Passive Thermal Management for Avionics in High Temperature Environments

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ABSTRACT

Under a program funded by the Air Force Research Laboratory (AFRL), Advanced Cooling Technologies, Inc. (ACT) has developed a series of passive thermal management techniques for cooling avionics. Many avionics packages are often exposed to environment temperatures much higher than the maximum allowable temperatures of the electronics. This condition prevents the rejection of waste heat generated by these electronics to the surrounding environment and results in significant ambient heat gain. As a result, heat must be transported to a remote sink. However, sink selection aboard modern aircraft is limited at best. Often, the only viable sink is aircraft fuel and, depending on mission profile, the fuel temperature can become too high to effectively cool avionics. As a result, the electronic components must operate at higher than intended temperatures during portions of the mission profile, which reduces component lifetime and significantly increases the probability of failure. To address this issue, ACT developed two passive thermal management approaches for avionics packages: heat pipe assemblies to reduce the internal temperature gradient and a Loop Heat Pipe (LHP) to transport thermal energy to alternative sinks. Laboratory testing demonstrated that the heat pipe assemblies were capable of reducing the internal temperature gradient by approximately 25 °C (45 °F). This reduction translates directly to an increase in the allowable sink temperature that will still provide sufficient cooling for the electronic components. To provide additional temperature margin, ACT developed a LHP design to cool the fuel prior to entering the avionics enclosure. This approach was determined to be more reliable than cooling the avionics directly. The LHP was designed to transport thermal energy from the fuel to two heat rejection sections. Two heat rejection sections were necessary as aircraft sink conditions can vary considerably throughout the flight envelope. Since these sinks can approach temperatures much higher than the intended operating temperature of the LHP, the condenser sections were separated by a unique flow balancer design that provided passive deactivation of the high temperature sink while maintaining flow to the low temperature sink. This passive sink selection technique and overall LHP performance as a pre-cooler were demonstrated through laboratory testing. The LHP was shown to reduce inlet fuel temperature by 5 °C. Together with the internal thermal management system, laboratory testing indicates the potential for an increase of 30 °C (54 °F) in the allowable sink temperature for a generic avionics package. This increase allows for a wider selection of potential sinks and significantly reduces the sensitivity of avionics packages to fuel temperature. As a result, electronic components can be maintained below their maximum allowable temperatures despite high fuel temperatures.

INTRODUCTION

Avionics provide many critical functions. Electronic Engine Controls (EEC), for instance, control engine operation in response to monitored engine parameters and pilot commands to maximize engine performance while maintaining safe and reliable operation. As the name implies, one or more digital processors and associated support circuits are contained within an EEC. Parameters such as engine speed, valve and actuator positions, engine and ambient pressures and temperatures are monitored by the controller. In response, the controller will control parameters such as engine fuel flow rate, compressor vane position and bleed valve opening[1]. The required high processor throughput required along with typical aerospace sensitivity to weight and volume result in dense circuit and component packaging and increased heat flux density.

An EEC is typically mounted on the engine case to minimize the routing length of the sensor and actuator wiring. This exposes the EEC to environment temperatures much higher than the maximum component temperatures of the electronics[2]. To maintain operation, the interior of the EEC must be kept at a temperature significantly lower than these high environment temperatures, which are realized during normal operation and during thermal soakback after shutdown. Many avionics find themselves in similar challenging operating environments.

Compounding the problem presented by these challenging operating environments, thermal management is becoming increasingly difficult for state-of-the-art aircraft. In fact, thermal management has been identified as the most difficult challenge associated with advanced aircraft design. The difficulty lies with the lack of available sinks, which are limited due to the low thermal conductivity of composite skins, high-altitude and high-speed operation, and Low Observability (LO) requirements[4]. As a result, aircraft fuel becomes the most attractive sink. In normal operation, waste heat collected by the fuel is rejected by burning this fuel in the engine[5].

To cool avionics, aircraft fuel is directed through channels built into the enclosure[2]. Within the enclosure, the electronics are mounted on stacked boards that are separated by a support structure. Waste heat generated by the electronics and absorbed from the hot engine environment is transported to fuel channels primarily by conduction through the aluminum support structure. This configuration results in significant temperature gradients within the avionics enclosure. The maximum operating temperatures of the electronics less this temperature gradient define the maximum allowable fuel temperature. Since the maximum electronics temperature is fixed, the high temperature gradient within the avionics enclosure drives the allowable fuel temperature down. In periods of high engine demand, this is not an issue as fuel temperature remains low enough that this temperature gradient does not pose any issues.

In periods of low engine demand, such as post-flight idle, fuel is recirculated to maintain electronics cooling and fuel temperature increases rapidly, as shown in Figure 1. This increase results as fuel is recirculated rather than burned in the engine, which requires the fuel to store the thermal energy produced by aircraft electronics and power systems as sensible heat. The temperature rise associated with this sensible heating depends on, among other parameters, the mass of fuel available in the aircraft. For this reason, as the mission progresses and fuel is burned, fuel temperature rise becomes more and more rapid. As seen in Figure 1, end of mission presents the most challenging thermal environment as fuel mass is at a minimum and temperatures rise rapidly. To meet idle time requirements set forth for the aircraft, the maximum allowable operating temperatures of avionics are sometimes increased at end of mission, which can severely shorten the lifespan of these devices.

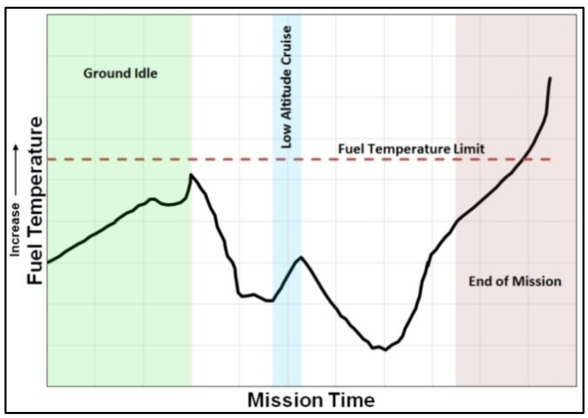

Figure 1. Fuel Temperature during a Generic Mission[3]

ACT approached these thermal issues by first identifying potential sinks not yet utilized in current military aircraft thermal management system design. Once these sinks were identified, ACT designed a LHP to passively transport waste heat from a selected avionics package to these sinks. In parallel with the LHP design, ACT investigated an internal thermal management solution also based on passive, two-phase technology. This internal solution included heat pipes, embedded heat pipe plates, and insulation from the high temperature environment. The end result was a design that efficiently collected and transported waste heat from within the avionics enclosure to selected sinks using a passive, two-phase thermal management system.

LOOP HEAT PIPE FOR EXTERNAL THERMAL ENERGY TRANSPORT

Loop heat pipes are very high thermal conductivity, self-contained, passive devices[6]. A schematic of a loop heat pipe is shown in Figure 2. 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 integral to the wick, shown in Figure 3. The vapor 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.

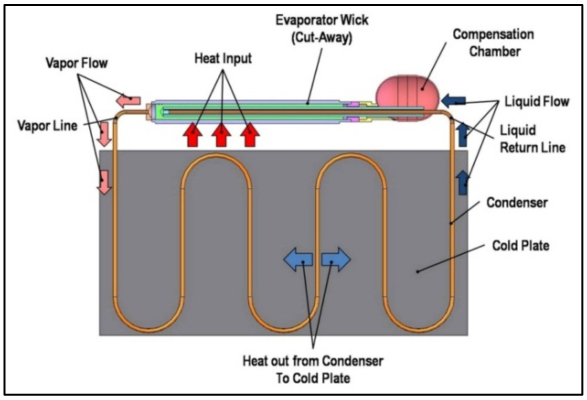

Figure 2. Loop Heat Pipe Schematic (Not to scale).

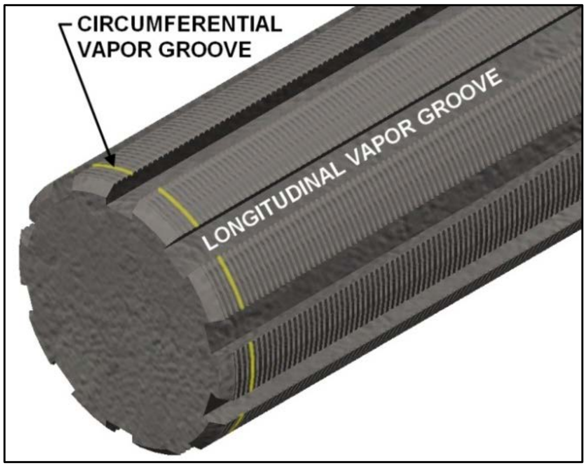

Figure 3. Example of the Grooved Outer Surface of a LHP Wick

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 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, moving liquid back to the surface, just as water will be absorbed by a sponge.

LHP performance depends on multiple factors, such as ambient conditions, sink conditions, and geometry. Due to limited thermal sink availability, sink conditions played an important role in the evolution of the avionics LHP design. Evaluation of available sinks relied on a proprietary LHP model, which provided steady state temperature, pressure, and quality for the working fluid throughout the LHP. The results of this modeling led to the selection of two sinks that met the design criteria. Neither of these sinks could provide heat rejection over the entire flight envelope. As a result, the final LHP design relied on two condensers. ACT previously developed a proprietary method to passively select the appropriate condenser based on sink temperature. This method was used to allow the avionics LHP to passively switch between condensers as dictated by the operating conditions of the aircraft.

SINK EVALUATION

As an example, LHP performance for two generic cases at the selected locations is shown as a function of heat load in Figure 4, Figure 5, and Figure 6. Figure 4, which shows LHP performance over a range of heat loads at Sink 2 during ground operation of the aircraft, indicates that the LHP evaporator temperature will rapidly overcome the maximum allowed temperature. This is due to low ambient air flow for this case and, as a result, this sink will not provide adequate heat rejection. However, as shown in Figure 5, which is the same operating conditions but at Sink 1, the LHP is capable of maintaining temperatures well below the allowable limit. On the other hand, during flight, the ambient temperature at Sink 1 more than triples and makes this sink incapable of heat rejection at the required LHP evaporator temperature. Sink 2, however, is capable of rejecting heat while meeting the temperature requirements, as seen in Figure 6.

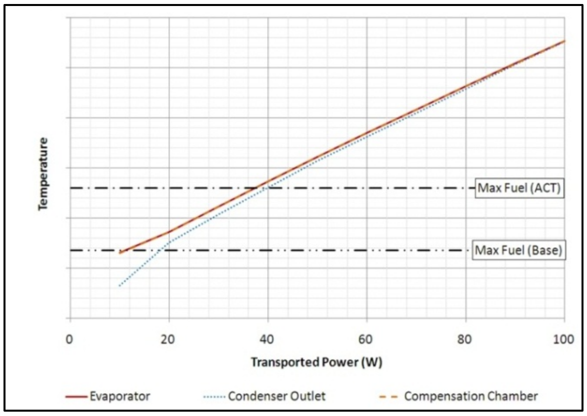

Figure 4. LHP Temperature for Varying Power at Sink 2, Ground Conditions

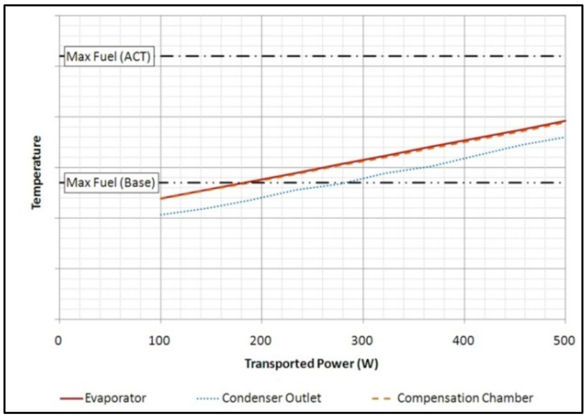

Figure 5. Temperatures for Varying Power at Sink 1, Ground Conditions

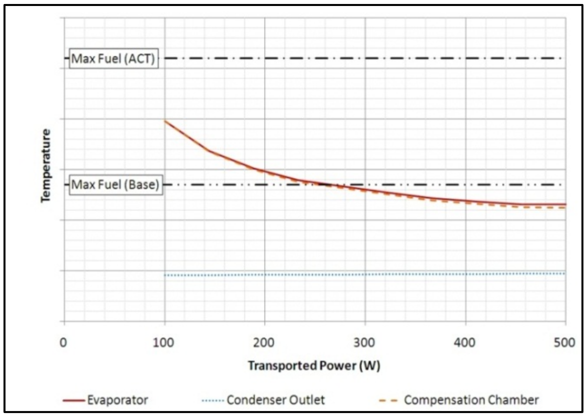

Figure 6. Temperatures for Varying Power at Sink 2, Dash Conditions

Both of these sinks provide adequate temperature margin between the evaporator temperature and maximum allowable fuel temperature for the improved avionics thermal design. Sink 1 provides this margin during ground conditions while Sink 2 is sufficient during flight conditions. The LHP is designed to passively select the most effective sink for heat rejection and is capable of passively deactivating a sink if high temperature conditions occur for that sink.

The parameters used in this model are maintained in the test hardware, with the exception of the condensers. For testing, the condensers are cooled by Liquid Nitrogen (LN) rather than forced convection. In addition, the condensers are not physically far from the LHP as they would be in the aircraft application. However, transport line length is maintained and, as a result, the effect of this distance on LHP performance is simulated. Both of these changes allow for a deliverable test bed of reasonable size.

LHP PRE-COOLER

The avionics LHP was designed to cool the fuel prior to entering the avionics using two sinks that, together, were capable of providing heat rejection over the entire flight envelope. Methanol was selected as the working fluid, stainless steel was used for the evaporator body, compensation chamber, and transport lines, and the wick consisted of sintered nickel powder. Unlike most LHP applications, the evaporator designed for fuel pre-cooling accepts heat from a liquid annulus that surrounds the wick. This liquid is the avionics coolant.   A section view of the LHP evaporator and heat exchanger annulus is shown in Figure 7. Heat from the avionics coolant vaporizes the working fluid of the LHP, which is driven by vapor pressure through the condenser.

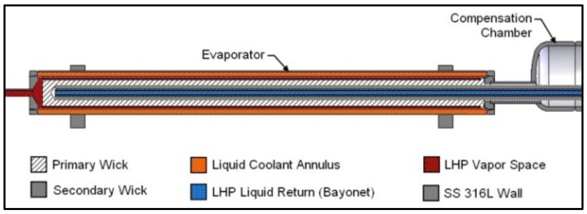

Figure 7. LHP Evaporator Geometry for Avionics Fuel Pre-cooler

Both condensers exchanged waste heat with Liquid Nitrogen (LN). The flow of LN was controlled to maintain the sink temperature at the desired value. Each condenser also had a surface exposed to an electric heater. This allowed the sink temperature to be raised above the LHP vapor temperature to simulate the passive condenser selection feature of the LHP design. During heating, LN flow was shut off. Together, the LN cooling channels and electric heaters allowed temperature control over the range necessary for demonstration of the LHP pre-cooler technology.

The condenser design, shown in Figure 8, is a single-pass, counter-flow heat exchanger arranged in a serpentine geometry. The methanol and LN channels are separated by the cold plate material: aluminum. As a result, vapor entering the condenser from the evaporator exchanges heat with two-phase LN through indirect contact and condenses. Since the saturation temperature of LN is -196 °C at atmospheric pressure, LN flow control was necessary to maintain the condenser cold plate at the desired temperature. The test unit design is shown in Figure 9.

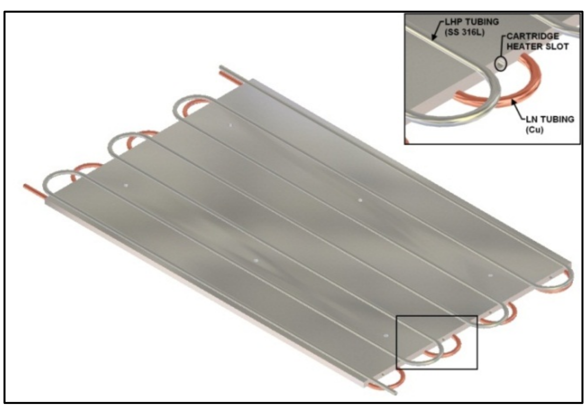

Figure 8. LHP Condenser Design for the Test Unit

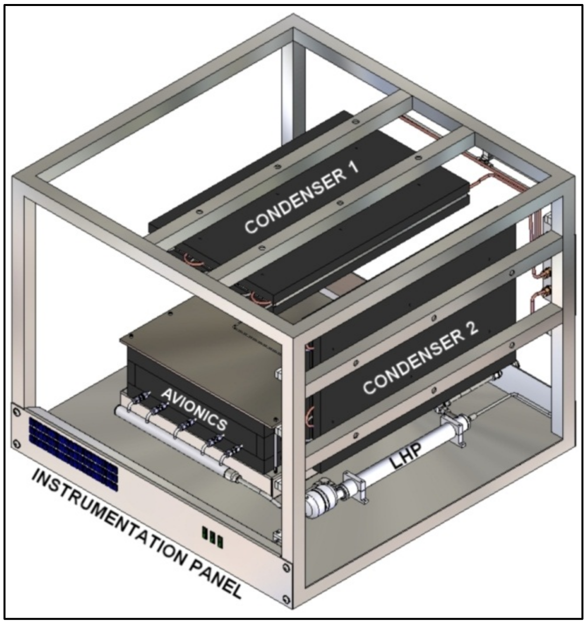

Figure 9. LHP Design Shown Mounted in the Test Unit

HEAT PIPES FOR INTERNAL THERMAL RESISTANCE REDUCTION

Heat pipes transport heat by two-phase flow of a working fluid. These devices consist of a vacuum tight enclosure that contains a working fluid existing at saturation as liquid and vapor, as well as a wick structure responsible for managing the liquid phase. Heat input vaporizes the liquid phase of the working fluid contained within the wick. The location at which this occurs is referred to as the evaporator. For heat transport to occur, heat must be removed at another location. Heat removal at this location results in the condensation of vapor. For this reason, the location of heat removal is referred to as the condenser. The vapor pressure difference resulting from evaporation at one location and condensation at the other drives the flow of vapor from the evaporator to the condenser. In addition to transporting vapor, the latent heat required to produce this vapor from the liquid in the wick also moves from the evaporator to the condenser. In this way, the heat pipe efficiently transports heat from one location to another. At the condenser, latent heat is removed from the working fluid as the vapor condenses. 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.

For the selected avionics application, heat-pipe-based components were designed to provide very low thermal resistance paths from the electronics to the coolant. These components included direct-cooling heat pipes and embedded heat pipe plates. The direct-cooling heat pipes were designed to provide a single path from the highest temperature electronics to the coolant channels. The embedded heat pipe plates were designed to replace the current aluminum heat spreaders located between the circuit boards to which the electronics are mounted. To evaluate the effectiveness of these approaches, ACT worked with the avionics manufacturer to produce a generic model for analysis and testing. The layout of this generic avionics package is illustrated by the test units shown in Figure 10 and Figure 11. Note that this test units represent half of the full avionics assembly. Only half of the assembly was modeled and tested due to symmetry.

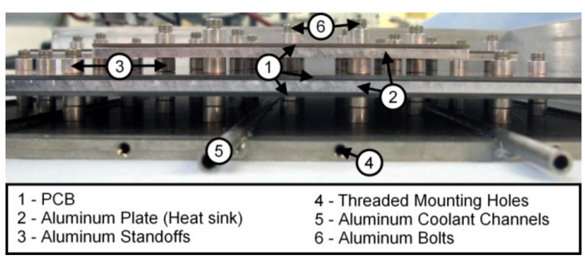

Figure 10. Side View of Generic Avionics Test Unit

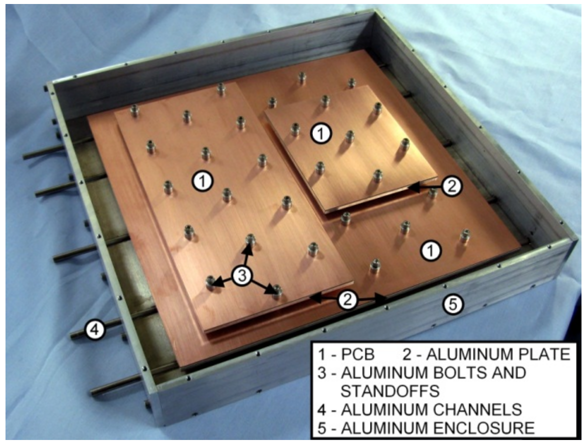

Figure 11. Generic Avionics Layout, Baseline Test Unit Shown

For comparison purposes, the baseline generic avionics unit was modeled first and tested alongside the advanced generic avionics unit. Results of the thermal testing are shown as Figure 12. As seen in this figure, the relative temperature gradient from the hottest chip to the coolant channel is 0.29. By reducing this temperature gradient, electronics temperatures can be maintained at their current value but with higher temperature coolant. A higher temperature coolant increases the maximum allowable fuel temperature of the aircraft and allowable engine idle time. Note, thermal management results for the heat-pipe-based approaches that are shown in the following sections use the same temperature scale.

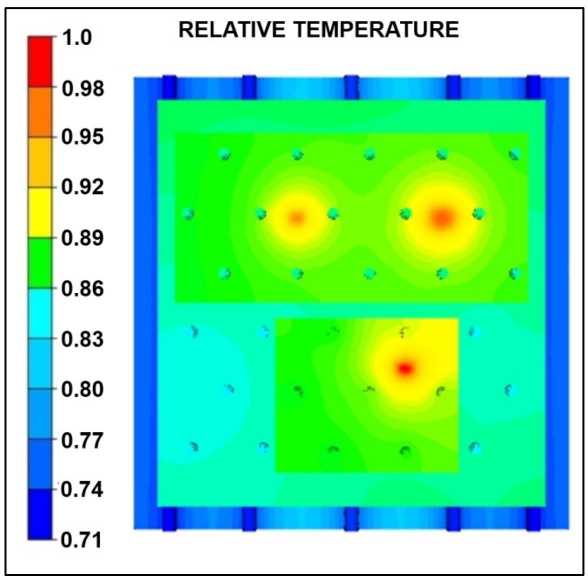

Figure 12. Baseline Temperature Profile for a Generic Avionics

DIRECT-COOLING HEAT PIPE ASSEMBLIES

Direct-cooling heat pipes (DCHP) were designed to collect waste heat directly from the highest temperature electronics and transport this heat to the coolant channel. In the generic avioncs design, these heat pipes interfaced with the electronics through a copper flange, or saddle, penetrated the aluminum spacers that separate the Printed Circuit Board (PCB) layers, and interface with the coolant channel through existing extrusions that connect the PCB to the outer wall of the enclosure. This layout is illustrated by Figure 13. Thermal analysis of this approach is shown in Figure 14.

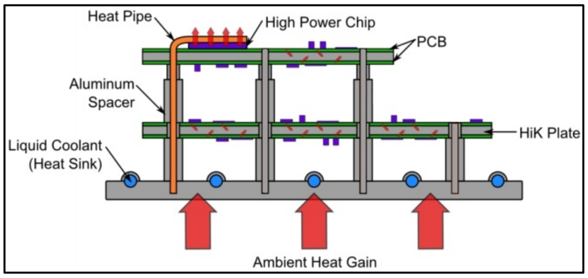

Figure 13. Diagram of Direct-Cooling Heat Pipe Layout

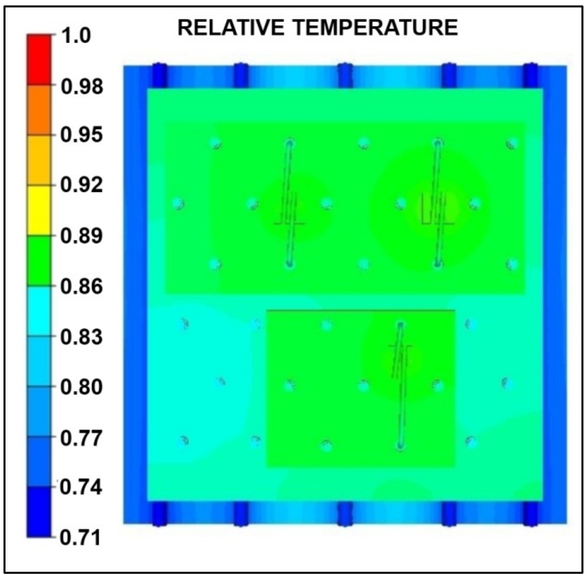

Figure 14. FEA Model Results for Direct-Cooling Heat Pipes

As seen in this figure, the maximum electronics temperature has been lowered by 12%. This would result in an equivalent increase in maximum fuel temperature. In addition, the hot spots seen in Figure 12 at the chip location are no longer present. The direct-cooling heat pipe effectively removes heat from the chip and the high, combined thermal resistance of the PCB and heat spreader is no longer an issue.

EMBEDDED HEAT PIPE PLATES

In the current design, aluminum plates act as heat spreaders to collect heat from the PCBs and transport this heat to the aluminum posts that separate each PCB layer. The posts then conduct the heat to the coolant channels. Since these heat spreaders tend to be relatively thin, approximately a sixteenth of an inch thick, they present a relatively high thermal resistance despite the high thermal conductivity of aluminum. In the advanced avionics design, ACT replaced these heat spreaders with embedded heat pipe plates, or HiK plates, to improve the movement of heat to the aluminum posts. For the generic avionics design, the heat pipe paths were laid out between posts, as shown in Figure 15. However, for an actual avionics design, the heat pipe paths would be customized according to the real heat load.

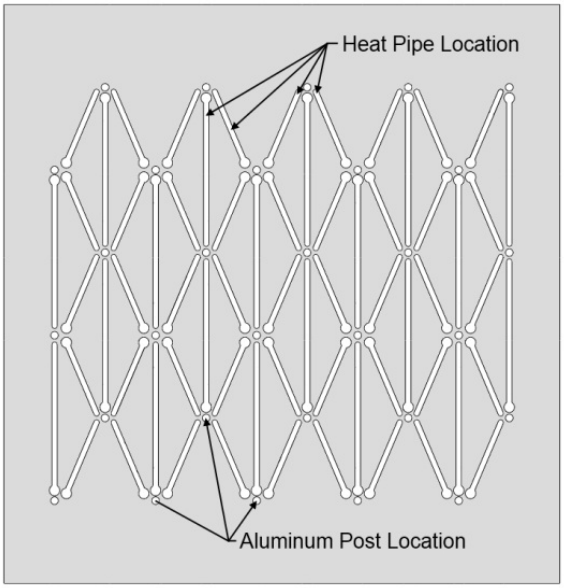

Figure 15. Generic Embedded Heat Pipe Heat Spreader

The effect of the embedded heat pipe plates were evaluated using the generic avionics Finite Element Analysis (FEA) model. Results are shown in Figure 16. As seen in this figure, the maximum temperature is reduced by 6%. However, the hot spots at the chip locations still remain. While the embedded heat pipe plates improve heat transfer to the coolant, as evidenced by the temperature reduction, they do not provide sufficient reduction in thermal resistance to completely eliminate the hot spots.

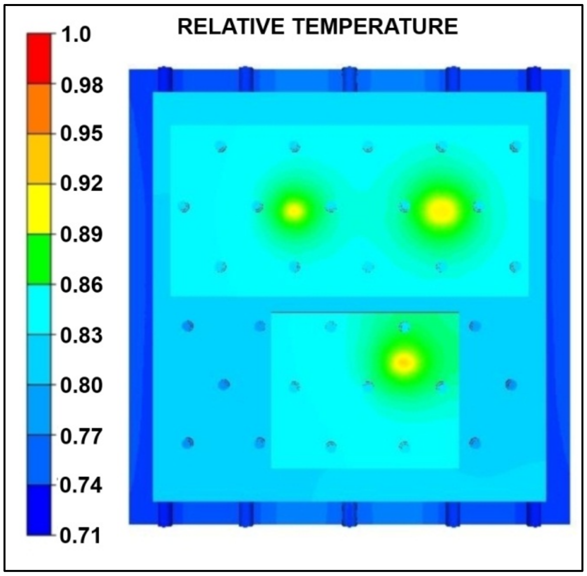

Figure 16. FEA Model Results for Embedded Heat Pipe Plates

ADVANCED AVIONICS MODEL RESULTS

The advanced avionics test unit incorporated both direct-cooling heat pipes and embedded heat pipes in the aluminum heat spreaders and coolant wall. The FEA model was used to estimate the combined benefit of these technologies. The results of this model are shown in Figure 17. As seen in this model, the hot spots are eliminated and the maximum temperature is reduced by 18%.

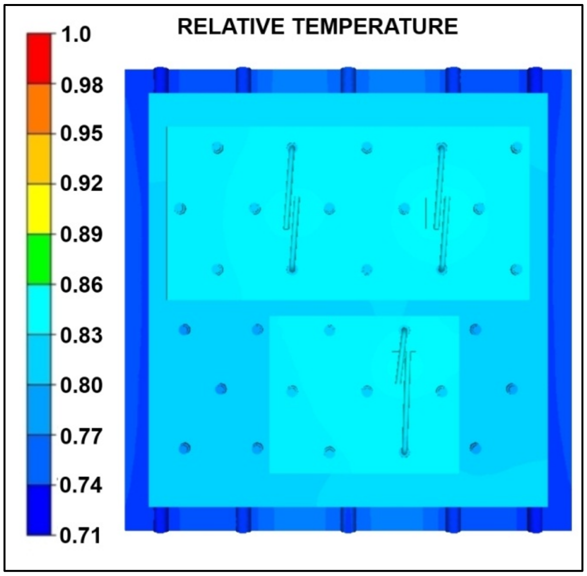

Figure 17. FEA Model Results for Direct-Cooling Heat Pipes and Embedded Heat Pipes

The final improvement to the generic avionics design is the addition of insulation. This feature was investigated for completion of the study but actual implementation is limited by Foreign Object Debris (FOD) concerns. As most of the heat gained by the avionics is from the environment, insulation should reduce the overall heat load of the cooling system and further reduce the maximum temperature. For the final FEA model, ACT evaluated the impact of direct-cooling heat pipes, embedded heat pipes, and insulation on the thermal profile of the generic avionics. The results are shown in Figure 18. As seen in this figure, the maximum temperature is reduced by 25%. For completion, the modeling results are summarized in Table 1.

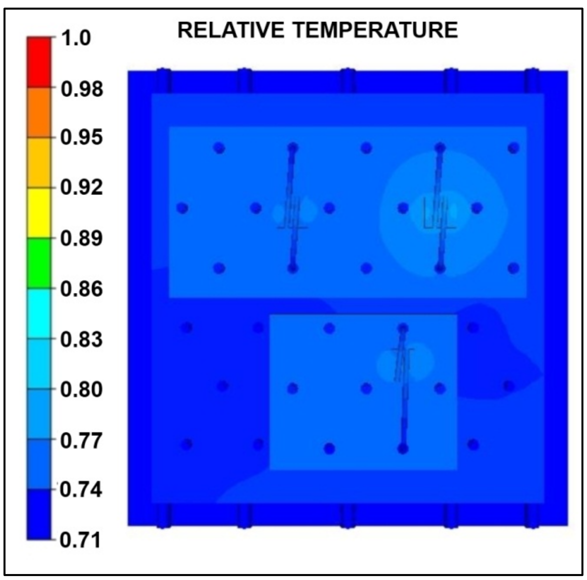

Figure 18. FEA Model Results for Direct-Cooling Heat Pipes, Embedded Heat Pipes, and Insulation

Table 1. FEA Model Results Summary

	Normalized Maximum Temperature	**Potential Fuel Temperature Limit Increase**
Baseline	1.0	-
DCHP	0.87	13%

HiK Plate	0.94	6%
DCHP + HiK Plate	0.82	18%
DCHP + HiK Plate + Insulation	0.75	25%

ADVANCED AVIONICS ANALYSIS AND TESTING

ACT fabricated two generic avionics assemblies. The first represents the baseline case with no cooling improvements. The second includes the improvements discussed in the modeling section: direct-cooling heat pipes, embedded heat pipe plates, insulation, and a LHP pre-cooler. Both test units were assembled to match the half-avionics thermal model and consisted of 4 adiabatic walls, a wall representing the symmetry plane, and the coolant channel plate. Ambient heat gain occurs through the coolant plate and is controlled using heaters. All walls are aluminum and insulated from the laboratory environment.

In both test units, PCB’s with a Direct-Bond Copper (DBC) layer are mounted in parallel tiers as shown in Figure 11. The DBC layer is on one side only and approximately 0.038 mm thick. In all cases, the DBC layer was mounted opposite the heat spreader and was used to interface with the electric heaters that mimicked the heat sources in the real application. The PCB’s are separated by cylindrical aluminum spacers. Aluminum bolts are used to secure the assembly and pass from the top-most tier, through the spacers, and fasten into the coolant plate. This arrangement can be seen in Figure 10. The PCB’s were instrumented with an evenly spaced array of Type T thermocouples.

For the baseline test unit, aluminum heat spreaders were mounted parallel to the PCB as seen in Figure 10. In the advanced test unit, embedded heat pipe plates of the same dimensions were used. Also in the advanced test unit, the direct-cooling heat pipes were mounted to the heaters that represented the high power integrated circuit locations. These heat pipes interfaced with the heaters using a copper flange that covered the heater and contained evaporator section of the heat pipe. The heat pipe was then run through the aluminum spacers to mate with the coolant wall. In this way, the heat pipe replaced the aluminum bolt. The coolant wall interface for the heat pipe was the hole used to fasten the aluminum bolt to the plate. The heat pipe condenser resided in this hole. Thermal grease was used to ensure sufficient thermal contact for effective heat pipe operation. Finally, in the advanced unit, heat pipes were embedded in the coolant wall plate to improve heat transfer between coolant channels.

INTERNAL THERMAL MANAGEMENT SYSTEM TESTING

To validate the modeling results, the baseline and advanced generic avionics units were tested at ACT. For these tests, two sources of heat were produced. The first represented the internal heat produced by the integrated circuits. Power equivalent to the waste heat produced by these chips was applied to heaters mounted at specific locations on the PCB within the avionics. In addition, larger area but lower power heaters were used to represent general heating of the circuitry. The total internal heat generation was on the order of 100 W. The second heat source represented heat gain from the nacelle environment. As heat is gained through the avionics walls, this source was represented by surface heaters that covered the area of each wall, including the coolant wall. The total heat input from these heaters was close to 1 kW. Both avionics units were tested at two heat input power percentages representing un-insulated and insulated units: 25% and 100%. Power was removed by coolant running through the five coolant wall channels. Prior to entering the avionics, the coolant passed through a distributor that ensured equivalent flow rates between channels.

The PCB’s within the avionics were instrumented with Type T thermocouple arrays to allow measurement of the temperature profile of each board. In addition, coolant inlet and outlet temperatures were measured using Type T thermocouple probes. To allow for calorimetry, the coolant volumetric flow rate was measured using a variable area flow meter. Coolant inlet temperature and flow rate were controlled using a process heater and metering valve, respectively. Both avionics units were tested at three coolant inlet temperatures.

Test results for the baseline and advanced generic avionics units are shown in Figure 19. As seen in this figure, maximum avionics temperature varies linearly with coolant temperature. This result is expected as the thermal resistance between the coolant and maximum temperature location is constant regardless of temperature (aside from some negligible material property variations). As a result, the temperature difference between the coolant and avionics should also be constant. This expectation is reflected in the data. Constant thermal resistance is also demonstrated by the equal spacing of each test case. The un-insulated baseline unit has an overall thermal resistance of 0.052 K/W. With insulation, the baseline case has a thermal resistance of 0.043 K/W. The advanced case, without insulation, is even better with a thermal resistance of 0.036 K/W, which is an improvement of 30%. This result is important in applications where FOD concerns restrict the use of insulation. Finally, with insulation, the advanced case, at 0.027 K/W, is almost half of the non-insulated baseline case.

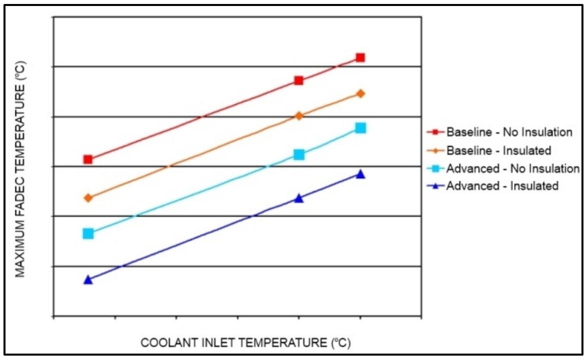

Figure 19. Maximum Avionics Temperature for Varying Inlet Temperature and Heat Gain

From these results, the improved avionics thermal management system provides a fuel temperature limit increase of 25.5 °C assuming the maximum temperature limit is 110 °C. This corresponds to an idle time limit increase of 60%.

Thermocouples were used in each avionics test unit to provide a thermal map of the avionics interior. These thermocouples were arranged along the surface of each Printed Circuit Board (PCB) in a diamond pattern with segments of approximately 2 in. (5 cm) and the thermocouples located at the intersections. These maps were compared with the model predictions as shown in Figure 20. As seen in this figure, the maximum experimental temperatures were approximately 10% higher than the model predictions. The minimum temperatures were closer with a difference of approximately 3%. The larger error at the maximum temperatures is due to the interface resistances found in the real system that were not modeled in the numerical system. These interfaces are numerous and are found primarily at the PCB fastening points where the bolts, posts, and, in the case of the improved avionics, heat pipe contacts the PCB and heat sink plane.

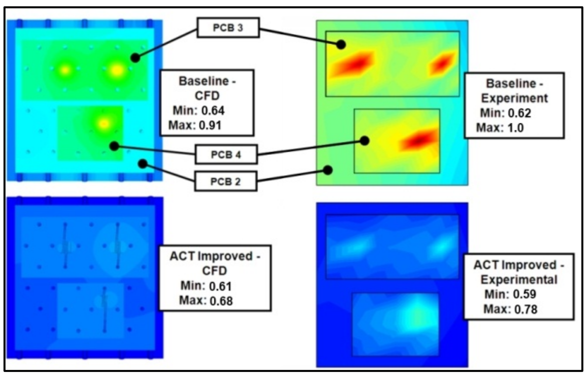

Figure 20. Thermal Profile Comparison of the Experimental Data and Numerical Results

EXTERNAL THERMAL TRANSPORT SYSTEM TESTING

After evaluation of the internal thermal management approach, the advanced avionics unit was mounted in the Thermal Management Test Unit (TMTU) as shown in Figure 21. In this unit, the coolant inlet line first passed through the LHP pre-cooler before entering the coolant distributor. The pre-cooler transported heat removed from the coolant to one of two condensers, depending on condenser sink temperature. Sink temperature was controlled to demonstrate passive condenser selection. After testing at ACT, the TMTU was delivered to AFRL for additional testing.

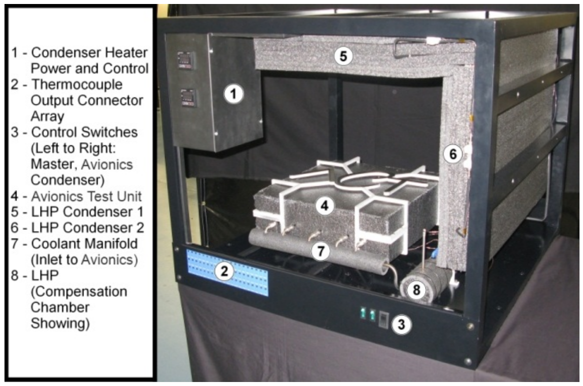

Figure 21. Avionics Thermal Management Test Unit

For the LHP pre-cooler test, the avionics heaters were operated at 100% and the control temperature for each condenser heater was set. To demonstrate passive condenser selection, only 1 heater was powered at a time. Water was set to flow through the LHP heat exchanger and avionics. This water would provide cooling for the avionics. Test data is shown in Figure 22. At the beginning of the test, Condenser 2 heater was powered on and allowed to reach steady state while Condenser 1 was maintained at constant temperature. At near 4700 s, heater power was switched to Condenser 1 and Condenser 2 was cooled rapidly using LN and then maintained at constant temperature. The system was again allowed to reach steady state. At 7500 s the system was shut down and allowed to cool.

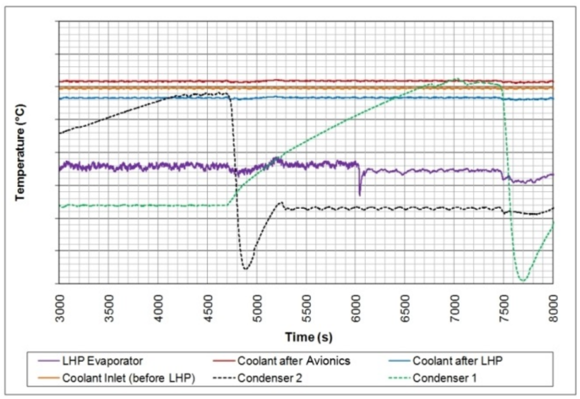

Figure 22. LHP Performance Test Data

As seen in this figure, the coolant temperature before and after the LHP and after the avionics remained relatively constant despite the variation in sink temperature. Throughout the test, the LHP provides approximately 500 W of cooling and reduces the coolant temperature, which was water for this test, by approximately 2%. For JP, this amount of cooling would provide a temperature reduction of 5%. This would provide an additional 10% of idle time.

ONGOING WORK

ACT is continuing the development of the avionics internal thermal management system through a program funded by AFRL. Under this program, ACT has designed and manufactured a direct-cooling heat pipe assembly and two embedded heat pipe plates for an avionics unit produced by our industry partner. One embedded heat pipe plate was designed to reduce the maximum temperature of the integrated circuits mounted to the plate. The other plate was designed to reduce the mass of the heat spreader while maintaining the current temperature of the integrated circuits. These units passed all component-level tests at ACT and have been integrated with the avionics unit. Component-level testing included hermeticity, proof pressure, burst pressure, and thermal performance tests. These tests showed the first embedded heat pipe plate reduced temperatures by 8%. The second plate reduced the heat spreader weight by 30% while reducing temperatures by 2%. System-level testing with a fully functional avionics is underway. The system-level tests primarily involve thermal performance of a baseline avionics and the advanced avionics unit.

SUMMARY/CONCLUSIONS

AFRL is interested in thermal management solutions that can avoid increasing the avionics operating temperature while providing at least 50% more idle time for military aircraft. ACT approached this problem by first identifying potential sinks not yet utilized in military aircraft thermal management system design. Once these sinks were identified, ACT designed a Loop Heat Pipe (LHP) to passively transport waste heat from the avionics to this sink. In parallel with the LHP design, ACT investigated an internal thermal management solution also based on passive, two-phase technology. This internal solution included heat pipes, embedded heat pipe plates, and insulation from the high temperature environment.

In the final design, fuel remains the primary heat sink for the avionics package. This feature was maintained for redundancy: if the advanced thermal management system should fail for some reason, the conventional, fuel-based thermal management approach would still function. As such, the LHP cools the fuel prior to the fuel inlet of the avionics rather than cooling the avionics directly. This pre-cooling of the fuel raises the fuel temperature that can be sent to the avionics and still provide sufficient cooling. Test results showed the LHP cooled water by 2%, which is equivalent to 5% for Jet Propellant (JP). According to thermal modeling of the aircraft, this would increase post-flight idle time by 10%. The target for this development was a 50% increase, which the LHP alone cannot achieve.

The internal thermal management system was designed to reduce the ambient heat gained from the environment and provide low-resistance thermal paths for waste heat generated by the electronics. Ambient heat gain was reduced by insulating the exterior of the avionics enclosure. This provided a heat in-leak reduction of approximately 75%. Low-resistance thermal paths were provided by heat pipes designed to transport heat directly between the highest heat flux electronics and the fuel channels. In addition, the aluminum heat sink plates used by the conventional design were replaced by HiK plates. The HiK plates used in the advanced avionics design consist of aluminum plates with embedded copper-water heat pipes. This type of HiK plate has an average thermal conductivity of 500 to 800 W/m·K depending on heat pipe density and heat flux distribution. This is much higher than the 180 W/m·K typical of aluminum. This design was integrated into a generic avionics enclosure for testing.

Through testing of conventional and advanced generic avionics test units, ACT experimentally demonstrated a 25% reduction in the temperature gradient between the fuel and hottest electronics location by applying only the internal thermal management solution. This reduction temperature gradient results in an equivalent increase in the allowable fuel temperature limit. This temperature reduction would result in an idle time increase of 60%. As such, the internal thermal management system alone exceeds the idle time improvement target of 50%.

The internal thermal management system provides a much greater fuel temperature limit, and therefore idle time, increase compared to the external thermal management system. The idle time limit increase was exceeded using the internal thermal management system alone. Since this system requires only integration into the avionics enclosure, these improvements are much simpler to realize than the LHP-based, external thermal management solution. For that reason, ACT recommends only the internal solution for military aircraft.

REFERENCES

1. Baer-Riedhart, J.L. and Landy, R.J., “Highly Integrated Digital Electronic Control – Digital Flight Control, Aircraft Model Identification and Adaptive Engine Control”, NASA Technical Memorandum 86793, Mar 1987.
2. Behbahani, A., Wood, B., Benson, D., Berner, A., Hegwood, B., Dejager, J., Rhoden, W., Ohme, B., Sloat, J., and Harmon, C., “Technology Requirements and Development for Affordable High-Temperature Distributed Engine Controls”, 58th International Instrumentation Symposium, Jun 2012.
3. Wolff, M., “INVENT Tip to Tail Energy/Engine/Power/Thermal Modeling, Simulation, & Analysis (MS&A)”, Presentation at 5th Annual Research Consortium for Multidisciplinary System Design Workshop, Jun 2010.
4. Bodie, M. and Wolff, M., “Robust Optimization of an Aircraft Power Thermal Management System”, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 2010-7086, Jul 2010, doi:10.2514/6.2010-7086.
5. Warwick, G., Aviation Week and Space Technology, p. 24, Aug 2008.
6. Anderson, W.G., Dussinger, P.M., Garner, S.D., Hartenstine, J.R., and Sarraf, D.B., “Loop Heat Pipe Design, Manufacturing, and Testing – An Industrial Perspective”, Proceedings of the ASME 2009 Heat Transfer Summer Conference, HT2009-88525, Jul 2009.

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ACKNOWLEDGMENTS

This work was completed under AFRL contract FA8650-09-C-2906. ACT would like to thank Andrew Fleming, Cindy Obringer, Elizabeth Scherrer, and Alexis Marruffo of AFRL for their support of this research.

DEFINITIONS/ABBREVIATIONS

ACT	Advanced Cooling Technologies, Inc.
AFRL	Air Force Research Laboratory
DBC	Direct Bond Copper
DCHP	Direct-Cooling Heat Pipe
FEA	Finite Element Analysis
FOD	Foreign Object Debris
HiK	High Thermal Conductivity (Embedded Heat Pipe)
JP	Jet Propellant
LHP	Loop Heat Pipe
LN	Liquid Nitrogen
LO	Low Observability
PCB	Printed Circuit Board
TMTU	Thermal Management Test Unit