillary forces accomplish this passively, sucking liquid back to the surface, just as water will be sucked up into a sponge.

An advantage of Loop Heat Pipes is that they can passively reject their waste heat to the colder of two or more heat sinks (Anderson et al., 2009). With dual condensers, the vapor flowing out of the pump body enters a tee that branches into the two, parallel condenser loops. The loops are connected again through a second tee which collects liquid from the condensers and returns it to the pump body. A parallel condenser flow balancer, shown in Figure 7, is installed to prevent the superheated vapor from one condenser segment from mixing with the sub-cooled liquid returning from the other segment. The flow balancer works by establishing a liquid - vapor interface on a porous membrane.

For example, the cooling capacity of the fuel is generally high, except when the engine idling on the ground, or during low velocity travel in the air. On the other hand, some air heat sinks are good, except during high velocity flight. The dual condenser LHP design, shown in Figure 8, effectively

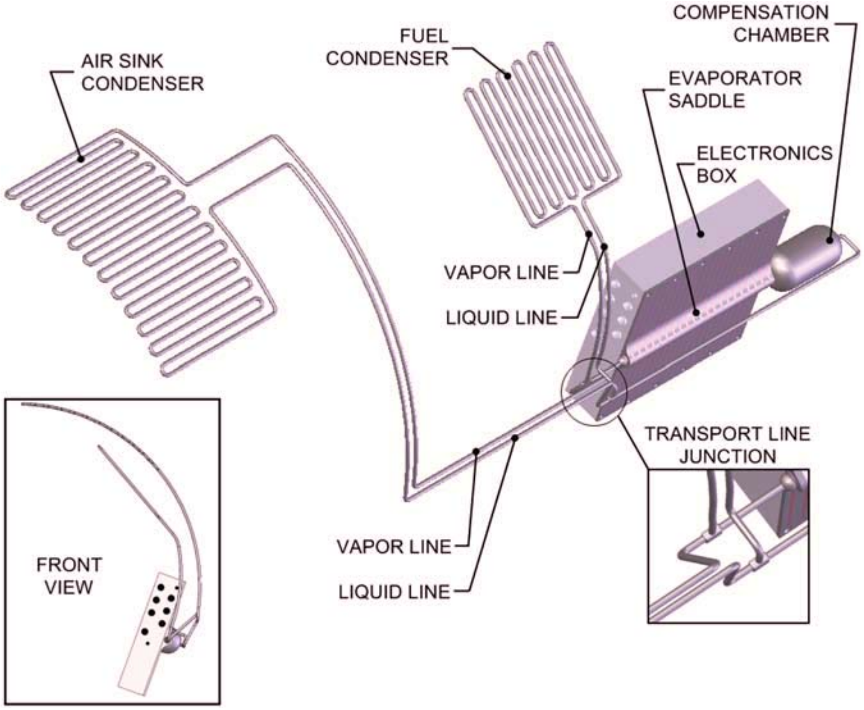


Figure 8. Dual-Condenser LHP Approach passively rejects heat to the colder of the two heat sinks.

Table 2. Generic Sink Conditions for REA

	Sink 1 Condition 1	Sink 2 Condition 1	Sink 1 Condition 2	Sink 2 Condition 2
Temperature	49 °C	60 °C	49 °C	127 °C
Air velocity	0 m/s	1.8 m/s	180 m/s	7.62 m/s
Available area	0.20 m^2	0.18 m^2	0.20 m^2	0.18 m^2

addresses this problem. One condensing section interacts with air while the other is cooled by fuel or PAO. Whether these condensing sections are active depends on the temperatures to which they are exposed. As the air temperature increases beyond the fuel temperature, this section of the condenser passively deactivates and the LHP relies on the fuel as a sink. As air conditions become favorable again, the air sink will reactivate. Note that switching from one sink to the other is completely passive: the higher heat temperature heat sink is automatically deactivated. The benefit of this approach is decreased load on the fuel as a sink when air conditions are favorable, while still allowing use of the fuel as a sink at other times.

LOOP HEAT PIPE DESIGN

The primary drivers for a LHP design are the evaporator conditions, condenser conditions, and overall transport length. For this design, the REA operating conditions set the evaporator conditions. As a result, much of this LHP design revolves around the condenser conditions and transport length, both of which are determined by the selected sink. ACT worked with industry partners to identify potential sinks and evaluate these sinks over the operating envelope of a representative aircraft. As an example, two sink locations and two flight conditions were selected for discussion, as shown in Table 2. Note that when the heat transfer conditions at Sink 1 are favorable, the conditions at Sink 2 are bad, and vice versa. In addition to the parameters shown in this table, geometry and ambient conditions were also considered.

Of primary importance in this evaluation was the evaporator temperature for varying heat loads. REA constraints dictated that this temperature remain below 82 °C. Alternatively, if the LHP was used to directly cool the fuel, LCS constraints dictate the evaporator temperature remain below 92 °C. As both of these approaches are being considered for REA cooling, ACT compared the predicted evaporator temperature against both of these limits. These limits, along with the sink inlet, compensation chamber, condenser outlet, and evaporator temperatures predicted by ACT's LHP model, are shown in the following figures and used to estimate the expected performance of the LHP for each sink condition.

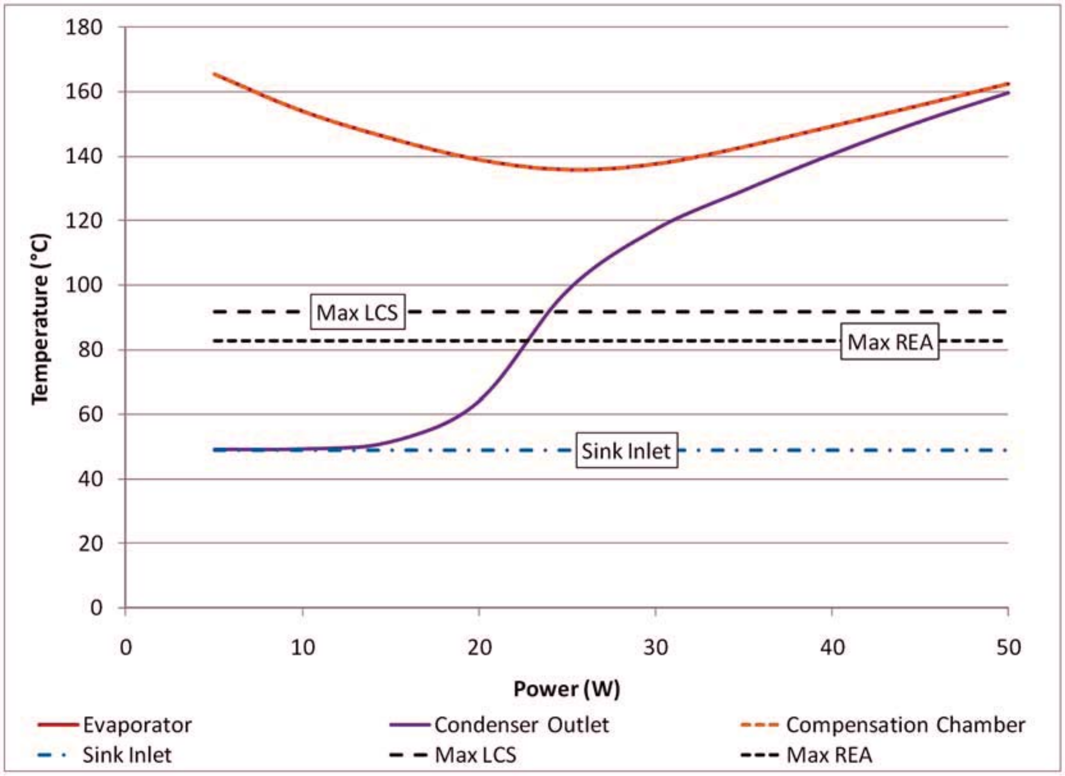


Figure 9. Model Results for Sink 1 Condition 1.

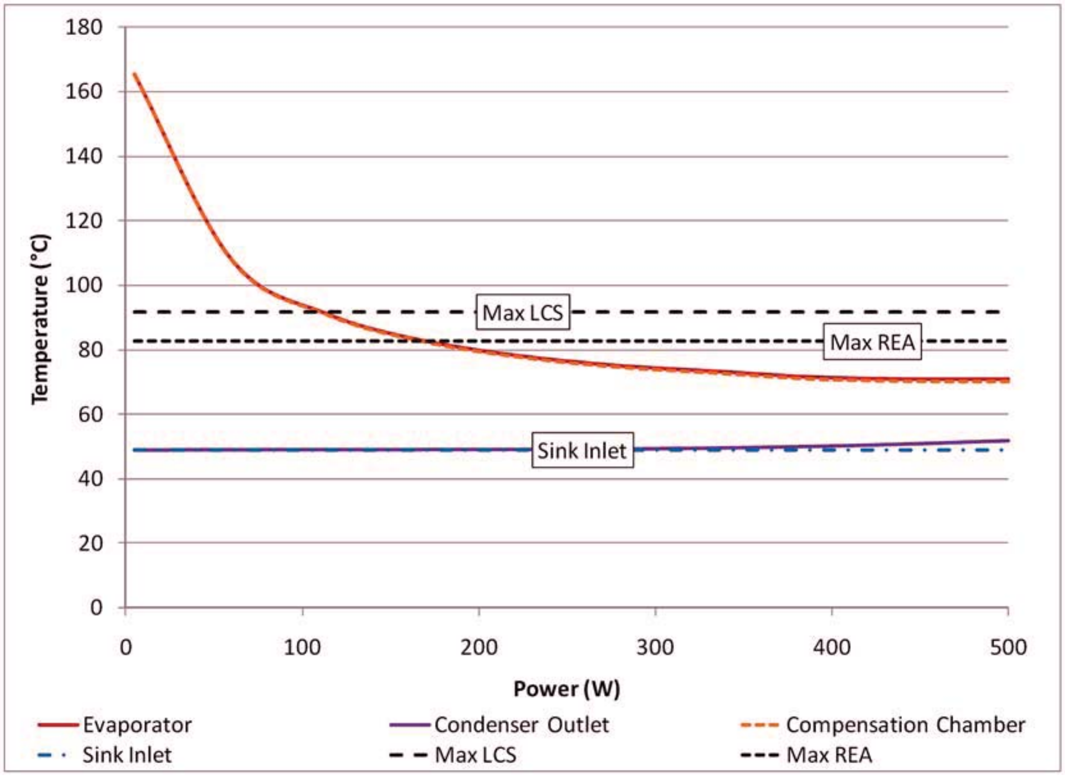


Figure 10. Model Results for Sink 2 Condition 1.

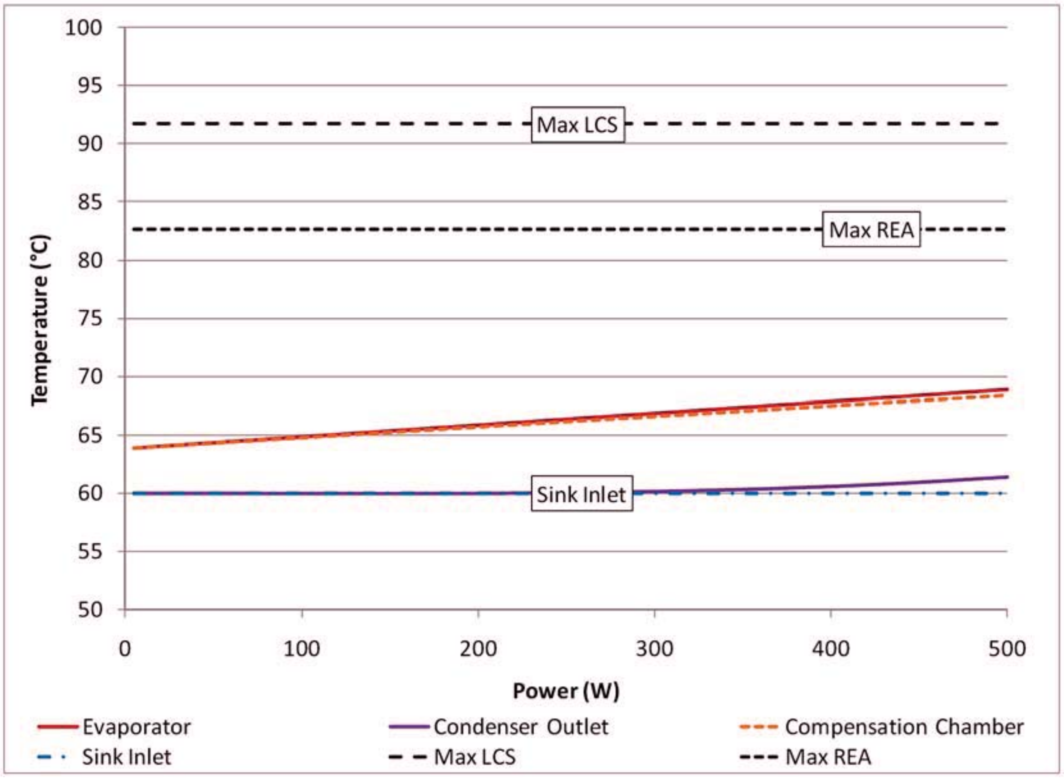


Figure 11. Model Results for Sink 2 Condition 2.

Sink 1 Condition 1, shown in Figure 9, did not allow for acceptable operation of the LHP at any power level. This sink, while relatively cool, must rely on natural convection to remove heat from the REA. At all power levels, this did not provide an evaporator temperature near either the REA or LCS temperature limit.

The results for Sink 2 Condition 1 are shown in Figure 10. Under these conditions, Sink 1 produced evaporator temperatures below the LCS limit for heat loads over 120 W. Heat loads above 170 W produced evaporator temperatures below the REA limit. As the expected REA heat load is approximately 400 W, this sink should function well under this condition.

The results for Sink 1 Condition 2 are shown in Figure 11. Due to the high air velocity and relatively cool air temperature, this sink performs very well. For all power levels, the evaporator remains well below the REA and LCS temperature limits. For this reason, this is the sink of choice while the aircraft experiences this condition.

Due to the high temperature that Sink 2 is exposed to during Condition 2, acceptable operation of the LHP was not possible. For this reason, modeling of this case was not necessary. The conditions are shown here to reiterate the transient nature of aircraft sinks. Under Condition 1, Sink 2 provides acceptable performance. Once Condition 2 is reached, however, Sink 2 is significantly over temperature.

From this general discussion, the importance of a dual sink cooling system is demonstrated. For the REA system, a LHP capable of selecting Sink 2 during Condition 1 and Sink 1 during Condition 2 would provide adequate cooling across the operating envelope of the aircraft. For this reason, ACT is pursuing a detailed design based on this analysis and more specific information provided by industry partners.

FUTURE WORK

A prototype to validate the thermal models is currently being fabricated. This prototype will include a simulated electronics enclosure and a loop heat pipe. In addition, the high temperature environment will be simulated to match data provided by the platform manufacturer. Testing will investigate the performance of the cooling system over the operating range of the platform.

SUMMARY/CONCLUSIONS

A thermal management system for electronics cooling in high temperature avionics environments is under development using Loop Heat Pipe (LHP) and heat pipe based technology. This development addresses limitations imposed on military platforms by the allowable operating temperatures of critical electronics systems. These limitations are primarily the result of the high temperature environment to which these electronics are exposed but are compounded by the lack of sufficient thermal energy sinks throughout the operating envelope of the platform. The thermal management system reduces thermal energy transport inefficiencies within electronics enclosures, identifies potential sinks to provide continuous heat rejection over the operating envelope of the platform, and provides passive thermal energy transport from the electronics enclosure to selected sinks.

The system developed to accomplish these tasks is divided into two subsystems. The first subsystem is responsible for improving thermal transport within the electronics enclosure and consists primarily of heat pipe assemblies. Model results of the first subsystem show considerable improvements over the current implementation. The overall temperature gradient within a generic electronics box decreased from 42.7 °C (76.9 °F) to 17.8 °C (32.0 °F) with maximum electronics temperature decreasing from 109.4 °C (228.9 °F) to 84.5 °C (184.1 °F). Alternatively, if electronics temperature limits are maintained at their current maximum, the required sink temperature increases from 66.7 °C (152.1 °F) to 91.7 °C (197.1 °F). This increase allows for more freedom in sink selection, which is typically limited aboard military platforms.

The second subsystem transports thermal energy from the external surface of the enclosure to appropriate sinks, which depend on platform operating conditions. The primary component of this subsystem is a LHP. ACT has completed the model for this subsystem and is working with industry partners to identify appropriate sinks. At this stage, several sinks have been identified and evaluated. Final sink selection is underway. Depending on sink temperature and capacity throughout the operating envelope of the platform, multiple sinks may be used. During operation, the LHP will passively select the appropriate sink.

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DEFINITIONS/ABBREVIATIONS

ACT	Advanced Cooling Technologies, Inc.
AFRL	Air Force Research Laboratory
LCS	Liquid Cooling System
LHP	Loop Heat Pipe
PAO	Polyalphaolephin
REA	Representative Electronics Assembly

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