Heat Pipe Embedded Carbon Fiber Reinforced Polymer Composite Enclosures for Avionics Thermal Management

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Abstract

Carbon fiber reinforced polymer (CFRP) composite material is an attractive structural material in applications where mass is critical. The carbon fiber matrix provides strength comparable to steel with only 25% of the density. The CFRP sheet can often also be made thinner than metal with similar mechanical properties, further increasing the mass savings. However, thermal challenges have arisen with the increased use of composites. In the area of electronics enclosures, traditional metal structures conduct and spread heat over large surfaces, but composites act as insulation. Heat generated by components causes internal temperatures to rise and has detrimental impact on the performance and reliability of the electronics. A method is proposed and tested that utilizes constant conductance heat pipes (CCHPs) that penetrate through the CFRP walls. The CCHPs are capable of transporting significant heat energy through a limited cross-section with a minimal temperature penalty. CCHPs are passive, two-phase, thermal transport devices which have extremely high effective thermal conductivities on the order of thousands of W/m-K. The heat pipes serve as thermal vias, providing a high conductivity path for heat energy to pass from within the enclosure to outside the enclosure with minimal impact on the structural integrity of the wall. The CFRP is fabricated without any change to the process or tooling and the pipes are embedded in a post-formation operation. A light-weight CFRP enclosure for a PC/104 module is developed, fabricated and thermally tested with actual PC/104 electronics.

Introduction

Modern military aircraft rely on an increasing number of electronic assemblies to achieve maximum performance and improve platform capability [1]. A typical assembly consists of a collection of electronics, mounted on printed circuit board, and encased in an enclosure. These assemblies provide critical functions such as engine control, actuator control, and power distribution management. Failure of these electronics would result in reduced aircraft performance, at best, and potentially render the aircraft inoperable.

Along with the increased use of electronics come increased waste heat loads. Since electronic failure rises exponentially with operating temperature [2], management of this heat load is as essential to aircraft operation as flight-worthiness. Providing sufficient thermal management, however, is becoming increasingly difficult for several reasons.

Avionics designs are calling for increased power density to reduce platform mass and volume. In addition, designers are integrating multiple components into single, multifunction units. In some instances, these components operate in high-temperature environments that result in a significant amount of ambient heat gain [3]. All of these factors lead to increased component heat flux. Without improvements in thermal management, higher heat flux results in larger temperature gradients between the heat source and sink, which leads to higher component temperatures.

The problem becomes worse for aircraft or component enclosures constructed with low thermal conductivity material. As this material increases the thermal resistance between the source and sink, sink temperatures must be lower to meet heat transfer demand.

CFRP has the potential to provide significant weight savings in aircraft but suffers from poor thermal conductivity. CFRP materials typically have thermal conductivities on the order of 5 W/m-K [4], while carbon steel is near 50 W/m-K and aluminum is near 200 W/m-K. Currently manufactured CFRP enclosures are restricted to low heat load applications. The fabrication process employed produces a low thermal conductivity material that precludes any other use at this time.

In this work, a method is developed for moving heat through relatively low thermal conductivity composite structure to an active sink located on the exterior of the avionics package. Multiple heat-pipe-based assemblies are developed and demonstrated as part of a fully-functional PC/104 avionics package.

The PC/104 embedded PC module was identified as a suitable platform to serve as a test bed for CFRP molded casing with thermal management technologies. The PC/104 is a rugged form factor used in a wide variety of applications, including both Tier II and Tier III UAVs, as well as in military ground vehicles [5]. For that reason, this form factor was selected as the basis for the design discussed herein. The test bed utilizes actual PC/104 electronic components.

Design

A new CFRP enclosure was developed for the PC/104 form factor that is scalable for various card requirements. PC/104 circuit cards stack vertically, each one plugging in to the next to assemble all the required hardware for the particular embedded computer application. The enclosure design follows this stacking approach, so that the height of the box can be customized for the number of cards to be included for the particular application. Each slice consists of four CFRP walls and four corner pieces. Typically one wall will have pass-through connectors to attach input and output cables.

A modular thermal management system (TMS) was designed to transport heat from within the enclosure through the poorly conductive CFRP walls to an external sink. The approach focuses on developing a generic solution for the box, rather than specific solutions for particular circuit cards and chip placements. The design consists of CCHPs that penetrate through the CFRP walls. The CCHPs are capable of transporting significant heat energy through a limited cross-section with a minimal temperature penalty [7]. The modular design allows for the TMS to be included only on slices that dissipate significant power. The TMS may be employed on one, two or three walls, again depending on how much power is dissipated by the particular card in that slice. In this way excess mass of TMS is saved when it is not necessary. Mass of the thermal management system is carefully considered, since weight reduction is the primary motivating factor to use CFRP in the first place. If the TMS results in a box that weighs the same or more than simply using an aluminum enclosure, then the entire purpose would be lost.

The TMS for the CFRP enclosure consists of three subsystems. The first subsystem is inside the box and transports heat from the highest power chips to the walls. An aluminum plate with embedded heat pipes, called a HiK™ plate [8], is secured to the motherboard where fins and a fan would typically be. The heat pipes extend from this plate and are attached to the walls of the box slice. The second subsystem consists of the heat pipes embedded in and jogged through the composite walls. These heat pipes collect heat from the inside of the box and transport it through the wall. Pipes that are not directly coupled to a HiK™ plate may have fins attached to facilitate in collecting the heat from the air within the box. The third subsystem is the external method for removing the heat. The testing demonstration uses an aluminum fin stack with a fan which is held solidly to the wall with the exposed wall heat pipes. Depending on the conditions and requirements in an actual application, this external heat sink could be swapped out for a liquid-cooled cold plate, thermoelectrics, or a natural convection fin stack. To allow access to the internal electronics the slices cannot be permanently attached together. Allowing the external heat sink to be removed and reattached easily is necessary in order to maintain the modularity of the computer and enclosure design.

A set of PC/104 cards was selected to provide a suitable test bed for a CFRP enclosure with embedded thermal solution. Table 1 shows a breakdown of the boards to be included and their power dissipation at peak operating conditions.

Table 1. PC/104 cards used as the test electronics, with their maximum heat dissipation.

Board Slot #	Description	Maximum Dissipation (W)
1 and 2	Motherboard Assembly	32.84
3	HDD	3.96
4	Communications Board	5.95
5	Power Supply 1	11.03
6	Power Supply 2	11.03
Assembly Total		64.81

The final design for CFRP enclosure and TMS demonstration unit is shown in Figure 1. Internally, copper fins are added to collect heat from the air for the lower power slices, while a HiK™ plate was designed for the high power chips on the motherboard. CCHPs are jogged through and flattened in walls. Externally, a single fin stack was designed with an attached fan to remove the heat brought through the walls by the embedded heat pipes.

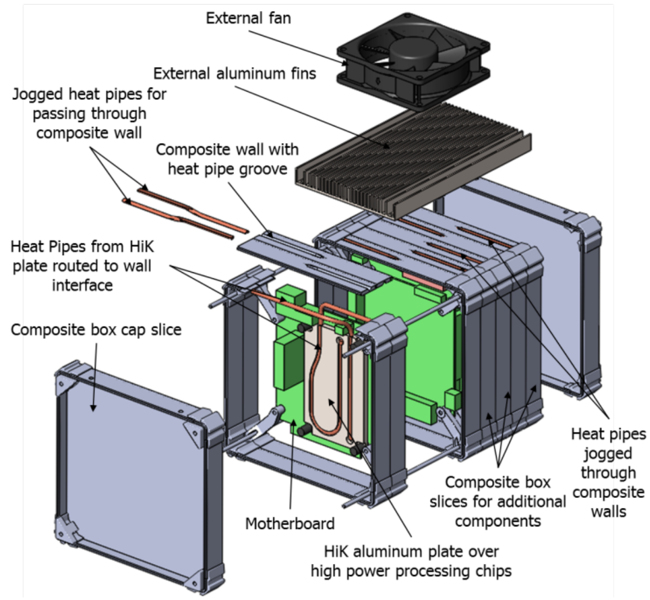

Figure 1. Exploded view of CFRP enclosure with TMS.

Analysis

Thermal analysis of the design was performed using the commercially available FEA software CFDesign. Figure 2 shows the air volume modeled around a single slice of the electronics enclosure. Power is applied to a 0.5 by 0.5 inch square on the green printed circuit board (PCB) supported within the enclosure. No thermal interface resistances were modeled. Table 1 lists 32 W as the maximum dissipation from any of the cards in the test system. Because the motherboard fills two slices, 16 W or half of the total dissipation is used as the applied power for this analysis. Natural convection to a 30 °C environment takes place on the outside of the enclosure. The volumes on either side of the slice where the rest of the box would be are suppressed to prevent air inside from mixing with air outside. The mesh in a region of the external ambient air volume is refined where the most complicated dynamics are expected from the buoyancy driven flow created by natural convection.

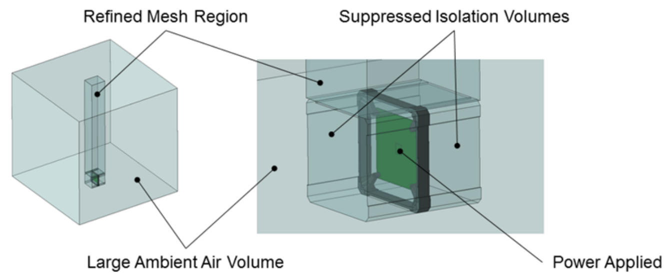

Figure 2. FEA thermal modeling set-up

Two baseline cases are run on a slice with no TMS. The first is with the CFRP box. Heat is transferred from the power application site via natural convection to the walls, which are then cooled on the outside by additional natural convection. Some heat is also conducted to the walls via the CFRP supports. This analysis predicts a maximum temperature on the PCB of 173 °C. A second baseline case uses the same geometry but the material properties are changed from those of CFRP to aluminum. The aluminum baseline analysis predicts a maximum temperature on the PCB of 154 °C.

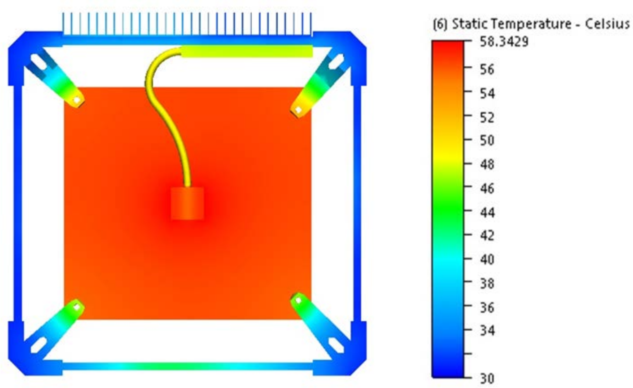

Figure 3. FEA Results in 30 °C ambient for the thermal solution.

The manufacturer provides temperature limits on these electronics as a maximum allowable of 85 °C, and the power supplies are de-rated above 60 °C. So, while applying all 16 W of power on only 0.25 in² may be overly conservative, the baseline results indicate that even an aluminum box needs additional thermal management. This is confirmed by the fact that existing aluminum PC/104 enclosures often include finned exteriors and internal heat spreaders or fans. When performing mass analysis to compare weight savings between the CFRP and aluminum, the mass of the CFRP TMS is partially cancelled out by the similar TMS required in an aluminum case.

The TMS is then modeled. Aluminum blocks are placed around the internal CCHP to spread the heat across the evaporator and condenser sections. A second CCHP is jogged through the wall and kept flush on both sides. On the exterior of the wall a thin aluminum fin stack is modeled with fin spacing configured for natural convection. The geometry can be seen clearly with the results in Figure 3.

The analysis predicts a maximum temperature on the PCB for this configuration as 58 °C. These results are promising, since they demonstrate a solution that keeps the temperature below the 60 °C point; here, the power supplies are de-rated. However, the absolute hot spot temperature should not be taken as definitive, because of the assumption made for the PCB heat load geometry and because interface resistances were neglected. The more reliable conclusion from these results is the comparison between the TMS analysis and the baselines. There is a 115 °C reduction in the maximum PCB temperature from the baseline CFRP case and 96 °C reduction from the aluminum baseline case.

Fabrication

Fabricating the TMS involves embedding a CCHP in the CFRP wall of the electronics enclosure. Two fabrication methods are proposed to achieve this. The first is to mold the CFRP wall directly on and around the CCHP. The second is to mold the CFRP wall and then later machine a groove in which the CCHP is sealed with thermal epoxy. To test the feasibility of these two methods several basic copper-water CCHP were fabricated and sent for insertion into the molding apparatus. Meanwhile sample plates of CFRP were tested with post-molding machining and embedding.

The CFRP components of the enclosure are injection molded from 40% carbon loaded PPS. The material is injected with 2030 psi of pressure and a gate temperature of 327 °C; the mold is preheated to 149 °C. Copper-water heat pipes are the obvious choice for the typical temperature ranges and power requirements of avionics boxes. However, survival of a copper-water CCHP in the molding process was not predicted due to the internal vapor pressure at that temperature and external pressure molding pressure. Testing confirmed these predictions. Most of the test pipes were crushed in the injection molding process. Therefore, the heat pipes must be integrated after the CFRP is formed.

The alternative option to molding the pipes with the CFRP is post-molding machining. A simple test was performed to discover the feasibility of this technique. The CFRP material was found to be easily machinable, causing no difficulty in creating the grooves. A thermal epoxy was used to secure two CCHPs into the machined grooves. One pipe was left round and sticking up out of the groove, while the other was flattened and completely encased in epoxy down in the groove. For the second flattened pipe, the excess epoxy on top of the pipe was then milled away to create a flat surface flush with the CFRP wall. The sample was then cycled repeatedly from room temperature to over 100 °C and back down again. No sign of cracking, pealing, or delamination of the epoxy was observed.

The TMS requires a copper/water heat pipe to be not only embedded in the wall, but actually jogged through the wall of the CFRP box. Figure 4 shows a cross section of this jogged concept. Three samples of CFRP wall section were machined with the jogged groove shown in Figure 4. With these samples, testing was performed to ensure that a heat pipe bent in that configuration will still operate properly. The technique to achieve this bend without damaging the internals of the pipe requires a careful procedure. Testing revealed that using a single wrap of screen wick helped prevent pinching off the vapor space at the bend. Also the angle of the jog was reduced from the originally designed 20° to only 10° from horizontal. The corners of the groove were also filed down to provide a bend radius rather than a sharp point.

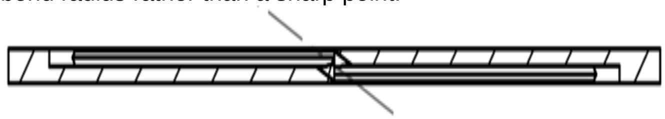

Figure 4. Cross-section of CFRP wall with jogged groove for embedding a CCHP

A series of CCHPs with a single wrap of screen were fabricated and carefully tested. With a given power load a 1 °C temperature difference between the heated end (evaporator) and the exposed end (condenser) was measured. The pipe was then inserted into the composite and bent into shape. Testing with the same power, the measured temperature difference at steady-state was about 15 °C. This result seems to show that the pipe was not working. But the pipe was carefully removed from the composite without un-bending it. When tested again, the newly liberated pipe again showed only a 1 °C temperature difference. This demonstrates that the pipe itself was not damaged. The larger temperature drop was a result of insulating three sides of the condenser with the composite material. This change in exposed surface area meant less heat could be rejected via natural convection, so the temperature had to rise. Additional testing was performed to ensure consistent results and more readily demonstrate that the jogged pipes can indeed transport the heat through the wall as analytical calculations predict.

A ball end mill was used to cut the simple groove geometry. A procedure was developed to flatten and jog the pipes into the wall with the epoxy. These samples were then tested with a natural convection heat sink clamped to the condenser end. The measured temperature difference from the evaporator to condenser was then found to be only 2 to 4 °C.

Typically, when CCHPs are embedded into metal plates, the plates are originally made extra thick. Once embedded in the plate, the pipes are completely encased in epoxy. After curing, a thin skim cut is performed across the plate and the epoxy creating a uniform flat surface without exposing any copper. That process is not feasible in this case, because the walls are already molded at the appropriate thickness. In addition, the copper must be exposed to attach fins or other pipes. A variety of processes to flatten, jog, and epoxy the heat pipes while maintaining functionality as well as keeping the surfaces clean and presentable were tested. Groove geometry and an embedding technique have been demonstrated that has successfully met these objectives by masking off the composite and copper when clamping between two fixture plates.

Straight out of the mold, the CFRP pieces have a smooth surface finish and the corner pieces require no additional machining. However, when the wall sections are molded, they are extra-long and are then cut to length. Wall sections selected for inclusion of the TMS are also machined with the appropriate groove geometry for embedding the through-wall jogged heat pipes.

With these procedures and techniques two separate CFRP electronics enclosures with integrated TMS are fabricated for a PC/104 computer with the components listed in Table 1. The CCHPs for the walls and HiK™ plate are fabricated then embedded into the walls with thermal epoxy. Copper sheets are cut and bent into simple fins and soldered on to the exposed wall pipes to serve as internal fins. These internal copper fins can be seen in the assembled unit pictured in Figure 5. Fins are not attached to the wall sections which are soldered directly to the HiK™ plate pipes.

Once the TMS has been incorporated into the walls, the TMS wall sections are assembled into slices with the corners and board stand-offs. The necessary electrical pass-through connectors are incorporated into the non-TMS boards prior to slice assembly. An aluminum HiK™ plate is fabricated to interface with the motherboard chips. The extended heat pipes from this board are bent and soldered to the pipes in the walls prior to attaching the electronics. The completed slices are then connected to the electronics. Additionally the top and bottom cover slices are assembled. Figure 6 shows the full assembly with the top cover removed so that the HiK™ plate on the motherboard and the solder joints on the right side wall are visible. Once all the electronics were assembled into their slices, the slices were plugged together and software was installed onto the system.

Figure 7 shows the assembled slices with exposed copper pipes where they bring the heat to the outside of the box. External aluminum fins are attached with screws into the top and bottom covers with a thermal gap pad to ensure good thermal connection with the heat pipes. A fan is attached to the fin stack and plugged in to the port that feeds electrical power to the fan from inside the box. Figure 8 shows the external fins and fan.

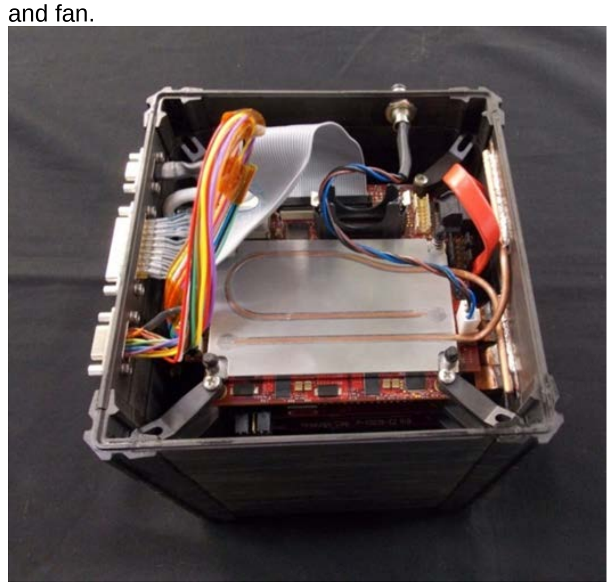

Figure 5. CFRP Deliverable with top cover removed showing the HiK™ Plate on the Motherboard with CCHPs Extending and Soldered to the Pipes in Embedded in the Right-hand Wall

Figure 6. Assembled CFRP Enclosure Slices with Exposed Copper Heat Pipe Sections prior to Attaching the External Finstack

Figure 7. External Finstack and Fan attached over the Exposed Thru-wall Heat Pipes of the CFRP Enclosure

The appropriate cables interface with the electrical connectors on the outside of the box. There are six total connections which are labeled in Figure 9. The input electrical power cable includes an AC to DC converter in-line with the cable similar to typical laptop power cables. The WiFi antenna goes through an adaptor/converter before connecting to the box. The VGA and Ethernet cables terminate in the typical standard connectors for attaching to other devices, but use a special micro-D connector to fit well on a single composite slice. The serial cable passes to another circuit card which is housed in a break-out box and features USB ports, indicator lights and a reset button. The breakout box can be seen with the completed unit in Figure 10.

For testing purposes, two thermocouples were passed into the box also. Special wall connectors were not included for these. Instead, port holes were drilled into two of the aluminum cover caps. The port holes tee into the through holes for the threaded rods which hold the stack together. Figure 11 shows one of the thermocouple wires passing into the port hole in the corner of the top cover.

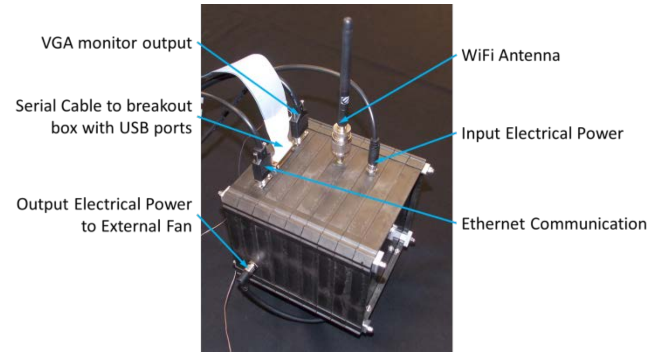

Figure 8. Assembled CFRP Enclosure Showing External Electrical Connections on Side Opposite of the Thermal Solution

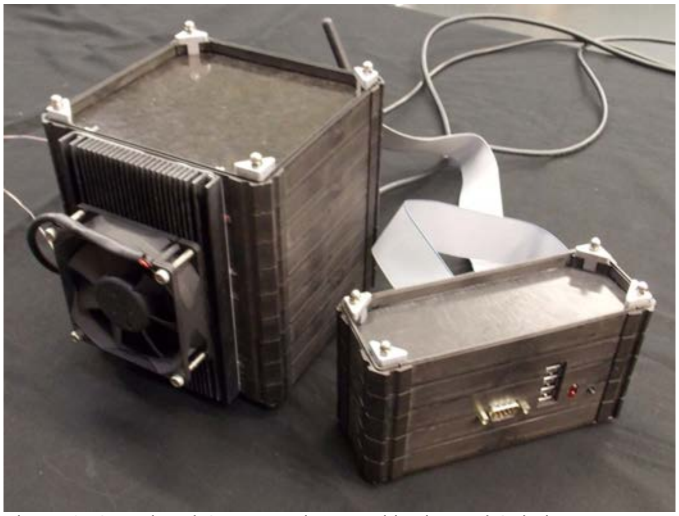

Figure 9. Completed CFRP Enclosure with Thermal Solution Connected to Matching Break-out box with USB Ports and Power Indicator Lights

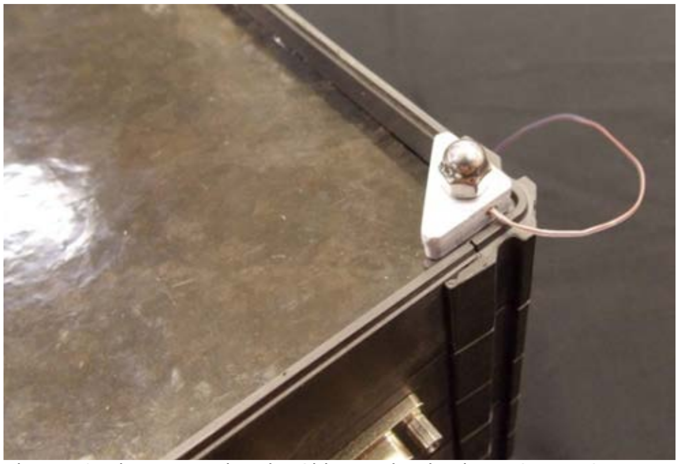

Figure 10. Thermocouple Wire Side Port in Aluminum Corner Cap Allows Monitoring of Internal Temperatures

Results

Testing with the electronics was performed which demonstrates that the thermal solution is effectively removing heat from the box. With the electronics Central Processing Unit (CPU) operating continuously at near 100%, the air inside the box reaches a steady-state of 6-8 °C above the external ambient temperature. The internally monitored core temperatures reach a steady-state of 75 °C above ambient when subjected to 100% CPU loading.

To thermally test the CFRP enclosure with the actual PC/104 electronics, the electronics need to be run at maximum power dissipation. The PC/104 computer runs with a windows operating system and can be connected to typical user interface peripherals such as a monitor, mouse, and keyboard. Two programs were installed in order to perform these tests. The first program is used to monitor and record the CPU usage and the temperatures of the cores as reported by internal measurements at the junction. The second program is a 3-dimensional fractal rendering program, which, while it is rendering the image, maxes out the core usage. Two thermocouples were inserted into the box. One was attached to the HiK™ plate and the other was left to measure the internal air temperature about half way down the box. In addition, the ambient external air temperature was also measured and recorded.

Figure 12 shows the results of a long-term full power test of the first CFRP enclosure. It should be noted that the maximum core junction temperature, T_{jmax} is 105 °C. At that point the dfccomputer's built in safety procedures would kick in and forcibly reduce the load on the processors. As can be seen, however, the core temperatures reach a steady-state of 98 °C after over an hour at nearly 100% processing load. Then the load is removed, and the temperatures quickly drop. At other points the temperatures reduce occasionally in response to temporary decreases in processing load. This occurs whenever the 3D fractal rendering program is not refreshed quickly enough and is allowed to complete its current task without having received a new task.

Since the external ambient is held at room temperature of 24 °C, there is a 74 °C temperature difference to the core junction temperature. This is significantly larger than desirable, as an increase of less than ten degrees in the ambient temperature would likely cause the cores to reach T_{jmax}. It should be noted, however, that the internal air temperature never rises above 30 °C, maintaining an excellent 16 °C temperature difference to ambient. This shows that the through-wall heat pipes are effectively removing heat from the box, however, the HiK plate is not effectively removing heat from the motherboard chips to the walls.

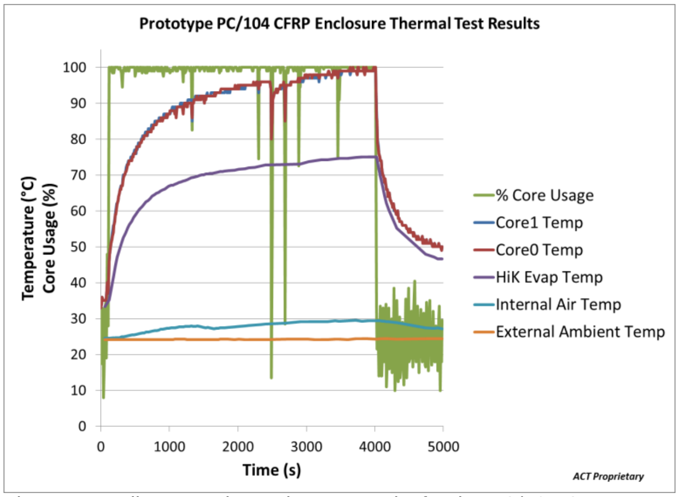

Figure 11. Full Power Thermal Test Results for the PC/104 CFRP Enclosure in Motherboard Side Down Orientation.

Because the motherboard and HiK™ plate get fairly hot, internal natural convection plays a role in cooling the box. Figure 13 shows results from a test, where the orientation is flipped partway through. It begins with the motherboard (i.e., the hottest components) at the top. In this case internal natural convection is not effective and the temperatures continue to rise even past 100 °C. When the box is flipped upside down, the heat source is at the bottom and air begins to circulate internally due to free convection. The core temperatures drop down to the 98 °C steady-state found in the previous test, and the internal air temperature also drops back below 30 °C. This finding further indicates that the HiK™ plate is unable to dissipate the maximum power from the chips effectively, but when the heat is convected and spread to the internal copper fins of the other wall sections the thermal control is more effective. The HiK™ plate contains only two small heat pipes, which for the predicted heat load, will be near or surpassing their maximum power capacity. A future design would require a rework of the HiK™ plate to operate for a higher power capacity.

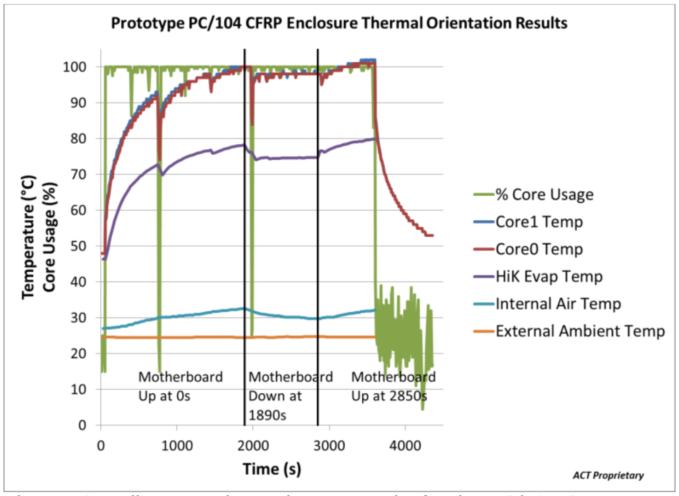

Figure 12. Full Power Thermal Test Results for the PC/104 CFRP Enclosure Showing Effects of Orientation on Thermal Performance

The final results shown in Figure 14 are from a repeat of the same experiment as was shown in Figure 12, but with an entirely different computer and composite electronics. The design remains the same, but this second unit demonstrates repeatability. As can be seen, the results are similar to those from the first box, with a steady-state core temperature of near 98 °C. The only notable difference is the internal air temperature, which is about 9° higher than was found for the first box. This variation is almost certainly due to variation in the exact location of the thermocouple within the box. The thermocouple wire is suspended in the air inside the box, and thus is not well secured to a particular point.

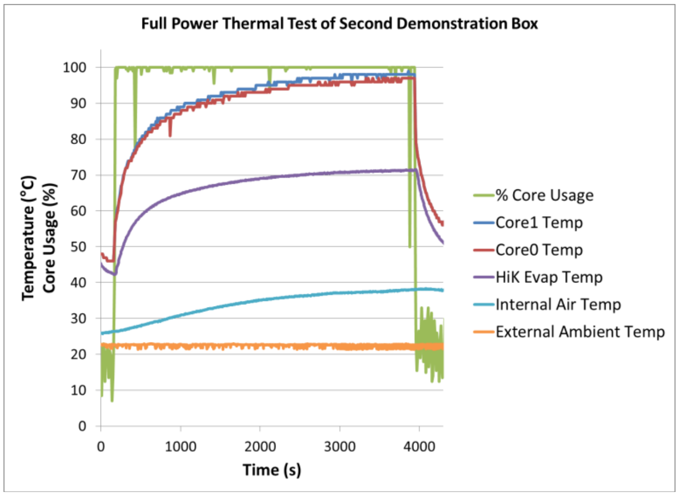

Figure 13. Full Power Thermal Test Results for the Second PC/104 CFRP Enclosure Demonstration Box in Motherboard-side Down Orientation

Summary/Conclusions

This work evaluated the integration of heat pipes with composite avionics enclosures. A method of embedding heat pipes into composite structures is developed. The final test results demonstrate a fully-functional PC/104 avionics package that uses an unvented composite enclosure and maintains all internal component temperatures below the maximum operating limits. This TMS was capable of maintaining these temperatures despite keeping both cores of the CPU at 100% load, which is not typical for most real-world applications.

For the composite avionics enclosure, this work demonstrates a method to overcome the primary weakness of composite structures: poor thermal conductivity. By embedding heat pipes in the composite structure and linking these heat pipes with finned, air-to-air heat exchangers, component temperatures are maintained for a fully-functional avionics unit under 100% CPU load. This achievement has the potential to realize the benefits of composite structures' strength and weight improvements, without the typical poor thermal management drawback.

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Definitions/Abbreviations

3D	Three-dimensional
AC	Alternating Current
CCHP	Constant Conductance Heat Pipes
CFRP	Carbon Fiber Reinforced Polymer

CPU	Central Processing Unit
DC	Direct Current
FEA	Finite Element Analysis
HiK™	High Conductivity
PC/104	Embedded computer standard form factor and bus structure
PCB	Printed Circuit Board
PPS	Polyphenylene Sulfide
T_{jmax}	Maximum allowable junction temperature
TMS	Thermal Management System
UAV	Unmanned Aerial Vehicle
USB	Universal Serial Bus
VGA	Video Graphics Array
WiFi	Wireless local area network