SSC21-VII-06

Advanced Concepts for Small Satellite Thermal Control

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ABSTRACT

The Thermal Control System (TCS) for small satellites is notoriously challenging because traditional thermal design practices, hardware, and testing, when compressed, may not produce the same performance outcome. Emerging technologies for thermal software and hardware are already available in the small satellite sector and more are quickly being developed. This paper will discuss the inherent challenges in designing thermal systems for small satellites, the advancements being made in thermal modeling, recent advances in thermal hardware, and emerging thermal control innovations. Technologies include specific small satellite applications for: thermal interface materials, thermal isolators, heat straps, heat pipes, wedge locks, graphite cores, deployable radiators, phase change materials, louvers, cryocoolers, and sunshades. With more exposure to these new technologies, small satellite designs will be able to sustain more thermally demanding missions on orbit.

INTRODUCTION

Thermal control for small satellites has become a small satellite design driver, because it can limit the overall design and performance of a small spacecraft. High power density, limited surface area for radiators, low volume, and limited power available for heaters are common technical challenges that affect the configuration of operations and limit the scope of payload design. Schedule pressure and budget constraints can further stress an already challenging system, especially while maintaining traditional thermal margins.

THERMAL DESIGN CHALLENGES

Concurrent Design

Thermal mitigation strategies are often necessary in the post-engineering design phase for small satellites that have not been preemptively identified during initial development. Concurrent design for the thermal system - when creating power budgets, mechanical layouts, electronics board layouts, orbit parameters, radio transmit profiles, maneuvering and thrust requirements, etc., - may need modifications to resolve unmet thermal requirements. Options for thermal mitigation post-design phase can be difficult, and can potentially drive adjustments to mission capabilities, and flight operations, by adding needed thermal hardware such as heat straps or thermal interface materials. Duty cycling the payload can bring temperatures back within limits.

Schedule and Cost Impacts

The nature of most small satellite missions is to have a faster and cheaper option to traditional large spacecraft. Time is often the challenge here, with small satellite programs being designed on the order of months instead of years. This can cause the time to analyze multiple configurations and adaptations of a mechanical or electrical design to be constricted. This can also leave little time for sensitivity studies, trade studies, or parametric analyses which are needed to optimize the layout and mitigate thermal obstacles.

High Power Density and Limited Radiator Area

The thermal systems on CubeSats and MicroSats can differ quite drastically, but both share similar design challenges when compared to their traditional large spacecraft counterparts. CubeSats, while very small, compact, and power dense, tend to be isothermal. Maintaining tight temperature control bands, overall cold temperatures for sensors, or discreet temperature gradients can be difficult, especially when radiator area is limited. Li-Ion battery life is longer when maintained above 0C, driving the components around them to run warmer in order to prevent this. MicroSats, or small satellites on the order of half-ESPA volumes, are also compact and power dense, but are more easily separated into distinct thermal zones. These zones can more easily facilitate varying temperature ranges, but still face the challenges of high-power density and limited radiator area.

Maintaining Traditional Thermal Margins

Likelihood of success on orbit for the thermal system depends heavily on the margins applied during design and testing. Maintaining a standard of 15 C margin from thermal model orbital predictions to test temperature limits while maintaining heater control authority can be challenging if the energy balance is tight.

ADVANCEMENTS IN THERMAL MODELING

Utilizing significantly faster thermal model processing software is directly beneficial to small satellite thermal analyses where thermal design time is limited. Since mechanical, electrical, and system engineering decisions need to be made quickly, Reduced Order Modeling (ROM) allows the thermal engineering inputs to keep pace.

Geometric Math Modeling (GMM) tools, which have the ability to calculate environmental heat loading at various orbital positions and spacecraft configuration of operations is critical to the success of the thermal design. Many software options exist and are often based on creating a finite element or finite difference network. Simplified geometries will process faster, but intricate geometries benefit from meshing surfaces into highly discretized entities (e.g., nodes). Increasing the node count and complexity of the thermal model can increase run times exponentially. This can hinder the ability to run fast trade studies or produce quick results in order to concurrently design the thermal system alongside the rest of the spacecraft design. In turn, increased run times lead to final design verification by analysis efforts that consist of stacked worst-case scenarios. This could potentially lead to over-designed and unoptimized solutions.

Reduced-order modeling is an innovative way to take a large thermal model with many nodes, convert the original model into a reduced-order form, and predict the output for a specific set of input parameters. It is a statistical method of relating input factors to output responses, based on sampling the high-fidelity thermal model and generating training data based on the high-fidelity model runs, and then performing a data-fitting step to predict how the thermal model behaves between the sampled points. Once created, the reduced-order model allows the thermal analyst to run optimization analyses, trade studies, sensitivity analyses, model correlation efforts, etc. in a few seconds or minutes. Using a ROM approach can cut the time it takes to complete thermal analysis efforts into a matter of hours or days instead of months. Veritrek is a ROM software that has been in use by NASA JPL on the Mars Helicopter thermal design to improve the analyses run time drastically, NASA MSFC on their lunar lander program to understand design sensitivities, Sierra Nevada Corporation to quickly perform design verification efforts, and ATA Engineering to perform design optimizations.

Table 1 shows the time savings that can occur by implementing a ROM approach. It is appropriate to note that this approach may not be ideal for all analysis efforts or thermal models. The biggest time investment with this approach is the time it takes to create the ROM, since this depends on simulations from the high-fidelity thermal model. Therefore, models with simulation times on the order of days are not good candidates for this type of workflow, as it would likely take too long to create the reduced-order form of the model.

Table 1: Time taken to obtain thermal analysis results

Model	Analysis Effort	Method	Time to complete runs, post-process data, and obtain meaningful results
NASA JPL Mars Helicopter Thermal Desktop® model	Sensitivity study to understand how best to control heater survival energy	Traditional	~4 months
		Veritrek	10 days
NASA Ingenuity Helicopter Thermal Desktop® Model	Model correlation and design optimization to quickly predict the best heater warm-up procedure based on the current day's telemetry measurement data	Traditional	Multiple days
		Veritrek	A few hours once the ROM is created
NASA MSFC Lunar Lander Thermal Desktop® Model	Sensitivity study to understand the heat load going into a cryo tank	Traditional	Multiple hours
		Veritrek	< 1 hour
ATA Engineering 6U CubeSat Thermal Desktop® Model	Design optimization of body-mounted radiator sizes	Traditional	1 month
		Veritrek	5 days

In addition to the time it takes to create a reduced-order model, the accuracy of the resultant ROM is another key metric in utilizing a reduced-order modeling approach. Using more training data to build a ROM will improve the accuracy of the ROM but it will take longer to create, and so there is a balance in ROM creation time versus ROM accuracy that will be use case and thermal model specific. Table 1 provides some industry examples.

ROM analyses have been successfully implemented on CubeSat thermal modeling efforts, in several different ways.

1. Optimizing the size of multiple body-mounted radiators on a CubeSat bus, based on maximum allowable temperature of electronics inside the satellite bus that were getting too hot in worst-case hot conditions. In addition, optimization based on maximum allowable heater energy available to keep the electronics warm enough in worst-case cold conditions.

2. Correlating a 6U CubeSat Thermal Desktop® model to thermal test data obtained in lab.

3. Creating early design trade studies to determine which of multiple thermal control options are most effective to meet mission requirements.

4. Developing detailed design sensitivity studies and risk analyses to understand which areas of the design space pose the greatest risk of failing to meet mission requirements.

ADVANCEMENTS IN THERMAL CONTROL HARDWARE

Passive thermal design is recommended before shifting to more complex, expensive, or long lead thermal hardware. Once the passive thermal design of the system has been achieved to gain the most efficient heat transfer, active thermal hardware can then be applied to meet remaining requirements. Starting at the internal spacecraft level with components on electronics and working out to radiators, the following are concepts, developments, and latest solutions related to thermal control.

Near Junction or On-Die Cooling

Hot temperature limits for electronics are typically driven by the derated junction temperature limits of the components on each board. Reducing the temperature rise from the junction to the case, Theta-JC, would allow the junction to run cooler. Embedded cooling in power dense electronics component packaging itself can increase the performance 3 to 10 times more than before depending on the high thermal conductivity medium added.

PCB Embedded Heat Pipes

Advancements in heat pipes for small satellites that are still in analysis phase include high heat flux pipes embedded within a metal core printed circuit board. This can lower the thermal resistance by 35- 45% compared to metal core PCBs, based on analyses by Advanced Cooling Technologies (ACT). Wick thickness and pore wick structure were evaluated as performance and manufacturability drivers.

Miniaturized heat pipes on the order of 1.5 to 2 mm embedded in four different types of printed circuit boards were analyzed by AT &S Austria Technologie. The temperature delta between the maximum heat-dissipating component and a defined heat pipe point at ambient temperature was studied. The thermal connection from the heat pipe to copper structure on the PCB, whether by copper filled slots or vias, was a determining factor in the performance of the embedded heat pipe system.

Thermal Interface Materials

Moving heat from the junction to the case of an electronics component is followed by the interface from the case to the board, Theta-CB. While many interface materials exist, it is difficult to find one that has a high thermal conductivity, is easier to apply than a traditional grease, maintains a discrete thickness, and is reworkable.

Thermal gap pads, tapes, fillers, and gaskets are light, reworkable, quick to acquire if schedules are fast, and cost effective. Chomerics, Bergquist, AIM Products, and Aerospace Fabrication and Materials are suppliers of various TRL 9 products.

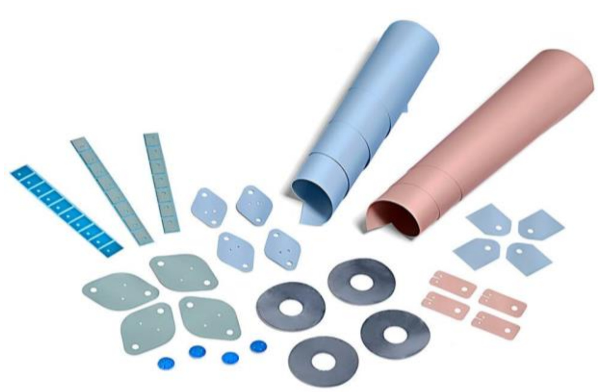

Figure 1: CHO-THERM Thermally Conductive Electrical Insulator Pads, photo compliments of Parker Chomerics

Graphene and carbon nanotube embedded films are being developed and show good performance in both test and on orbit. Due to the nature of graphene, the heat transfer is excellent in-plane but not axially. When crosslinked, better thermal performance can be achieved, and when rolled into carbon nanotubes, both the axial and in plane conduction is enhanced.

Annealed Pyrolitic Graphite (APG) has an in-plane thermal conductivity that is extremely high at 1,700 W/mK, but low through-plane conductivity near 10 W/mK. APG alone is brittle and low strength, thus requiring encapsulation by a stronger material. The mass savings and increased thermal performance when encapsulated in Al or Mg is desirable for small spacecraft, but can be cost and schedule prohibitive. Encapsulated Conduction Cooling by Advanced Cooling Technologies, and K-Core by Boyd Corp. are both products with TRL 9 on the market today.

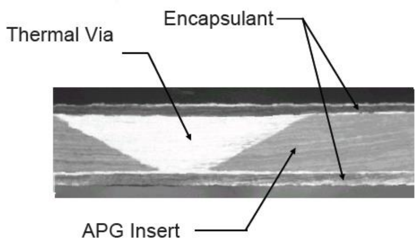

Figure 2: Encapsulated APG, photo compliments of Advanced Cooling Technologies

Carbon nanotube (CNT) embedded thermal interface materials combine through-plane with high in-plane thermal conduction by aligning the carbon nanotubes. CNT on an aluminum substrate is available at TRL 9 though Carbice, Corp.

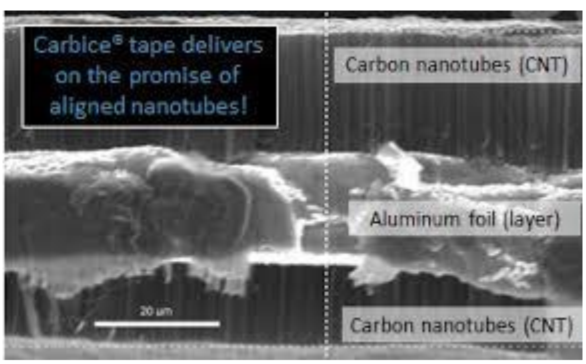

Figure 3: Carbice Carbon Thermal Interface Material, photo compliments of Carbice Corp.

Thermal Straps

Following on the innovative use of graphite for thermal interface materials, thermal straps have begun to benefit from excellent in-plane thermal conductivity. By layering sheets of graphene like a traditional layered heat strap, the heat transfer is increased while the mass is decreased. For the same conductance, fewer layers can be used, minimizing the volume, which is desirable for space-constricted satellites.

Thermal Space Ltd. has developed a **L**a**y**ered **N**anostructured Cross(**X**)-Linked (LyNX) Graphene Heat Strap, which has high performance due to the structure of the graphene within the layers. Thermal LyNX has orders of magnitude higher flexibility with twice the thermal conductance to mass ratio than pyrolytic graphene sheet (PGS) or graphene composite sheets.

Figure 4: Thermal-LyNX heat strap, photo compliments of ThermalSpace

Thermotive Technology offers Pyrovo™ Pyrolytic Graphite Film (PYRO PGF) heat straps with a specific thermal conductivity (k/rho) that is 20 X better than Copper and 10x better than Aluminum.

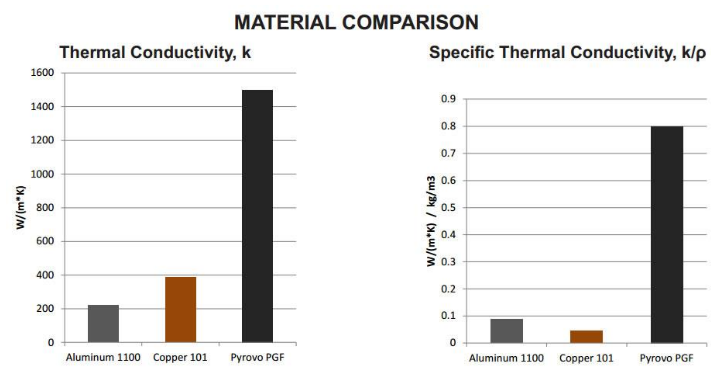

Figure 5: PYRO PGF Heat Straps, image compliments of Thermotive Technology

Boyd k-Core straps utilize an encapsulated APG core in a flexible strap. It provides thermal conductivity up to 1200 W/mK, with increased conductivity at cryogenic temperatures.

Figure 6: k-Core Heat Strap, photo compliments of Boyd Corp.

Aerogels

Isolating components within a small spacecraft can reduce the temperature swings induced, maintaining tighter temperature requirements, and reducing heater power needed to maintain minimum temperatures. Low conductivity materials like plastics or metals can be used as shims, but can take up volume and interfere with mechanical structures. Aerogels have been used since the 1950's, but recent advancements are lighter, smaller, and more stable.

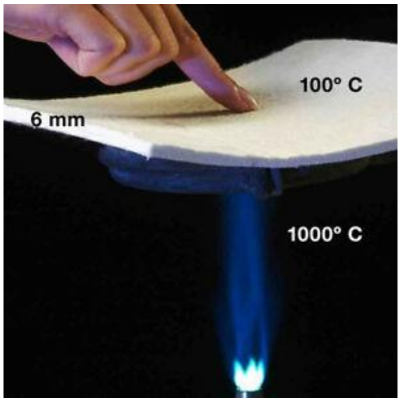

Figure 7: Insulation performance, image compliments of Aspen Aerogels

Electronics Board Retainers

Mounting electronics boards with card retainers, such as wedge locks, can conduct heat effectively by creating contact from the wedge lock mating surface area to chassis. Increasing the area by utilizing a larger segmented wedge lock can improve this contact, and Advanced Cooling Technology has created ICElock with a larger footprint, increasing conductance by 30%.

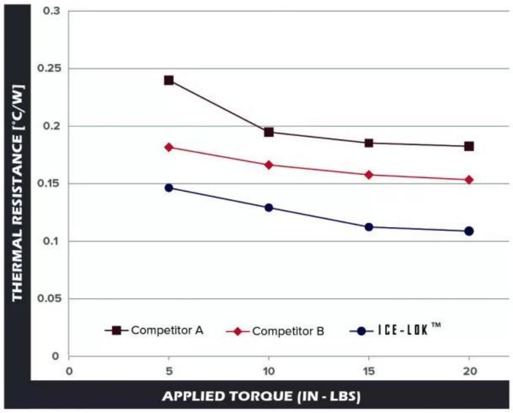

Figure 8: ICELock Performance compliments of Advanced Cooling Technologies

Thermal Storage

Thermal storage devices are an important consideration for high-power SmallSats, because they offer the ability to more effectively manage heat loads, especially for Low Earth orbits and low duty cycle components [2].

Thermal energy storage devices such as phase change materials (PCMs) can be used to reduce the size of the radiator by reducing peak loads. This has direct application to a majority of SmallSat missions and components like propulsion systems, radios, avionics, and most payloads that do not need to be continuously running at full capacity. Consequently, PCMs are currently a popular focus of thermal subsystem advancement efforts. Thermal Management Technologies and Redwire have both created PCM panels that are of the CubeSat form factor, allowing them to be easily stacked in between critical components [10]. Redwire's Q-Store is an approach at TRL 5/6 for thermal storage that also includes thermal spreading features (Figure 9). It is a tailorable approach that can handle a broad range of transition temperatures and storage requirements.

Figure 9: Illustration of Q-Store, image compliments of LoadPath

Mini Cryocoolers

Instruments and payloads that require cryogenic cooling need heat sinks colder than radiators alone can typically provide. Cryocoolers are in use and reliable on traditional-sized spacecraft but are on the order of 4 kg, which is too large and heavy, especially for a CubeSat.

Miniature cryocoolers have been developed by Creare, Sunpower, Inc., Riccor-USA, Inc., Thales & NASA JPL, Northrop Grumman, and Lockheed Martin [14].

Heat Pipes

Oscillating Heat Pipes (OHPs) from ThermaVant are two phase cooling devices that act like an active system but run passively. The channel patterns within the substrate create 180 degree turns which move bubbles and slugs fluidly within the channels as the phase changes. This creates volume and pressure differences as in a standard condenser/evaporator heat pipe. OHPs can be made very small, and used as heat spreaders (figure 10), heat sinks, or heat straps [15].

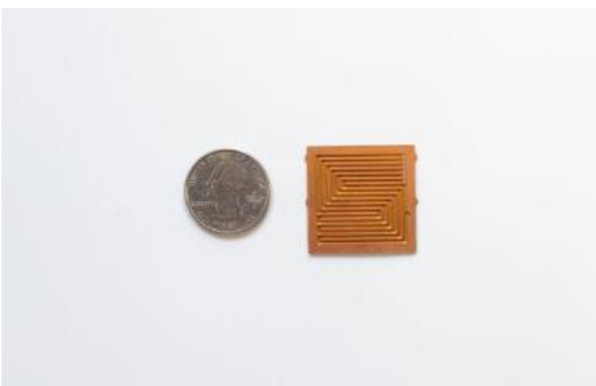

Figure 10: Oscillating Heat Spreader, photo compliments of ThermaVant

Advancements also include flat heat pipes which are essentially a cross between a heat strap and a heat pipe. "FlexCore" from ROCCOR, is a flat heat pipe, 1 mm thick, and capable of ten times the conductivity of copper while being 90 % lighter. FlexCore is TRL 9 and was flown on the 6U TechEdSat 10.

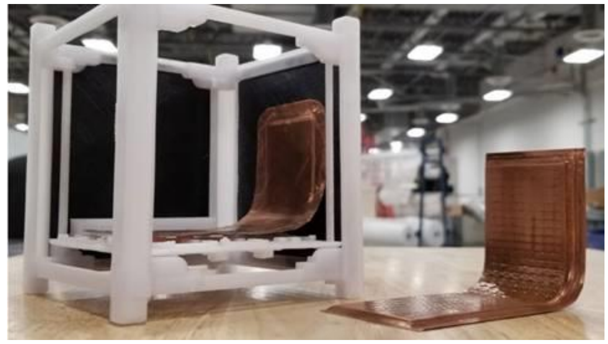

Figure 11: Flat Heat Pipe photo compliments of LoadPath

Insulation

Multi-Layer Insulation, typically applied to larger space craft, requires a keep out thickness on the external volume of the chassis. For CubeSats, volume is at a premium and using this area is not always viable. MLI can be applied to the external surfaces of CubeSats, but avoiding deployment rails and mechanisms makes it risky due to possible interference. Single layer MLI, using just the outer layer of the blanket taped on the surface, can be an effective solution to maintaining a warmer biased CubeSat.

MicroSats, which have more volume available and less risk when deploying, benefit from MLI blankets. Custom blankets can be designed and manufactured by Aerothreads, Aerospace Fabrication and Materials, and others. Base materials are available from Dunmore and Sheldahl. Dunmore has a specific kit for small satellites called the SatKit which includes Aluminized Kapton outer layer, embossed Mylar internal layers, transfer adhesive, and closeout tape.

Figure 12: SatKit image compliments of Dunmore

Radiator Coating Application

Small satellite radiator coatings often use flexible OSRs and other optical tapes to control the absorptivity and emissivity of the surface. They are easy to apply, light weight, and cost effective. When external surfaces are smooth, the tape can be applied easily. If features on the surface must be taped around, especially on the larger MicroSats, it can be time-consuming. One way to cut 1:1 drawings of taped surfaces is by using a drag cutter. A Cricut cutter, often used in crafting and easily available, efficiently and cleanly cuts 5-10 mil Silver Coated Teflon, Aluminum Coated Teflon, Aluminized Kapton, and other assorted tapes. It produces precision cut pieces that are more easily applied.

Miniaturized Louvers

Internal heat mitigation strategies can be bypassed if the heat rejection of the system can be adjusted. Traditional louver systems are efficient ways to mechanically switch the emissivity, radiating more heat when hot, and less when cold by closing the louver. This is a highly reliable system but can be costly and heavy. Micro Louvers have been developed under the NASA IRAD program that are lighter, smaller, and effective for CubeSats. The Dellingr satellite demonstrated to a TRL 7 level by operating several times as expected on orbit. Life testing over 12,900 cycles showed no performance degradation [12].

Variable Emittance Radiators

Radiator coatings using thermochromic materials on various substrates produce an emissivity that changes with temperature. Based on the phase change properties of vanadium dioxide (VO2), significant change in optical properties when the phase change temperature is met near +67 deg C, is observed. Recent experimental demonstrations of this technology using VO2 on varying substrates have optimized the emissivity change. A delta in emissivity of 0.4 is an effective change, producing a radiator that can emit less at colder temperatures thus conserving heater power, and more when the radiator is hot [13].

Deployable Radiators

One of the most significant challenges facing higher-power SmallSat thermal designs is thermal dissipation. Although we could take advantage of the $q \sim T^4$ relationship (where q = dissipated heat and T = rejection temperature), rejecting enough heat at elevated temperatures is often not possible or practical.

A more practical way to meet this challenge is by increasing the radiating surface area by means of body-mounted and deployable radiators. Body-mounted radiators for SmallSats provide limited cooling, simply because their surface area is limited. An ideal body-mounted radiator analysis was conducted to demonstrate these limitations. The radiating area required to dissipate a certain power level at a given temperature was obtained, as shown in figure 13, and shows radiator areas from 0 to 2 m^2 [10].

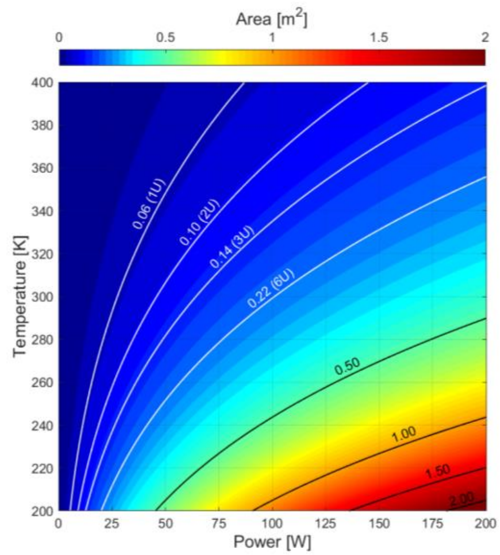

Figure 13: Ideal Radiator Areas (0 to 2 m^2) with ε = 0.9 as a Function of Power and Temperature, figure compliments of LoadPath

Figure 13 includes maximum body-mounted radiating area curves for typical CubeSats. For example, a 6U CubeSat has a maximum surface area of 0.22 m^2 and can dissipate at most ~90 W, assuming that every external surface is acting as a body-mounted radiator, unless the spacecraft can run hot. For higher powered systems, deployable radiators are imperative.

Realizing an effective deployable radiator system is a significant challenge, as there are many options and design considerations. For example, deployable effectiveness can partially be characterized by the stowage volume versus deployable area. A deployable thermal radiator could be deployed from the side of a bus to provide additional area; but must be sized based on their conductance to provide a mass efficient solution. In addition, deployable radiator effectiveness depends on the thermal conductance through the hinge line (where there is a lot of thermal resistance).

Redwire, Thermotive, and Thermal Management Technologies have created versions of deployable radiators and are in various stages of development. Redwire's Q-Rad (14) is a lightweight, deployable radiator for SmallSats. This product is at TRL 5/6 and can be modified/scaled for a broad range of applications.

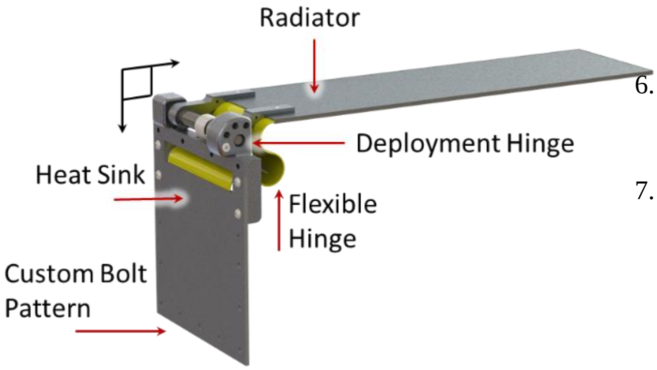

Figure 14: Deployable Radiator Illustration compliments of LoadPath

CONCLUSION

The increase in small satellite demand has pushed thermal control needs to the forefront of engineering design. Challenges due to higher power densities and transient dissipations with limited radiator area are pushing the demand for new thermal control technologies. Advanced thermal concepts for small satellites will continue to develop in terms of TRL, lower cost, and availability, allowing for even higher small satellite capabilities.

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