Next-generation CubeSats and SmallSats thermal control subsystem

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13.1 Satellite thermal design

The goal of thermal design for a satellite is to maintain temperatures of components throughout the spacecraft within their operating limits while in orbit in a harsh space environment. Most electronics and mechanisms like motors, actuators, and optics, for example, are designed for use on earth with their protective atmosphere. Convection due to air allows for cooling and heating methods that are not available in the vacuum of space, such as fans and fins. Primary heat paths are different in space vs. earth, where heat transfer, heat absorption, and heat rejection are dominated by conduction and radiation.

Temperature balance of the spacecraft (SC) is determined by the heat being produced internally, and the external heat loads from the environment. Internal heat loads may be steady, while others might change over the time. Similarly, the external heat loads from the sun, albedo, and infrared (IR) of a planet can change over time as the satellite orbits, which also depends on the position, altitude, and orientation of the SC. What this creates is a very complex network of heat paths, heat absorption, and heat rejection which needs to be maintained to meet temperature requirements. Exceedances can reduce the performance or lifetime of the satellite or cause complete failure of the mission (Fig. 13.1).

13.2 Satellite thermal design early history

Before diving into the details of modern-day small satellite thermal control and its challenges, learning from the past is key toward understanding the intention of thermal design, testing, correlation, and flight. In the past, thermal control for satellites was often applied at the end of the configuration design cycle. Thermal balance testing was the key to verifying that a satellite would maintain the required internal temperatures within acceptable levels for all phases of flight (Ed Powers, GSFC history of thermal satellite design). View factors were hand calculated. Projected areas were measured from photographs via cameras taking images at different sun angles on small-scale physical models. Heaters were generally not available because the

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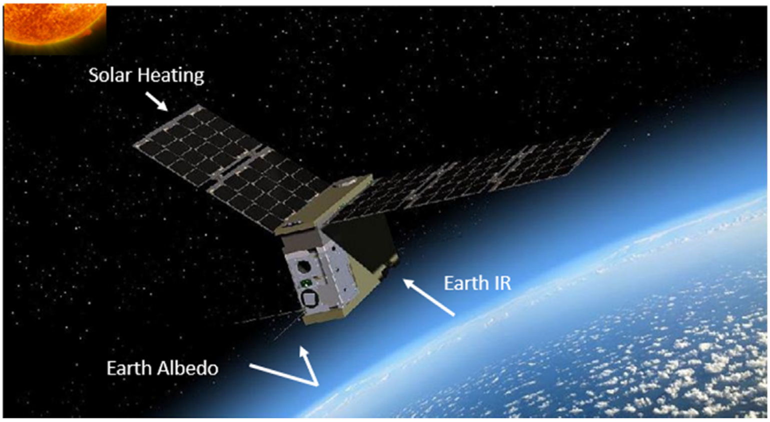

Figure 13.1 Thermal environmental heat loads in space.
Source: Blue Canyon Technologies.

total power generation was insufficient due to the low efficiency of the solar cells. The passive thermal designs for these explorer-class missions relied primarily on the surface coatings to adequately maintain temperature control. These initial SC were the first to use thermal design and thermal control, utilizing spinning to keep the temperatures in nominal ranges.

What these pioneers learned early on was that thermal engineering had to be an essential participant in the early development of the system's configuration. These SC, in general, had multiple thermal zones, capable of being maintained within temperature ranges based primarily on their external coatings and their placement in effective proximity to radiators. As the power system advanced, the use of heater power allowed satellites to have more discrete control over specific components. Multi-Layer Insulation (MLI), for example, was developed early and used as an insulating method in conjunction with heaters to maintain lower bound temperatures. Further developments during this era included louvers and heat pipes, which increased flexibility of the spacecraft configuration significantly.

Thermal analysis software, although extremely useful but primitive in the early days, advanced rapidly, allowing for much greater precision in the analyses. Thermal balance testing remained the primary tool for design verification. The testing, including solar simulation, was very effective.

Large observatory class SC with deployed solar arrays, generate more power. Ample heater power is generally available to maintain payload temperature ranges compared to small satellites. The placement of internal components is more flexible, radiators can be larger, and more efficiently located. The dependency on very reliable, stable coatings is reduced. Thermal technologies were developed with larger SC volumes and mass in mind. Design and test durations, on the order of years, allowed the thermal models to be detailed with emphasis on trade studies and parametric analyses. Integration between the bus and payload takes time to iterate and develop. These integrated models optimize the interfaces, heater power, and hardware placement.

13.3 Small satellite thermal design challenges

The process for thermal design on small SC follows the lead and philosophies of larger satellites as described in the previous section. The path to success has been paved by the history of thermal design and testing on a larger scale, with key portions of the process specifically applied to smaller satellites. As described in the SC Thermal Control Handbook by Gilmore, the thermal design process begins with understanding the SC's thermal environment. Thermal designs often begin by gathering internal power dissipation information and environmental heat loading. The development of simple models for concept development has been an essential part of the process.

Low earth orbit is still a prime destination for CubeSats, but the boundaries of exploration are reaching farther and farther beyond Low Earth Orbit (LEO). They include highly elliptical orbits that are employed for magnetospheric science projects, Lunar Gateway, Lunar, Mars, solar cruiser, deep space, and more. In addition to drastically different orbits, thermal environments on CubeSat missions are only becoming more challenging due to an increase in performance potential. Highly maneuvering SC with high-duty cycles on reaction wheels, push the capabilities of buses to dissipate heat. Payloads with high-powered transmitters, lasers, and high-power instruments are becoming more common, as are SC with multiple payloads and numerous functions.

Consideration can be given to widening the range of acceptable temperature limits for small satellites. The wider the temperature range can be, the more flexibility the SC has in terms of mission operations and the range of orbits it can withstand. The easiest way to reduce heater power is to reduce the radiator area, and the easiest way to reduce the radiator area is to allow components to get hotter or reduce their duty cycle. With the higher risk posture of small satellites comes the question of how hot we can reliably get with the electronics. When electronics and Li-ion batteries are kept cooler, the lifetime of the SC is longer, which is commonly required for larger SC, but not necessarily for smaller ones. Conservative temperature limits that are implemented in order to maximize operating lifetime can often be traded against true maximum operating temperature for smaller, shorter missions.

When comparing the flexibility of thermal designs on larger satellites to that of CubeSats and small satellites, the challenges are significant. Programmatically, both space and time are compressed for smallsat programs: heat-dissipating components are placed inside a much smaller area, and the project timelines are reduced from years down to months. A primary technical challenge is the former: power density accommodation. Smaller SC, while scaled down in size, are not equally scaled down in power dissipation. Since the primary heat transfer in vacuum is conduction within the SC and radiation from the SC out to space, component location and radiator area is paramount. The radiator size is drastically reduced on a smallsat, and the SC struggles to dissipate heat loads adequately. Radiators, designed to reject heat, can put further demands on the limited power system during eclipse. This issue is self-reinforcing when using conventional passive designs, as component and radiator area locations are critical and because radiator sizes are significantly reduced. Effective heat dissipation to space becomes more challenging for these small SC [1].

13.4 Advancements in thermal design processes for small satellites

Not only is an expansion of technology occurring for thermal hardware, but the thermal design process, including methods, margins, software, and testing, are expanding as well. Focusing on optimizing passive thermal designs by following basic thermal practices is a key to conserving power, volume, and cost. Once these methods have been exhausted, more complex active control thermal systems are applied. It is common that small satellites are procured with the intent to keep costs as low as possible, which prevents many projects from utilizing complex thermal hardware.

As satellites have been reduced in size and compressed into smaller and smaller volumes over the years, so too have the schedules for the completion of each phase of the SC design process. For thermal, this is a challenge to complete adequate bounding of the thermal environments and concept of operations during the design phase. What was traditionally done over the course of years is now compressed into a matter of months. Trade studies, parametric analyses, and detailed models need to be streamlined without missing any critical inputs.

As an example, the 6U CubeSat mission, TEMPEST-D (Temporal Experiment for Storms and Tropical Systems—Demonstration), successfully produced the first CubeSat with global atmospheric data. This 3-year mission was a NASA Earth Venture Technology mission by JPL, Colorado State University, and Blue Canyon Technologies (Fig. 13.2). The success of this mission spearheaded the use of small satellites to obtain critical Earth Science [2]. The thermal challenge of TEMPEST-D was maintaining sensitive science hardware within a tight thermal control range, while maintaining both an aperture for an articulating mirror as well as bus components within a small volume.

The bulk of thermal analysis and design was completed in three months by creating a simplified thermal model and widely bounding environmental inputs for hot and cold cases. Critical components were more heavily nodalized to produce accurate temperature gradients and interfaces when necessary. The design started with passive control, and was able to maintain a tight temperature dead band within an isothermal system by pulling the science components into a separate thermal zone. The sensitive items were thermally isolated to decouple temperature fluctuations from radio transmission power dissipation and were heated with a patch heater to compensate for environmental temperature changes during eclipse (Fig. 13.3). External coatings were applied to optimize the heat radiated from the CubeSat or absorbed from the environment.

The flight data for the TEMPEST-D payload showed excellent thermal stability during the cold case of $\pm 0.5°C$ while under positive heater control with the SC at a 5 degrees beta angle and a 36-minute eclipse (Figs. 13.4 and 13.5).

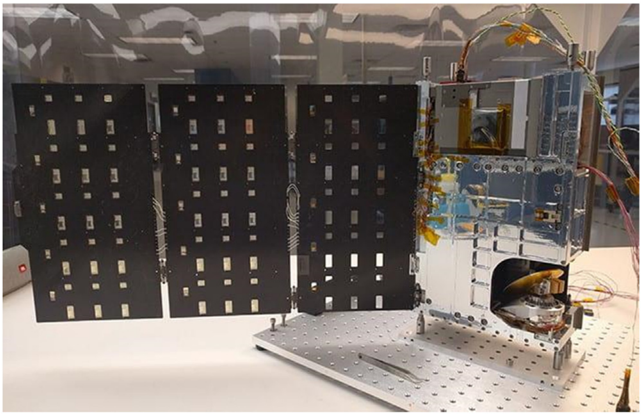

Figure 13.2 Temporal experiment for storms and tropical systems−demonstration 6U CubeSat.
Source: Blue Canyon Technologies.

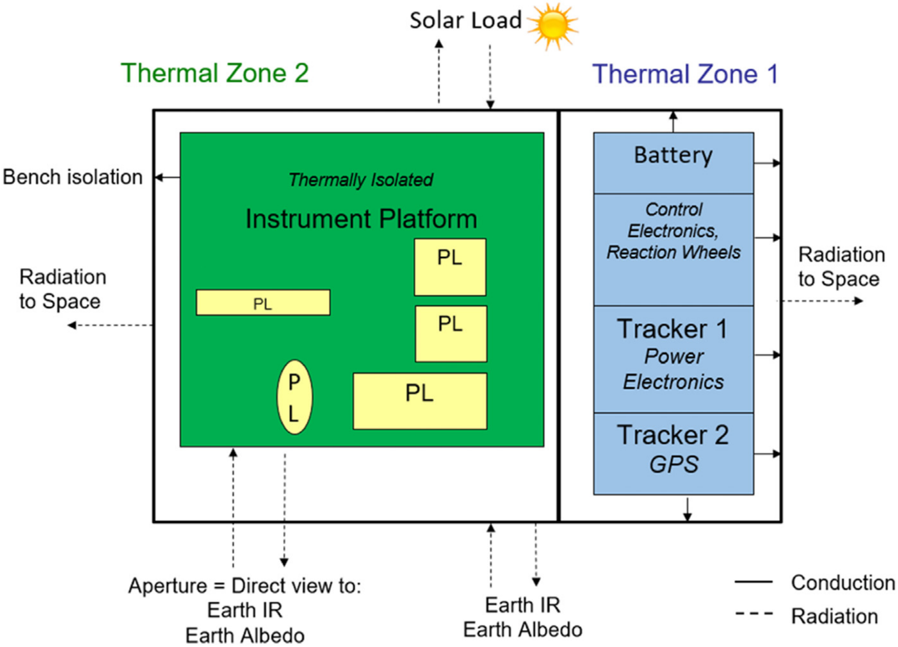

Figure 13.3 Temporal experiment for storms and tropical systems−demonstration Thermal Zones Heat Map.
Source: Blue Canyon Technologies.

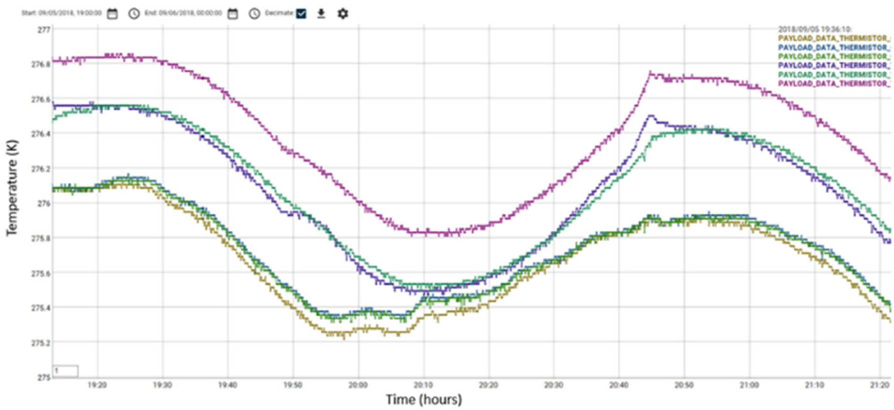

Figure 13.4 Temperature telemetry showing tight thermal control of the science payload. *Source*: Blue Canyon Technologies.

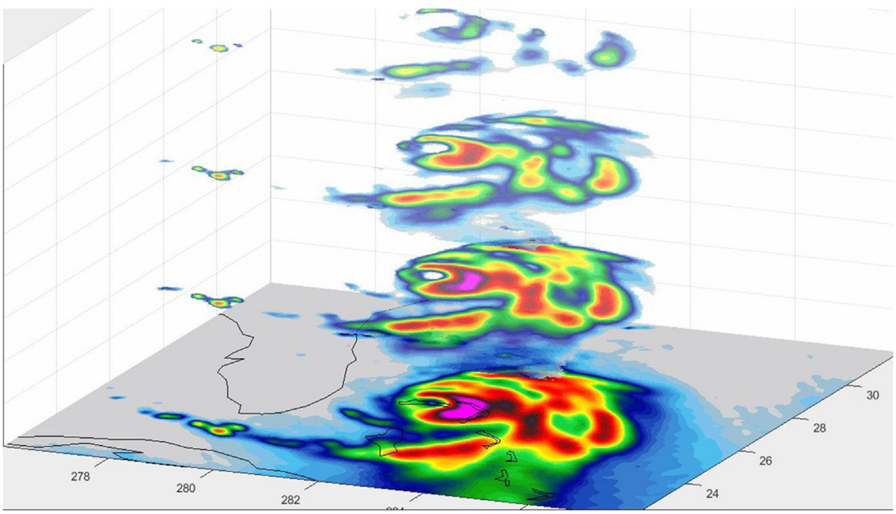

Figure 13.5 Hurricane Dorian as seen by temporal experiment for storms and tropical systems−demonstration on 9/03/2019 at 2 am EDT. High-intensity rain is shown in yellow, red, and pink while low-intensity rain is shown in green.
Source: NASA/JPL-Caltech/NRL-MRY. The full animation can be viewed here: https://photojournal.jpl.nasa.gov/archive/PIA23431.gif.

13.5 Advancements in thermal software

Utilizing significantly faster thermal model processing software is directly beneficial to small satellite thermal analyses where thermal design time is limited. A baseline thermal model is created to represent the SC, components, instrument, and orbit. Since mechanical, electrical, and systems engineering decisions need to be made quickly, reduced order modeling (ROM) allows the thermal engineering trade studies to keep pace with rapidly changing power, layouts, radiator sizes, and SC operations.

Thermal modeling software that uses both geometric math modeling (GMM) tools and transient environmental inputs are essential to the success of the thermal control subsystem design. Unlike standalone GMM tools, which calculate resultant temperatures at one environmental input, SC-specific GMM software has the capability to calculate environmental heat loading such as solar flux, Earth IR, and Earth albedo at various orbital positions. SC orientation can be adjusted throughout the orbit to match the mission configuration of operations.

Missions with tight thermal margins or complex geometry can benefit from meshing surfaces into highly discretized entities (e.g., nodes). However, increasing the node count and complexity of the thermal model can increase run times exponentially. When fast trade studies or quick results are required, geometries can be simplified, and analyses can be bounded with a smaller set of cases. The downside to this method is the resulting SC may be overdesigned and unoptimized.

Instead of trading accuracy and time management, as we do with conventional modeling tools, ROM 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, 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 (Fig. 13.6).

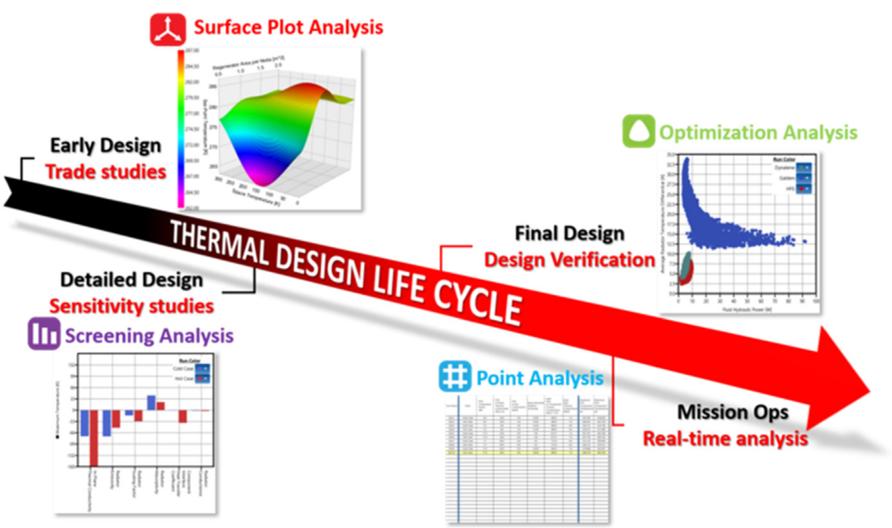

Figure 13.6 Reduced order modeling within the thermal design life cycle.
Source: Veritrek.

Table 13.1 Time taken to obtain thermal analysis results.

Model	Analysis effort	Method	Time to complete runs, postprocess data, and obtain meaningful results
NASA JPL Mars Helicopter Thermal Desktop model	Sensitivity study to understand how best to control heater survival energy	Traditional Veritrek	~4 months 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 Veritrek	Multiple days 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 Veritrek	Multiple hours <1 h
ATA Engineering 6U CubeSat Thermal Desktop Model	Design optimization of body-mounted radiator sizes	Traditional Veritrek	1 month 5 days

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 [3]. Veritrek is the leading thermal-specific ROM software that has been in use by NASA JPL on the Mars Helicopter thermal design to improve the run time of analysis 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 13.1 shows examples from the industry of time saved using ROM software.

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 the maximum allowable temperature of electronics inside the satellite bus that were initially exceeded in worst-case hot conditions. In addition, optimizing based on the maximum allowable heater energy available to keep the electronics warm in worst-case cold conditions was conducted.
2. Correlating a 6U CubeSat Thermal Desktop model to thermal test data obtained in the 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.

13.6 Advancements in thermal hardware for CubeSats and SmallSats

The drive for advancing thermal technologies for small satellites is ramping up within the industry. Small business innovative research (SBIR) contracts allow emerging companies to develop their technologies, and small satellites with a higher risk posture can validate their designs and hardware much more easily than before. CubeSats were once primarily for university projects with very small budgets. This trend has shifted with several enabling technologies, including star tracker-based three-axis control attitude control systems for very accurate pointing, deployable solar arrays for power generation, high data-rate radios and antenna, and advancements in thermal control. Cubesats offer substantial benefits by providing a low-cost platform, which, because of its low cost, enable multiple Cubesats to carry out a specific mission. Multiple Cubesats work together, to provide rapid re-visit time and global coverage, which is typically unaffordable with traditional large satellites. With the realization that real science can now be achieved with a smaller package. With thermal as a critical factor for the performance of smaller satellites, thermal technologies are advancing. Passive thermal control technology, requiring no power to actuate, is the first line of design focus and will be described below, followed by active thermal control. Passive and simplistic thermal design options are recommended before shifting to more complex, expensive, or long-lead thermal hardware. Passive methods have less failure modes. Once the simplified, passive thermal design of the system has been optimized to gain the most efficient heat transfer, active or complex thermal hardware can then be applied to meet the remaining requirements. Starting at the internal SC level with components on electronics and working out to radiators, the following are concepts, developments, and the latest solutions related to thermal control.

13.7 Electronics board level thermal control

Limiting the maximum predicted temperature of electronic components is important for parts reliability. As an electronic component junction temperature increases, the lifetime of the part decreases creating the potential for part failure in a vacuum.

The primary heat path within an electronic component is different in vacuum vs. air. Component specification sheets from manufacturers contain a Theta j-c value, which is the thermal resistance between the junction and case of the part, and which is substantially larger than Theta j-a, since air is not present in space. Junction temperature limits are derated to provide margin and reduce the risk of overheating. Fig. 13.7 illustrates the junction where power is generated, which flows via conduction to the component case, through the leads and then to the board. Theta c-pwb is the resistance between the case and the printed wiring board (pwb). If conduction is increased at the source of the power production to the case, or to the board, or within the board, electronics would be able to run at higher power without overheating (Fig. 13.8).

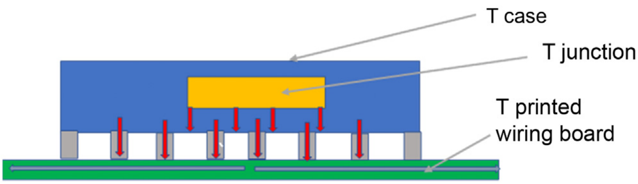

Figure 13.7 Heat flow from within an electronics component in a vacuum is dominated by conduction.
Source: Blue Canyon Technologies.

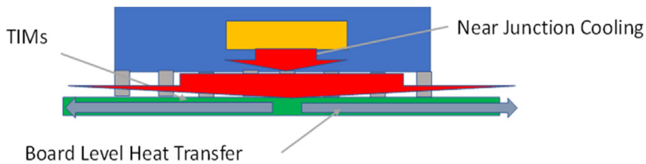

Figure 13.8 Heat flow is greatly increased when conduction is increased through near junction cooling, thermal interface materials, and board-level conduction.
Source: Blue Canyon Technologies.

13.7.1 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 3−10 times depending on the high thermal conductivity medium added.

13.7.2 Printed circuit board embedded heat pipes

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

Miniaturized heat pipes on the order of 1.5−2 mm embedded in four different types of PCBs 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 the copper structure on the PCB, whether by copper-filled slots or by vias, was a determining factor in the performance of the embedded heat pipe system [4].

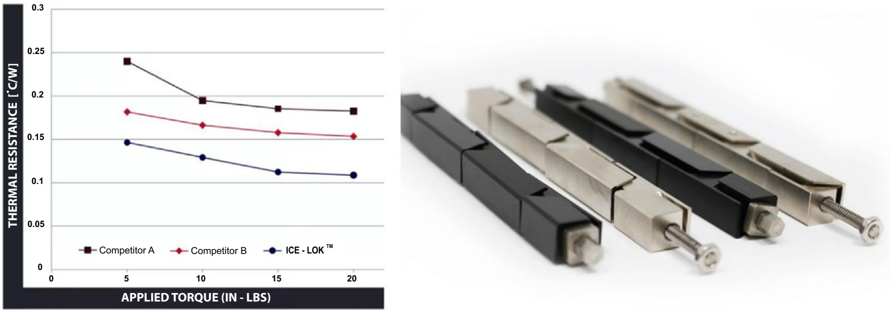

Figure 13.9 ICELock Performance and Photo.
Source: Advanced Cooling Technologies.

13.7.3 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 the chassis. Increasing the area by utilizing a larger segmented wedge lock can improve this contact, and ACT has created ICElock with a larger footprint, increasing conductance by 30% (Fig. 13.9).

13.8 Thermal interface materials

SC, operating in a vacuum environment, suffer from high resistance to heat flow across bolted interfaces. In terrestrial applications, a small air film helps conduct heat across a thin joint. But, in SC, this thin joint is actually a vacuum gap, which resists heat flow. So little heat transfers across bolted joints, that the common analysis technique is to assume that heat only conducts at each specific bolt location. But, by using thermal interface materials (TIMs), the bolted interface is much less of a bottleneck to heat flow.

TIMs are common products used to increase the heat transfer between a heat-dissipating component and its mounting interface. These can be reworkable or permanent depending on the material used. Some of the original interfaces include thermal compounds, also referred to as a grease, which are silicones or hydrocarbons with varying fillers to increase the thermal conduction. While applicable to small satellites, they may be avoided due to their difficulty in application, maintaining a discreet thickness, and because silicone propagation can occur in small spaces, which can interfere with contamination-sensitive payloads. Gap pads, thermal interface tapes, and epoxies with thermally conductive fillers are trending more as alternatives for small satellites, with graphene options emerging as a very effective and reworkable heat transport gap filling method.

While graphene and carbon nanotube (CNT)−embedded films have been developing, the ability to apply the technology in a durable way for thermal aerospace

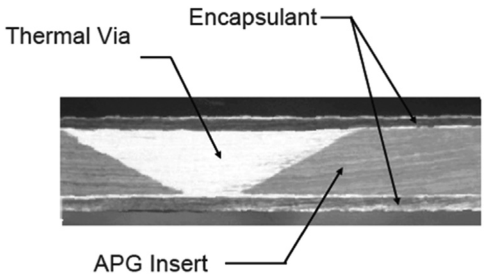

Figure 13.10 Encapsulated annealed pyrolytic graphite within a radiator.
Source: Advanced Cooling Technologies.

applications has challenges. The material is often fragile and can cause debris if not encapsulated. Graphene-embedded sheets can transfer heat very well in the axial but not within the plane direction. For TIMs, the goal is to increase the higher through-plane conduction. Carbice (Technical Readiness Level TRL 9[1]) is gaining traction as an effective aerospace TIM based on CNT-embedded films in various forms for specific heat transfer applications under electronics components and small interfaces that require high heat dissipation. The heat transfer due to the structure of the graphene into CNTs creates a higher thermal conductivity in the desired direction to fill micro-gaps between mounting surfaces.

Future applications of graphene and CNTs are being investigated at the integrated chip (IC) level within electronics packaging. The thermal conductance between the junction and the case of the IC can be increased. As electronics advance, so does the power dissipation, creating a heat mitigation challenge that can be addressed with new graphene and CNT technology.

13.9 Annealed pyrolytic graphite cores

Graphene and CNT-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 CNTs, both the axial and in-plane conduction is enhanced.

Annealed pyrolytic graphite (APG) has an in-plane thermal conductivity that is extremely high at 1700 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 SC but can be cost and schedule prohibitive. Encapsulated Conduction Cooling by ACTs, and K-Core by Boyd Corp. are both products with TRL 9 on the market today (Fig. 13.10).

[1] In development as of this writing.

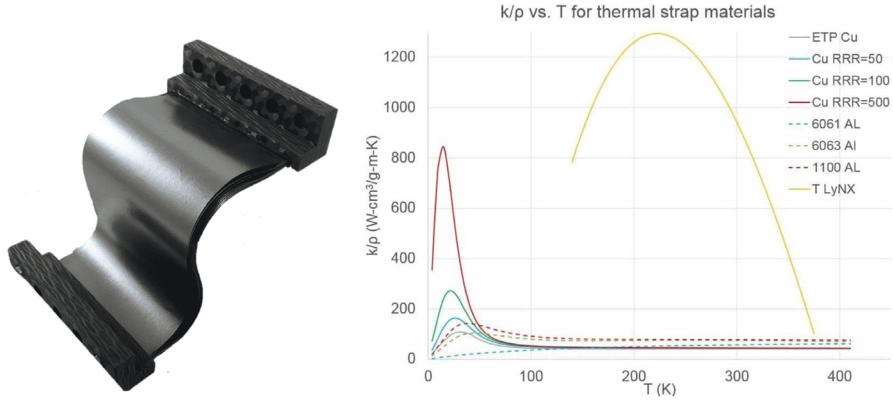

Figure 13.11 Thermal-LyNX high thermal conductivity heat strap.
Source: ThermalSpace.

13.10 Thermal straps

Following the innovative use of graphite for TIMs, 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 compared to copper or aluminum straps. For the same conductance, fewer layers can be used, minimizing volume, which is desirable for space-constricted satellites.

While graphite within heat straps is not uncommon, the structure of the graphene within a composite is. 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 of pyrolytic graphene sheet or graphene composite sheets (Fig. 13.11).

13.11 Thermally isolating interfaces

In many instances where payloads within small SC need to be held to tight temperature ranges, exhibit low gradients, or maintain low temperatures, thermal isolation is required. Within smaller spaces, there is less room to create physical gaps between surfaces. Washers and shims made of thermally isolating materials can be placed between joints, with thermal control coatings inside to reduce radiative coupling. When mounting payloads to small buses, mechanically designed thermal flexures, struts, or posts made of titanium can greatly reduce the heat transfer between the interfaces. This allows payloads and buses to run independently and reduce temperature effects on each other when required. Aerogels, around 1950, began being used in larger SC applications, including the space shuttle, the Mars Rover Sojourner, and interplanetary propulsion in 1990. Today, aerogels are more stable, smaller, and lighter. Aerogel blankets (Aspen Aerogel Inc) and aerogel beads (Cabot Corporation) are products that could potentially be used for small satellite applications.

13.12 Heaters

Heaters are essential thermal hardware on any SC to maintain minimum temperatures of internal components, especially batteries. While it is possible to design a CubeSat or SmallSat with completely passive thermal control, the internal components must be able to withstand a wider temperature range if the beta angle is low and the SC is subjected to operating in eclipse. The available heater power for smaller satellites needs to be conserved, so efficient heater placement is the first design aspect to focus on. Localized heating of the critical components that need heat the most help will save on total heater power. Kapton patch heaters, commonly used on large SC, are still the primary type of heater for small satellites because they are thin, lightweight, customizable, cost-effective, and have a high TRL.

Heaters have multiple methods of control. Thermostats are easy to implement but often large. As the size is reduced on a thermostat, the on/off temperature range due to the switch increases. This, in turn, requires a higher heater power to maintain a wider heater set point range. Very small satellite buses utilizing software-controlled heaters can narrow the temperature range drastically and save heater power.

13.13 Thermal control surface coatings

While internal heat transfer within small satellites is dominated by conduction, heat transfer to and from space is by radiation. Thermal control surfaces are specifically chosen for their absorptive and emissive optical properties. Absorptivity is the percent of energy absorbed in the solar wavelengths (240 nm to 2.5 μm) and emissivity is the energy emitted in IR (2.5−50 μm) as compared to a blackbody. External radiator coatings include MLI blankets, tapes, paints, flexible Optical Solar Reflectors (OSRs), and traditional rigid OSRs, with developments into meta-OSRs and aerogels. Internally, radiation heat transfer does occur in the IR wavelengths, and surfaces can be coupled or decoupled with either high or low emissivity (e) coatings (tapes, paints, films).

The most useful radiator coatings for SmallSats are tapes. Flexible OSRs are lightweight, easy to apply, and cost effective when bought in larger quantities. One of the primary hurdles for CubeSats when building in smaller numbers is obtaining aerospace radiator tapes in small quantities. MLI blankets are somewhat avoided on

Figure 13.12 Photo of Dunmore's SatKit for SmallSats.
Source: Dunmore.

CubeSats due to deployer interference, but small satellites with larger envelops can benefit from MLI. The Dunmore SatKit blanket materials is a small kit at a lower cost, avoiding minimum purchase quantities (Fig. 13.12).

13.13.1 Radiator coating application

Small satellite radiator coatings often use flexible OSRs and other optical tapes to control the absorptivity and emissivity of the surface. Silver Teflon tape is the most widely used radiator tape in industry, developed and first flown by NASA Goddard Space Flight Center since 1969. It is very stable in the space environment, especially against UV degradation. They are easy to apply, lightweight, 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.

13.13.2 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 occurs when the coating temperature reaches +67°C. 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 more at higher temperatures and less at colder ones, thus conserving heater power [5].

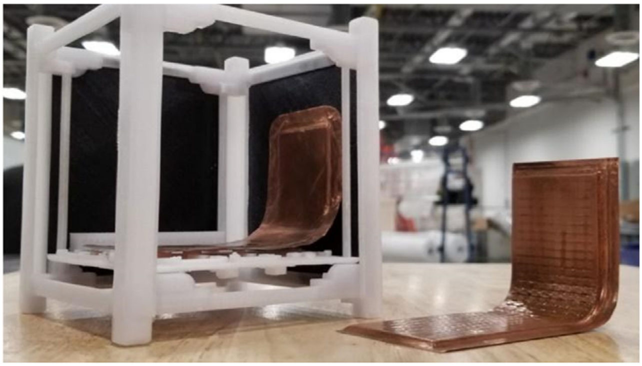

Figure 13.13 Flat heat pipe in a 3U form factor.
Source: RedWire.

13.14 Heat pipes

Pulsating heat pipes (PHPs), also called oscillating heat pipes (OHPs) are two-phase cooling devices that act like an active system but operate 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 occurs in a traditional condenser/evaporator heat pipe. They can be made very small, and used as heat spreaders, heat sinks, or heat straps [6]. PHPs from ACTs or OHPs from Thermavant are quickly becoming viable thermal control solutions.

Advancements in thermal hardware also include flat heat pipes, which are essentially a combination of a heat strap and a heat pipe. "FlexCore" from RedWire, 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. Other flat heat pipes, like those by Advanced Thermal Solutions, are similar to round heat pipes but with a lower profile, which are also beneficial for low-volume SC (Fig. 13.13).

13.15 Cryocoolers and thermoelectric coolers

13.15.1 Mini cryocoolers

Payloads that require cryogenic temperatures to operate need more heat rejection than radiators alone can typically provide. Cryocoolers are in use and reliable on traditionally sized SC, but are on the order of 4 kg, which is too large, heavy, and high powered for most CubeSats.

Miniature cryocoolers have been developed by Creare, Sunpower, Inc., Riccor-USA, Inc., Thales & NASA JPL, Northrop Grumman, and Lockheed Martin [7] for use in small satellites. The TRL is 6, which is anticipated to improve in the near future.

13.16 Thermal storage

13.16.1 Phase change materials

Thermal storage devices are an important consideration for high-power smallsats because they offer the ability to manage transient heat loads more effectively, especially for Low Earth orbits and low-duty cycle components [8].

Thermal energy storage devices such as phase change materials (PCMs) can be used to reduce the size of a radiator by storing thermal energy (heat) with minimal temperature rise during the solid-to-liquid phase transition. During this phase transition, the latent heat (J/kg) is at least one to two orders of magnitude higher than the sensible energy that can be stored by the specific heat of a material in its solid or liquid phase. Fig. 13.14 illustrates this phenomenon by plotting the temperature rise of a PCM over time with steady-state energy input.

This has direct application to a majority of SmallSat missions and components, including 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 [9] and Redwire have both created PCM panels that are of the CubeSat form factor, allowing them to be easily stacked in between critical

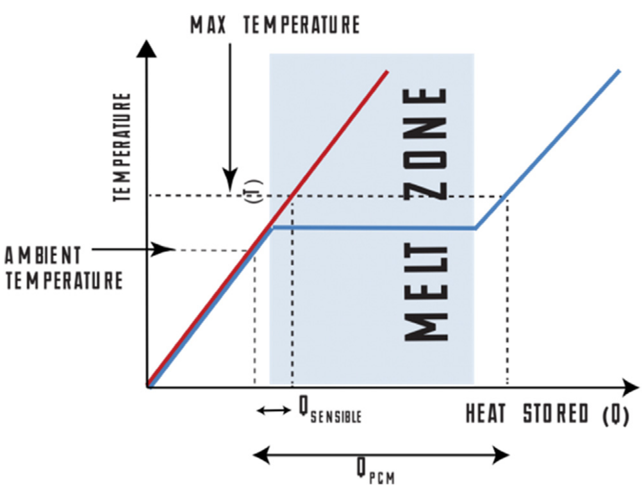

Figure 13.14 Phase change material temperature rise versus time. Temperature is maintained during phase transition.
Source: Courtesy Advanced Cooling Technologies.

components [10]. Redwire's Q-Store is an approach at TRL 5/6 for thermal storage that also includes thermal spreading features (Fig. 13.15). It is a tailorable approach that can handle a broad range of transition temperatures and storage requirements. One challenge is mass and volume, which increases as the thermal capacitance increases (Fig. 13.16).

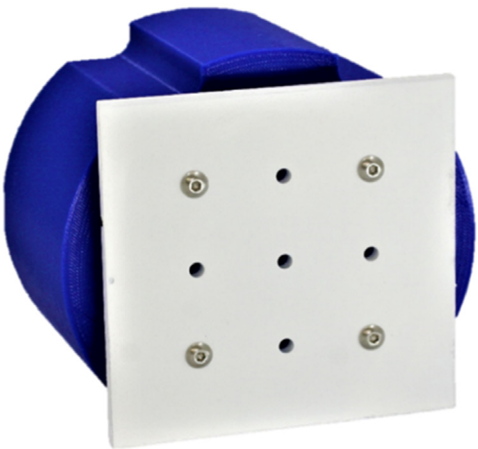

Figure 13.15 Illustration of Q-Store.
Source: LoadPath.

Figure 13.16 Phase change material cross-section.
Source: Advanced Cooling Technologies.

13.17 Deployable radiators and shades

The limited surface area on the outside of CubeSats bounds the amount of heat that the SC can reject. Being able to increase this area, especially when external surfaces are already covered in solar cells, can greatly benefit these satellites. Extending a surface to block incoming environmental heat is also a way to utilize deployable. Deployable surfaces require power for active control, a mechanism to extend a stowed surface, and available volume to stow it. The effectiveness of extending the radiator area, as well as how well it will perform, depends on the thermal conductance through the hinge line of the deployable, where there is typically a lot of thermal resistance. LoadPath (Redwire), Thermotive, and Thermal Management Technologies have created versions of deployable radiators now in development.

13.17.1 Deployable radiators

One of the most significant challenges facing higher-power SmallSat thermal designs is effectively maximizing radiator efficacy. Although we could take advantage of the $q \sim T^4$ relationship (where q = dissipated heat and T = rejection temperature) in order to make smaller radiators more efficient, rejecting enough heat at elevated temperatures is often not possible.

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 Fig. 13.15, for radiator areas from 0 to 2 m^2 [10].

Fig. 13.17 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 approximately 90 W, assuming that every external surface is acting as a body-mounted radiator, and that the SC must operate at close to room temperature. 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, one way deployable effectiveness can be assessed is 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 this must be traded against adding additional mass. In addition, deployable radiator effectiveness depends on the thermal conductance through the hinge line (where there is a lot of thermal resistance) [11].

Redwire, Thermotive, D-Cubed, and Thermal Management Technologies have created versions of deployable radiators and are in various stages of development. Redwire's Q-Rad (20) 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 (Fig. 13.18).

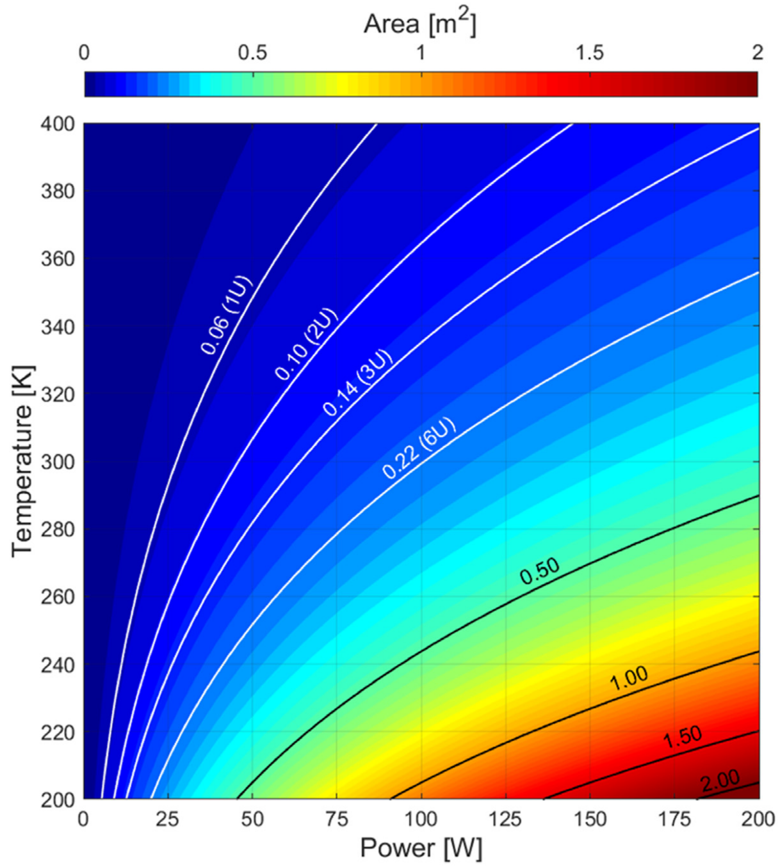

Figure 13.17 Ideal radiator areas (0–2 m^2) with $\varepsilon = 0.9$ as a function of power and temperature.
Source: LoadPath.

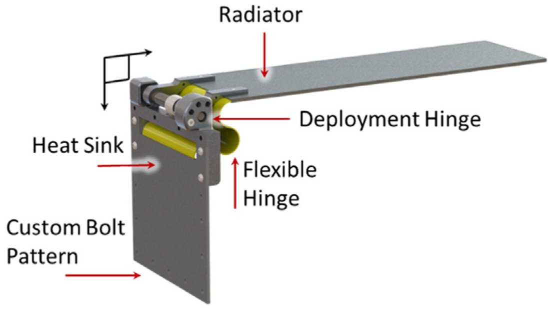

Figure 13.18 Deployable radiator illustration.
Source: LoadPath.

13.18 Louver systems

Louvers have been used for many years, starting with early satellites. They are robust, effective, and conserve heater power within the SC. They also reduce the need for complex detailed analytical models since the open-to-closed blade configurations reflect a 600% range in heat rejection capability. In many cases, they reduce or eliminate the need for thermal balance testing. While the technology and application are sound, they are considered newer technology for small satellites, as the size is reduced [12]. The mass and volume make them less desirable on smaller CubeSats but are still a viable option as demonstrated by Dellinger in 2017. Developed by industry for early NASA Observation Missions, they are now being produced by Sierra Nevada Corp.

13.19 Future of CubeSat and SmallSat thermal subsystems

Small satellites have become transformational for the scientific, commercial, and defense industries, and the need for optimizing thermal control has placed thermal design and hardware advancements at the forefront of engineering design. Thermal challenges due to higher power densities and transient dissipations with limited radiator area are driving the call for new thermal control technologies at all levels of thermal interfaces. From heat rejection at the source of internal components, through the pathway within the SC, and out to the radiators, small optimizations can have great results. New technologies will allow small satellite missions to reach goals previously unobtainable. Advanced thermal concepts for small satellites will continue to develop in terms of TRL inherently, because, by nature, small satellites are faster to build, cheaper to produce, and less risk-averse. New products will be widely available as demand is driven. With increased use, these technologies will become more available, cost-effective, and allow for even greater small satellite capabilities.

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