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Microvascular Composite Radiators for Small Spacecraft Thermal Management Systems

Devin T. Bunce, Kevin P. Bassett, Alexander R. M. Ghosh, Philip R. Barnett, Dawn M. Haken, Stephen Vrkljan,
Rashi Jagannatha, Tiago Silva, Victoria L. Coverstone
University of Illinois at Urbana-Champaign
104 S. Wright St. Urbana IL, 61801; (217)265-0142
aghosh2@illinois.edu

Bruce D. Yost, Jeffery R. Feller, Elwood F. Agasid
NASA Ames Research Center
Moffett Field, CA, 94035; 650-604-0558
elwood.f.agasid@nasa.gov

ABSTRACT

Small spacecraft have typically relied on thermal control systems in which waste heat is conducted through structural elements to the surface where it is radiated away. This simplistic approach is adequate for low-complexity missions at low Earth orbit (LEO), but increasingly complex mission profiles are being proposed, including missions to deep space locations which present a harsher thermal environment. In addition, small satellites are incorporating increasingly advanced capabilities which have challenging thermal control requirements such as cryogenically cooled sensors or propulsion systems. The University of Illinois at Urbana-Champaign, in partnership with NASA Ames Research Center, is developing a thermal control system for small spacecraft. This thermal control system utilizes a deployable radiator made of a micro-vascular composite material through which a coolant can be circulated. These microvascular composite radiators contain tiny channels that can be as small as 100 micrometers in diameter. These channels can only be manufactured using a novel fabrication technique developed at the University of Illinois, the Vaporization of Sacrificial Components (VaSC). Preliminary thermal simulation as well as vacuum leak tests were evaluated to determine the design guidelines for the cooling system. Moving forward, thermal vacuum testing of the prototype will raise the TRL to 6 by the end of the two-year development program.

INTRODUCTION

Small spacecraft missions are evolving beyond simple low-power profiles in low Earth orbit. Increasingly complicated and sensitive payloads such as cryogenically cooled sensors and complex biological experiments are requiring substantially demanding levels of support from the spacecraft bus. Spacecraft require support such as precise payload thermal control, high payload power draw, and large energy storage capacity. Deep space missions will encounter harsher thermal environments, require advanced electric propulsion, and need high power communication sub-systems to close a link back to Earth. To mitigate the power challenge related to these sub-systems, they will operate in ‘burst’ modes where they will draw significant amounts of power and dissipate significant amounts of waste heat in short time periods. Managing these high specific power sub-systems on a spacecraft with temperature sensitive payloads, as well as the low thermal capacitance inherent to a small spacecraft, is a significant challenge. Therefore, advanced thermal management becomes important for dealing with the corresponding waste heat. The University of Illinois at Urbana-Champaign, in partnership with NASA Ames Research Center, is developing a thermal control system for small spacecraft by means of a deployable radiator.

The thermal control system has been designed to be compact and lightweight. The prototype is intended for CubeSat applications; however, the radiator geometry can be easily varied and the size easily scaled to accommodate other small spacecraft form factors. Furthermore, since composite panels are a common substrate for supporting solar cells in small spacecraft, the radiator can naturally integrate with a deployable solar array. This allows the radiator to take advantage of resources by sharing the same gimbal, support structure, and stowage/deployment system.

Early mission concepts have been evaluated to determine the design guidelines for the cooling system definition. This includes not only the expected heat removal capacity desired by various payloads and sub-systems, but also the attachment and deployment fixtures for the radiator. Furthermore, the material interactions between the composite and the coolant are the subject of on-going study. Moving forward, thermal vacuum testing of the prototype will raise the TRL to 6 by the end of the two-year development program. When the system is complete, it will be a critical technology for enabling small spacecraft to support high power communication and orbital maneuvering capabilities as well as demanding payloads.

DESIGN

Figure 1: Left: Stowed Radiator System, Right: Deployed System.

The active cooling system concept can be seen in Figure 1 in a barebones form for a 6U demonstrator scale. The radiator itself is made from carbon fiber, with micro-vascular channels woven throughout. A coolant can be circulated through these channels and returned to the spacecraft. The microvascular channels can be as small as 100 micrometers in diameter, and they can only be manufactured using a novel fabrication technique developed at the University of Illinois, the Vaporization of Sacrificial Components (VaSC). The radiator panel itself is very thin. Current prototypes are less than 2mm thick, so multiple such panels may be able to be stowed together to increase the radiator surface area when deployed. The final thickness of the flight model may be larger, as research into some of the challenges discussed later could require additional carbon fiber layers.

A support module is housed inside the main bus. It contains a coolant reservoir, control electronics, circulation pump, valves, and radiator pointing gimbal. For CubeSat applications, this support module is being designed to occupy 0.5U. The radiator panel has been designed to stow against the side of the satellite within the standard deploy volume. Within the CubeSat, heat can be exchanged to target systems in a number of ways. With appropriate integration, the coolant could circulate directly through a compatible payload or thruster, but it is anticipated in most cases that the coolant will instead circulate through a dedicated cold block, to which other systems can reject their heat.

The concept is highly scalable. By adding additional panels, and possibly changing the reservoir and pump, an increased cooling capacity can be achieved.

One of the key advantages of this system is its ability to be throttled. If a spacecraft mission requires constant cooling, or if a spacecraft requires only cooling during peak loading, both can be easily provided. During a science operation, thruster activation, or communication window, the system can turn on and circulate fluid, but otherwise remains in a low-power, low circulation velocity state when the spacecraft does not want to dump significant heat. This also would allow for deep-space missions, where a constant dumping of heat could lead to freezing conditions for the satellite bus.

ESTIMATED COOLING CAPACITY

Early calculations have shown that a deployable micro-vascular composite panel with dimensions of 210 mm x 330 mm (which can be stowed on a 2U x 3U face) with a low absorptivity and high emissivity coating can act as an excellent radiator for a small spacecraft. Assuming magnesium oxide aluminum oxide paint ($\alpha=0.09$, $\varepsilon=0.92$) [1], using a grey body assumption, and assuming a 90% cooling system efficiency, a single radiator panel can provide 51.4 W of cooling at 25º C and 90.18 W of cooling at 70º C (a common upper limit for microsatellite temperatures). The radiator could be deployed from the body of the spacecraft, orthogonal to the solar panels and gimbaled with them (see Figure 2). The radiator can be cooling the system at all times unlike body mounted panels whose cooling capacity will change based on spacecraft orientation. Active coolant loops have been studied before for small spacecraft applications, even at extremely small scale leveraging thermal loads on micro-electro-mechanical systems (MEMS) [2]. To date, heat pipes used in microsatellites have been relatively simple, perhaps incorporating only a single bend and with no gimbaled articulations. Although much more complicated heat pipes and heat pipe loops can be designed, they complicate satellite ground testing as they often require the satellite to be held in a very specific orientation with respect to gravity. Additionally, control of heat pipes can be difficult. Switching them off when heating is required instead of cooling typically requires some amount of heat to be injected at a key point in the heat pipe to break the flow of the working fluid. The main advantage of an active cooling system, however, is flexibility. By simply branching one of the cooling circuits to a remote cooling block through some plumbing, a future extension of this system could transfer excess cooling capacity to the bus for use in any location within the spacecraft.

MANUFACTURING TECHNIQUE

VascTech

VascTech (Vaporization of sacrificial components Technology) is a unique process developed at the University of Illinois to imbue composites with three-dimensional vasculature. Fabrication begins by incorporating sacrificial fibers into preforms followed by infiltration with epoxy resin and curing at elevated temperature. After curing, the fiber is removed by heating the sample to about 200 °C under vacuum to vaporize the fiber, yielding empty channels and a 3D vascular network throughout the composite. Work to date has been focused on developing light-weight cases with integrated cooling channels for large battery packs in terrestrial applications, particularly electric and hybrid-electric vehicles. Studies so far have resulted in the fabrication of panels, testing of the conductive cooling capacity of these panels mated to a patch heater, and simulation to correlate experimental results for analysis and optimization. Work to optimize the flow patterns is ongoing.

PRIMARY DESIGN CHALLENGES

Integration

The VascTech manufacturing process is a well-established technique, but it has previously only been applied to terrestrial applications such as electric vehicle battery cooling. In these types of applications, minor leak rates are acceptable due to the ease of periodically replenishing the reservoir. Unfortunately, with spacecraft applications, the system must be demonstrated a priori to have a low enough leak rate that total fluid loss by the end of life of the mission is low enough the system still functions, and provides adequate capacity. Furthermore, should the fluid leak into space, it will be in the vicinity of other spacecraft systems, and therefore must be carefully chosen to prevent the risk of condensation back onto sensitive optics and satisfy range safety guidelines.

Figure 2 shows a concept for an integrated power system with a microvascular radiator sized for a 6U CubeSat, and demonstrates some of the other development goals of this program. Subfigure A shows a design for flexible, solid composite hinges between the solar panels, which are proposed to be be manufactured as a monolithic carbon fiber piece. The radiator too is directly integrated into this monolithic carbon fiber structure such that after deployment it is oriented behind and orthogonal to the solar panels, so it will be guaranteed to radiate to cold space assuming the solar panels are pointed at the sun. This flexible carbon fiber hinge must be designed such that the deployment motion does not add undue stress onto the radiator, damaging the microvascular channels or causing them to develop a leak. Subfigure B shows the University of Illinois standard ‘flexible cable’ methodology for lightweight electronic interconnect. A thin polyimide flexible printed circuit (FPC) is used both for power lines to the solar cells as well as for integrated monitoring electronics such as temperature sensors. The use of the FPC in place of typical PTFE insulated cylindrical wires shaves even more thickness off the panels, decreases weight, and increases reliability. It is also possible to fabricate additional microvascular channels directly into the solar panels themselves as both the fluid return path to the satellite bus and also as a solar panel cooling method. Subfigure C shows one possible use for the cooling capacity provided by the radiator; maintaining the bus battery pack at the correct operating temperature. The same microvascular carbon fiber technique, or any number of other traditional techniques could be used to make a battery cooling jacket. Rapid charging and discharging processes on high rate lithium cells can be significantly exothermic and lead to battery pack overheating, causing safety overrides to cease the charge or discharge operation to prevent a thermal run-away explosion. With adequate cooling, the range of practical charging and discharging rates can be extended

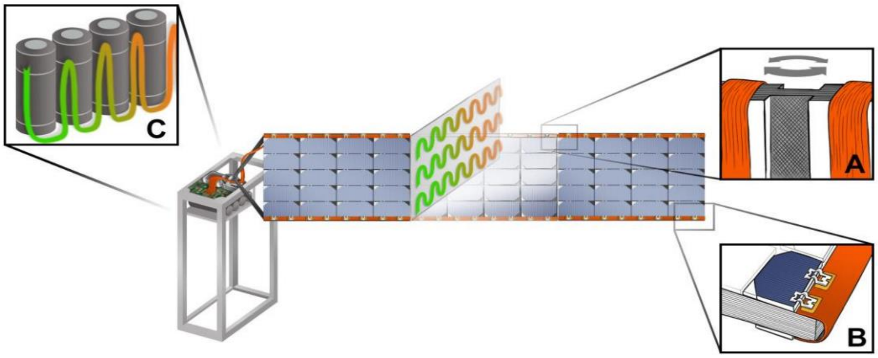

Figure 2: 6U System concept of integrated power and active thermal system A) embedded composite hinge B) flexible cable power system C) battery cooling jacket

beyond what is currently practical on a small satellite.
Leakage

Research must be conducted into methods to improve the leak rates of the microvascular channels when in a vacuum. Microvascular composites have to date only been proven operating in standard atmospheric conditions. While it may be possible that no special modifications need to be made, it is more likely that vacuum-induced leaking will occur through two main avenues.

The first path for leakage will be at the fluid-to-panel interface. In the existing ground applications, the fluid-to-panel interface has typically been either a fitting that has been epoxied into place, or some sort of tapped threaded insert (for sufficiently thick panels). While there are many acceptable standards for leak-resistant connections for vacuum chambers, most of these are intended for tube-to-tube or pass-through interfaces, not a tube-to-edge interface. Further, none of them are intended to attach to a microvascular channel on the size scale of 100-500 microns. A new interconnection system will need to be developed.

The second path for leakage is through the carbon fiber itself. Depending on the choice of coolant fluid, the epoxy matrix chemistry, the carbon fiber weave, and the number of carbon fiber layers, it is possible that some fluids may be capable of permeating through the carbon fiber, or traveling through a chain of micro-cracks and small local delaminated areas in layers, both inherent to composites. Should this be the case, there are a number of research paths that could solve this challenge. These include changing the number of layers, changing the carbon fiber properties, and looking at sealant coatings that could be applied to the VascTech material and left behind in the microvascular channel after processing.

Fluid Selection

Current microvascular cooling testing for terrestrial applications use a single phase coolant such as a water-glycol mix. Depending on the spacecraft mission requirements, this may not have a sufficient heat transfer rate, nor may it have appropriate properties for space operations, such as freezing when the system is not in operation. A significant portion of this project will be to survey and test compatible fluid-carbon fiber pairs in thermal vacuum conditions. This will be to determine their leak compatibility and permeability resistance, while also determining if they have sufficient heat transfer potential. Finally, the fluid viscosity on a micron level will lead to increased head pressure which will cause increased power consumption on the primary spacecraft as the pump must apply more work. A list of fluids being considered include the following (among over 15 others):

- Helium
- 50/50 Water/Propylene-glycol
- 50/50 Water/Ethylene-glycol
- Methanol
- Syltherm XLT
- Fluorocarbon
- Dynalene HC-40 & HC-50
- R134a
- Neon

Thermal simulation will help narrow down the fluid candidates.

TESTING AND ON-GOING ACTIVITES

Thermal Simulation

A thermal model is being constructed in Siemens NX Space Systems Thermal to produce a better estimate on the expected cooling capacity, help with fluid selection, and choose the microvascular channel path within the radiator panel.

The simulation consists of flow circulating from a reservoir to a heat exchanger. From the heat exchanger the coolant flows to the radiator panel and finally back to the tank. In an application, the heat sink could be an aluminum block fixed to the processors or other heat generating devices on board the satellite. The reservoir tank would be a small excess amount of fluid to account for any minor leaks over long mission lifetime. There are several constraints on the system. The circulation flow rate is fixed also, the material starts with an initial nominal temperature and runs until reaching steady state. The panel dumps heat via radiation at 50 Kelvin (an approximation for LEO).

Figure 3 shows a heat sink has a thermal load of 60 W and the temperature range is from 7 to 65 C. The simulation is iterated over a large set of scenarios to help with final fluid selection. Per fluid the system is tested over a range of fluid flow rates and input heat load on the heat exchanger. Each test is measured to find the max temperature of the heat exchanger. A test is deemed successful if the maximum temperature of the heat exchanger is at most 80 C because maintaining CPU processors below this temperature reduces the risk of long term damage. The simulations performed as expected for all fluids in the sense that the lowest flow with the highest wattage resulted in the highest temperature of the heat exchanger while the lowest heat load and the highest flow rate results in the lowest maximum temperature of the heat exchanger. The most promising fluids were those which kept the heat sink at or below 80 C for the highest heat load at the lowest flow rate. This fluid would allow the most work done by the electronics while putting the lowest power load on the pump.

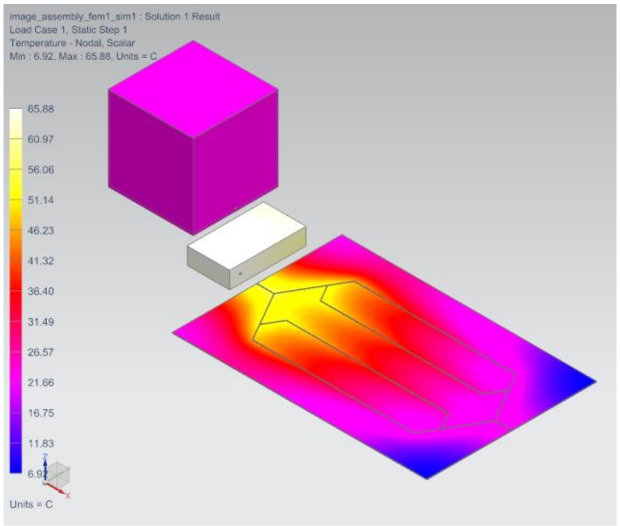

Figure 3 Thermal system with reservoir tank, heat sink, and panel with 50/50 water/glycol passing through it.

Few fluids were able to conduct adequate cooling for a heat load of at least 80 Watts. The few fluids from preliminary results that were able to handle at least 80 Watts were 50/50 water/ethylene glycol, 50/50 water/propylene glycol, Dynalene HC-40, and Dynalene HC-50. Table 1 shows the range of results for 50/50 water/ethylene glycol with green cells meeting the cooling requirements of the heat sink. Orange cells indicate test cases where the fluid achieved boiling temperatures. NX Space Systems Thermal cannot calculate phase change and while it is clear these load and flow combinations are insufficient at cooling the heat sink sufficiently it is a less accurate model of what the true final temperature would be.

The current flow path is a simple bifurcation path with two tiers of branching nodes. There has been extensive research optimizing the flow path across the panel to minimize the temperature (maximize heat exchange) and minimize the pressure drop from the entering flow to the exiting flow [3]

Preliminary analysis with this flow configuration for 50/50 water/glycol has found minor improvements in heat transfer but more importantly a lower pressure drop across the panel which will lessen the load on the pump. As design and development continues, the path configuration may be re optimized for this specific mission constraints such as minimizing the fluid temperature and therefore maximizing the amount of heat dumped to the environment.

Heat Load (W)	Flow Rate (mL/min)				
	7	14	28	56	84
40	69.94	38.76	26.91	21.93	19.91
60	128.7	83.06	65.09	56.15	52.78
80	178.9	122.1	96.32	84.15	78.53
100	190.4	156	123.8	107.3	99.45

Table 1: Example of heat sink temperatures in degrees C for a range of test cases using 50/50 Water/Ethylene Glycol.

. From these preliminary simulations a prototype can be constructed so that initial testing in the thermal-vacuum chamber can be compared with the results of the thermal model. Additionally, the prototype will help show the true pressure drop across the system where the wall roughness from the VascTech channels can be fully applied. In this manner a space ready pump would also be able to be designed and tested.

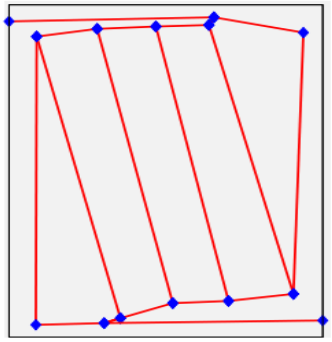

Figure 4: Optimal microchannel path [3].

Permeability and Leak Testing

A permeation cell fixture has been designed and fabricated. It has been designed to interface with the University of Illinois Thermal Vacuum Chamber. The cell can test sample coupons that are 3” x 3” at vacuum pressures down to 1e-6 Torr. Once the VascTech process has been perfected to ensure the microvascular channels do not leak with a given candidate fluid under these conditions, a full-scale panel will be constructed and tested in the full thermal vacuum chamber.

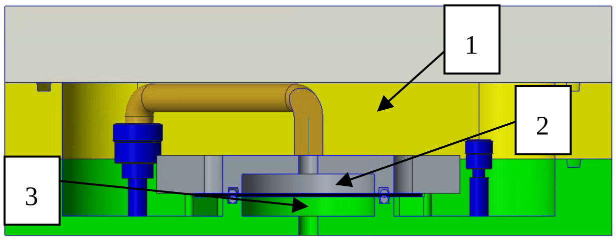

Figure 5: Interior of test chamber. 1) Surrounding test volume. 2) Top test volume. 3) Bottom test volume.

The permeation cell can be seen in Figure 6. There are three independent vacuum areas within this design. The semi-octagonal middle piece with a pipe through it constrains a carbon fiber sample between itself and the bottom piece. Two O-rings, one above and one below, create small test volumes separate from the main volume. Each of the three volumes (above the sample, below the sample, and the main volume) can be pumped down to vacuum pressure or filled with a tracer fluid. For each test two of the three volumes are at vacuum and the final volume filled with a tracer fluid such as helium. The tracer fluid can be detected and the leak rate through the composite can be quantified using mass spectroscopy. The tests will determine pure permeation compatibility of the carbon fiber in the absence of the microvascular channels. The system has two additional ports which can be connected to the tracer fluid. These ports will be the inlet and outlet for the microvascular channel and comprise a fourth test volume. In this test, all three original test volumes (above, below, and surrounding) will be evacuated and analyzed with the mass spectrometer, while the microvascular channel will be filled with the tracer fluid. Leaks in the “above” or “below” volumes indicate a permeation problem, while leaks in the “surround” suggest either a leak at the fluid interface to the microvascular channel, or a carbon fiber delamination. A design will be deemed successful and ready for full-scale panel testing once none of the three volumes demonstrate leaks.

Permeability and Leak Testing

Thirty-two samples have been generated for testing in the permeability cell. All the samples conform to the 3” x 3” form factor. There are three different carbon fiber materials being tested: a plain weave, a twill weave, and a unidirectional weave. Further, panels have been fabricated in 2, 3, and 4 layer samples without microvascular channels for pure top-to-bottom permeation testing. Samples were also produced in 4, 6, and 8 layer panels which contain a single microvascular channel, with samples made for both 300 micron and 500 micron diameter fibers. These channel-containing samples will be used in the second test described above. Multiple samples of each type were produced, so that repeatability evaluations can be conducted. Figure 7 shows a sample with plain weave carbon fiber and 6 layers thick.

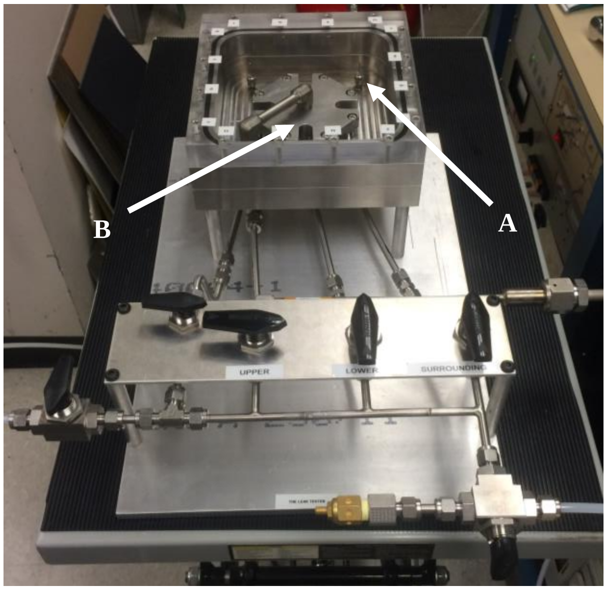

Figure 6: Permeation Cell. A) Surrounding vacuum test envelope. B) Internal Sample testing area

The carbon fiber samples proved to be extremely leak tight when testing for permeability through the sample. Only two samples leaked through the material. These two samples were two-layer plain weave with visible holes between the layers after curing. All other samples proved leak tight with no measurable drops in pressure. There were a few samples which leaked to the surrounding and not through the sample. For most failures this was due to the difficulty to control the pressure of helium and simply overcoming the seal the O-ring is capable of making. However, a few samples warped in the curing process and this made it very difficult for the O-ring to get a proper seal. These leaks to the surrounding were deemed artificial after retesting the samples.

A sample was intentionally broken repeatedly until it began to leak helium through the sample. The sample was bent about either the strong or weak axis until audible cracking was heard.

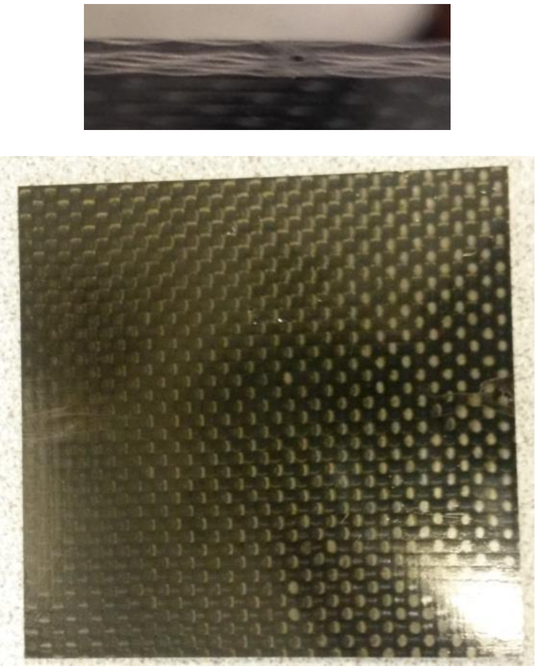

Figure 7: Sample plain weave test coupon, with microvascular channel.

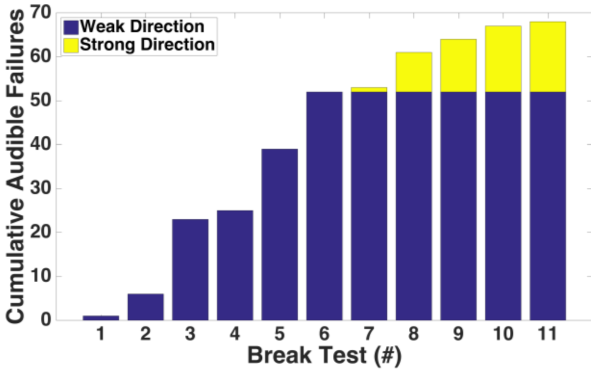

Figure 8: Cumulative Count of Audible Failures vs Break Test Count

The numbers of cracks were recorded per break test and then put back into the test chamber for a permeation leak test.

The mass spectrometer can only be turned on at 5e-4 Torr. Eventually the breaks become so severe (break test 11) that the vacuum pump pulls out most of the helium before the proper pressure is obtained for the mass spectrometer to be turned on.

The next major component of design for the panels will be making an edge connector that can also be leak tight and handle the CubeSat form factor requirements. The main two paradigms being considered are trying to come up with an external connection that can be fixed to a sample that has already undergone VascTech treatment or to find a way to embed a connector before the carbon fiber has been cured.

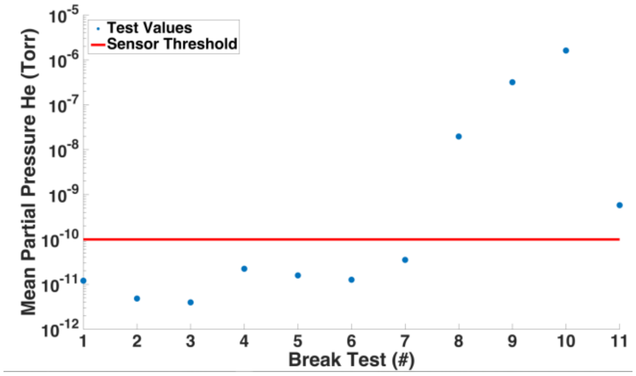

Figure 9: Pressure of helium leaking through the sample as a function of break tests.

TECHNOLOGY APPLICATIONS

To scope the system and design a build-to interface control document, NASA Ames has been surveying existing and proposed deep space satellite missions and compatible technology. Their on-going Biosentinel program has been identified as a candidate case study; while this technology will not be ready to fly on that mission, existing mission simulations already show significant duty cycling will be necessary for communication system on that mission. NEA Scout and Lunar Flashlight were further identified as missions which could benefit from an active cooling system. While this system will not be integrated in any of these missions, they do stand as good case studies as build-to goals for determining what the target heat transfer capacity should be, and how the system should be built for a non-invasive integration into the satellite.

Specific subsystems have also been identified as popular deep-space CubeSat components which have cooling challenges. Recently unveiled by NASA JPL, the IRIS V2 will allow communications farther than previous generations of transponders have been capable of. This is achieved by having the capability to communicate with NASA's Deep Space Network at X-band frequencies for command, telemetry, and navigation. The IRIS was designed specifically for use in a CubeSat, with a .5U volume and a mass of 1.2kg. The IRIS consumes 26W when transponding at 5W and only 8W for receiving commands. JPL has reported heat management issues and that a cooling system is needed for navigation sessions lasting several hours.

Additionally, and the 49-Core MAESTRO aims to dramatically raise the performance of spaceborne computing. The MAESTRO, developed by Boeing, is a radiation hardened version of a Tilera architecture chip currently used for embedded applications on the ground. This chip typically consumes 20W in standard configuration. The Maestro is already being tapped as a payload for CubeSat applications, with USC's program expecting to launch one in the coming years.

CONCLUSIONS

The active cooling systems described in this paper is a key enabling technology for future deep space CubeSats. Existing missions such NEA Scout and Lunar Flashlight as envisioned with current technology have significant heat management problems, and are forced to duty cycle their communication systems to avoid overheating. With technology being developed on this program, such as heat bearing fluid in microvascular channels through carbon fiber panels, these duty cycles will no longer be necessary.

Over this past year a base groundwork through several tests were completed to set year two of the program on the path for success. The Siemens NX thermal model has been applied to a wide range of coolants over both a range of applied thermal loads and flow rates to narrow down the coolant selection. Some finalized coolants include 50/50 water/ethylene glycol, 50/50 water/propylene glycol, and Dynalene HC – 40. This reduced list will be the starting point for full scale thermal vacuum tests to come. Thirty-two carbon fiber samples have been teak tested for permeation through the sample. These samples proved largely leak tight and sufficient for full scale models.

Over the next year, the cooling radiator will continue development and design. Key areas that need to be further explored are the fluid bearing edge connectors for the micro channels, the controller, deployment mechanism, and pump design. Lastly, a flexible hinge will be designed and tested. By the end of the program, the system is anticipated to reach TRL 6.

Further, an early LEO demonstration of a 3U-scale demonstrator is slated to launch in late 2018 as part of the CAPSat technology demonstrator mission. While it may be a low-TRL technology now, active cooling technology for CubeSat-scale craft will be possible in time for the next generation of deep space small satellites.

ACKNOWLEDGEMENT

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REFERENCES

1. Gilmore, David G., and Martin Donabedian, eds. Spacecraft Thermal Control Handbook: Vol. 1. AIAA, 2003.
2. Birur, Gajanana C., et al. "Micro/Nano spacecraft thermal control using a MEMS-based pumped liquid cooling system." SPIE Micromachining and Microfabrication. Vol. 4560. 2001.
3. Tan, M. H. Y., Najafi, A. R., Pety, S. J., White, S. R., and Geubelle, P. H. (2015) "Gradient-based design of actively-cooled microvascular composite panels." To appear in the *International Journal of Heat and Mass Transfer*.