20 Technology Projections

T. T. Lam,* T. D. Swanson,† G. C. Birur,‡ B. E. Hardt,*
J. G. Santiago,** and T. P. O'Donnell‡

Introduction

As the number of space vehicles increases, and those vehicles operate with greater power over longer life spans, their thermal management becomes ever more critical. Accompanying this trend is an unprecedented need for spacecraft size and weight reduction, and recurring launch costs are strongly tied to this need. However, reduced weight leads to higher power densities, and waste-heat dissipation densities have grown by orders of magnitude as smaller, more powerful electronics are continually flown, thanks to technology advances in semiconductor devices. In recent years, spacecraft power dissipation has increased relative to the weight of the thermal control subsystem as well as the spacecraft.

Thermal design problems that deal with these issues must be solved quickly, and, more important, the solutions must provide highly producible, cost-effective products required for all spacecraft and instruments. These trends drive development of advanced thermal control devices, materials, and techniques.[20.1] Accordingly, thermal control technologies must evolve over time.

The development effort is not, however, without its challenges. For example, one difficulty often encountered is the development of effective performance metrics for new thermal control technology. Many new thermal control technologies do not simply replace existing ones, but rather offer entirely new options for the design of the rest of the spacecraft and/or instrument. The ability of two-phase technology to separate a heat source from its eventual sink is a classical example of this capability. Hence, while the new thermal control hardware may actually be heavier or more expensive than the hardware associated with a conventional design, it may also allow mass/cost savings or performance upgrades in other subsystems. Such benefits are often indiscernible to nonspecialists, and thus the opportunity to employ new technology may be missed.

Garnering support for the development and use of new thermal control technology is often difficult. Part of this challenge is the classic "catch-22" problem: mission architecture and design are based on the projected capabilities of new technologies, but the development of technologies with broad, system-wide impacts (such as some thermal control technologies) is directly impacted by the definition of such mission architecture. Hence a trend has arisen to develop more-generic technologies that can be broadly applied to a variety of related mission concepts. This situation reflects the way technology innovations develop in other areas. Although often "necessity is the mother of invention," in actuality a great many

*The Aerospace Corporation, El Segundo, California.
†NASA Goddard Space Flight Center, Greenbelt, Maryland.
‡Jet Propulsion Laboratory, Pasadena, California.
**Stanford University, Palo Alto, California.

significant inventions either result from nondirected curiosity or find their greatest applicability in a purpose entirely different from that for which they were developed. While the steam engine, cotton gin, and atomic bomb resulted from directed-development efforts, the phonograph, gasoline engine, airplane, and transistor were initially inventions in search of a popular application. The same development patterns are found among thermal control innovations; hence the difficulty in anticipating both future performance capabilities and applications.

Technology Drivers

Clearly, the purpose of many new missions is to achieve new science or observational capabilities, and this goal inevitably requires more sensitive measurements, greater pointing accuracy, the ability to operate in more challenging environments, and other capabilities. To achieve these advanced capabilities the demands on the engineering subsystems will naturally increase. Conventional thermal control technologies, such as heaters, multilayer insulation (MLI), heat pipes, louvers, and specialized radiator coatings, are even now inadequate for many spacecraft. For example, numerous recently launched spacecraft (e.g., TERRA, Mars Pathfinder, high-power comsats) and others in the development stage (e.g., ICESAT, SWIFT, Mars Exploration Rover) use "new" technology, such as two-phase heat-transport devices and long-life mechanical pumps, simply to meet mission requirements. However, even these recent technology innovations will clearly be inadequate for future missions currently being envisioned. The future top-level system-level design drivers that will influence the development of thermal control subsystems include:[20.1]

- spacecraft functions and missions
- mission operational plan and specific requirements
- spacecraft orientation and orbital constraints
- spacecraft weight and size envelope (volume) constraints
- launch vehicle
- bus and payload configuration, equipment locations, deployments
- propulsion needs
- power and on-time percentage
- equipment operating-temperature ranges, power dissipations, power densities, and duty cycle
- requirement for temperature stability down to a few milliKelvin
- materials
- cryogenic cooling capacity
- integration and test
- manufacturability and cost

Thermal control subsystems must improve as spacecraft and instruments become increasingly sophisticated. The thermal subsystem is more and more intimately tied to other parts of the spacecraft, and it affects, and is affected by, other subsystems. These interrelationships greatly complicate the thermal design effort. Some of the current and emerging technical requirements pushing the development of new thermal control technology include:

- stringent temperature control (±1°C or less, as opposed to the much larger range, perhaps ±20°C, of earlier equipment)
- optics and instruments operating at increasingly deep cryogenic temperatures (40 K down to 4 K)
- components, such as lasers and microprocessors, with very high flux requirements (> 100 W/cm^2), possibly also coupled with tight temperature control
- small allowable temperature gradients over very large areas, included in designs to maintain dimensional stability for large mirrors, optical benches, antennas, or similar devices
- extremely challenging thermal environments (e.g., environments near the sun, planetary surfaces)
- minimal spacecraft resources (e.g., heater power, control circuitry, mass and volume allowances) with which to accomplish tight thermal control
- increasing interdependency of spacecraft/instrument subsystems that restrict use of conventional approaches to thermal design
- miniaturization of spacecraft, which may preclude the use of conventional devices because of space or resource issues
- fleets consisting of large numbers of spacecraft that must be designed nearly identically for cost reasons but that will be exposed to a wide variety of thermal environments
- radiator field-of-view constraints on complex spacecraft

Programmatic Concerns

In addition to the system and technical drivers discussed above, a variety of programmatic issues also impact the development of new technologies. These include: the shortening of spacecraft/mission development cycles, which compresses the technology-development effort; funding difficulties; perceived risk involving the introduction of new technology (e.g., performance, cost, schedule); the increasing use of "standardized spacecraft buses" that may not be ideally suited for scientific spacecraft; and the recurring push to minimize ground verification testing.

Future Technologies and Innovations

Despite programmatic and technical difficulties, to meet these new requirements and thus enable and enhance future missions, development of advanced thermal control technology is important. Accordingly, selected technology development efforts are currently underway. Many other technology thrusts are possible, but given the technical challenges and programmatic limitations addressed above, only some efforts are being pursued. What follows is a noninclusive discussion of such efforts.

Composite Materials

Composite packaging and structural materials have been used in the development of a variety of spacecraft components, including electronics packages, microwave components, heat sinks, chassis, and spacecraft structures.[20.2] Schmidt and

Zweben[20.3] and Zweben[20.4] discuss the large number of possible composite materials that can be achieved via combining various reinforcement materials (e.g., carbon/graphite fibers) with a large variety of matrix materials. Composites reduce weight and are excellent paths for the removal of excess heat from electronic devices. Kibler and Davis[20.5] identified possible applications for carbon-carbon (C-C) composites in spacecraft designs. They also predicted the possible range of properties for C-C composites and estimated the payoffs of using these composites over alternatives (typically aluminum). The four components considered to be appropriate candidate applications were

- thermal doublers
- electronic circuit-board heat sinks
- advanced battery components
- nonstructural radiators

The use of C-C composites in these applications should result in components with thermal conductivities greater than twice that of pure aluminum with a 20 to 40% decrease in weight. Glatz *et al.*[20.6] presented a succinct survey of possible electronic-component applications for advanced composites. Components and applications were divided into the following categories: power-generation devices, power-storage devices, electronic devices, heat-rejection devices, power signal/transmission devices, and structures. Glatz *et al.*[20.6] listed typical designs, suggested candidate materials, and discussed potential performance improvements.

Figure 20.1 shows the thermal conductivity of various carbon composite materials and conventional metals. K1100 fibers have been developed specifically for thermal management applications. This carbon fiber has a thermal conductivity three times that of copper (1100 W/m·K) and a density one-fourth that of copper,

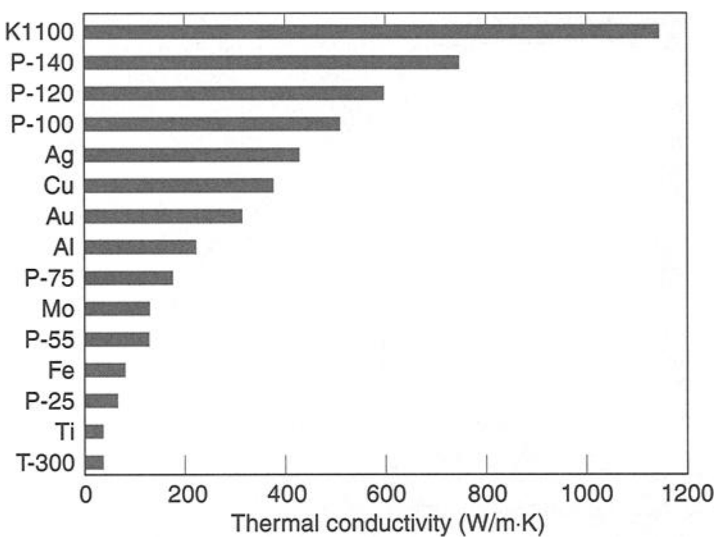

Fig. 20.1. Thermal conductivity of carbon composites.

and it is available commercially. This fiber has been successfully incorporated into organic and metal (e.g., copper, aluminum) matrices. Prototype substrate/heat sinks for electrical components on printed wiring assemblies and radiator panels have been successfully created utilizing these materials.

The carbon-composite conductivity values in Fig. 20.2 are for one-dimensional fibers only. Note that the theoretical value for a carbon fiber is 2400 W/m·K. The effective conductivity depends greatly on fiber orientation and processing techniques (carbon filled, epoxies, and metal matrix). It is very important to note that practical limitations prevent the achievement of such dramatic theoretical conductivity values. For example, while the carbon of a carbon fiber/resinous composite material may have conductivities on the order of 2400 W/m·K, the resin and/or other fill material can reduce such values by half or more. Additionally, such composite structures typically have high conductivity in one or at most two dimensions. In the other dimension they often function as thermal insulators. This can have a big impact on effective thermal conductance across joints.

Material properties desirable for satellite applications include tailorable and/or low coefficient of thermal expansion (CTE), extremely high thermal conductivity, high stiffness and strength, and low density. Other desirables include low cost and resistance to severe environments. As examples of recent advancements, Schmidt and Zweben[20.3] cited materials such as an experimental vapor-grown carbon fiber with a conductivity five times that of copper. A commercially available pitch-base carbon fiber combines a conductivity 50% greater than that of copper with an elastic modulus 12 times that of aluminum. In addition, materials with a CTE as low as 1.7×10^{-6} K^{-1} have been achieved.

Zweben[20.4] presented an excellent discussion of key trends in packaging and structure technology accompanied by a summary of material properties and applications.

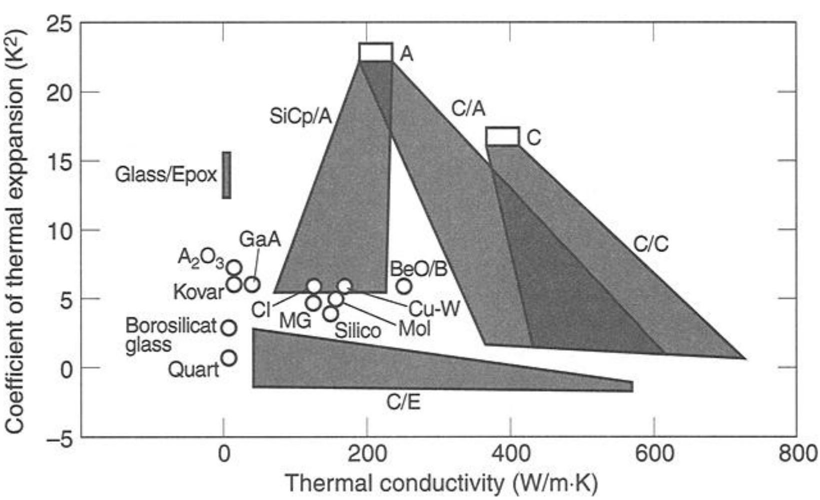

Fig. 20.2. Thermal conductivity and coefficient of thermal expansion.

The applications discussed include electronic and microwave packages, heat sinks for printed circuit boards (PCBs), and electronic enclosures. Furthermore, Zweben[20.4] discussed new and developing fabrication techniques such as pressure infiltration, pressureless infiltration, and investment casting. Also discussed were solder and brazer material technologies that would improve strength and creep resistance, and reduce CTE. Zweben[20.4] cited the potential of technologies such as diamond particles and fibers made using chemical-vapor deposition, two technologies that possess highly desirable properties but are, however, too costly to be practical.

C-C materials have been the subject of research and development efforts at the Air Force Phillips Laboratory, NASA, Amoco, Lockheed Martin, TRW, and the Naval Surface Warfare Center. The use of carbon as both the fiber and matrix material offers the advantage of much higher thermal conductivity through the thickness of the panel as well as the potential for high-temperature applications. Drawbacks, however, include much higher cost and a limited satellite-level manufacturing experience base compared to that of graphite-reinforced polymers.

As part of the C-C Spacecraft Radiator Partnership (CSRP), which consists of members from government and industry, a C-C radiator/structural panel (Fig. 20.3) was flown on EO-1 by NASA/GSFC (Goddard Space Flight Center) in November 2000, and the technology was successfully validated.[20.7,20.8] C-C radiator panels can reduce spacecraft weight and can be used as part of the spacecraft structure. The disadvantage of the C-C radiator is that it is easy to damage and is not very practical unless one is really pushing weight margins. Further development must take place on the C-C process to generate ways to reduce fabrication time and cost.

Aluminum matrix composites and C-C composites based on vapor-grown carbon fiber (VGCF) have been fabricated. Because of the highly graphitic nature of VGCF, the resulting composites exhibit high overall thermal conductivity. The new materials are useful for thermal management applications such as the packaging of high-power and high-density electronic devices. Figure 20.4 shows the thermal conductivity of VGCF in a carbon matrix (VGCF/C) composite as a function of temperature. A thermal conductivity of 1200 W/m·K at 160 K has been measured for VGCF/C composites (Applied Sciences, Inc.). NASA/Goddard has

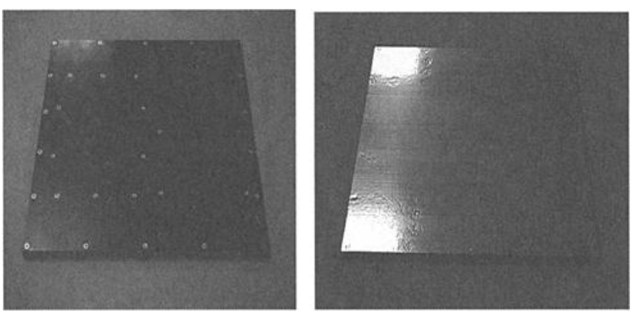

Fig. 20.3. EO-1 C-C radiator.

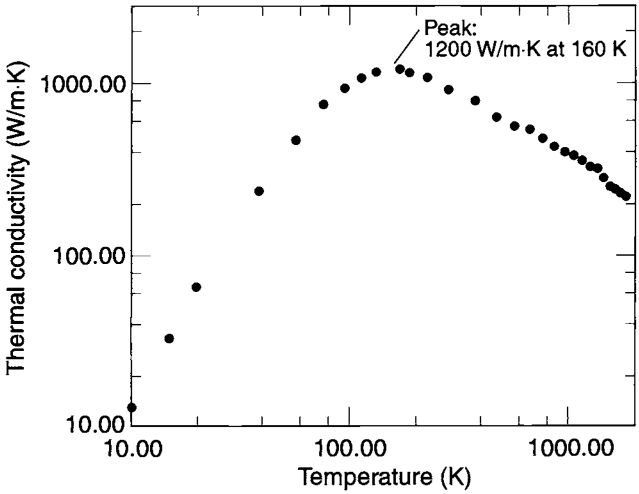

Fig. 20.4. Vapor-grown carbon-fiber/carbon-matrix composite thermal conductivity.

obtained similar test data that indicated the materials are suitable for midlevel cryo-type applications but not as good as Cu and others at very deep cryo.

Current Applications

Talley[20.9] presented a discussion of practical composite applications currently under development at Lockheed Martin Astro Space. Structures that combine highly thermally conductive carbon/cyanate-ester facesheets with more traditional aluminum components to provide low weight and high overall conductivity were presented. These structures use unidirectional and quasi-isotropic laminates, sandwich panels, and epoxy adhesives to provide thermal management and high strength. Solar panels in development that use carbon/cyanate-ester facesheets, film adhesives, and Kapton to provide lightweight construction were also discussed. Other applications presented included structural joints, transitional joints, and radiators.

Lockheed Martin[20.10] presented a forecast of its technological advancements over the next 10 years. In the area of high-conductivity composites, the following applications were cited: battery sleeves, thermal doublers, electronics substrates, thermostructures, and high-temperature applications (including aerobrakes and solar shields). Swales[20.11] presented a listing of advanced material applications that, for instance, use Kevlar-Epoxy and Graphite-Epoxy in the construction of solar panels, structural brackets, structural composite panels, tubes, and struts.

Most of the materials discussed in their presentation, such as pitch-based and pan carbon fibers, Aramid, and thermoplastic resins, are commercially available. Montesano and Cassin[20.12] presented a patented material that can be used in heat-sink applications; it consists of graphite blocks encapsulated in aluminum. The material offers high thermal conductivity (more than four times that of pure aluminum) and low mass density (slightly lower than that of pure aluminum), and it has been used successfully in specialized aircraft avionics. This "macrocomposite" can be manufactured using different encapsulates such as copper and aluminum/beryllium alloy.

Material Property Measurements and Basic Research

In the last few years, significant research involving the basic study and measurement of the properties of composite materials has been conducted. Riley[20.13] discussed the properties of ThermalGraph (a C-C composite manufactured by Amoco), which has a conductivity 3.4 times that of pure aluminum and approximately 80% of its density. Ting and Corrigan[20.14] presented an investigation of the conductivity, density, strength, and CTE of vapor-grown carbon fibers.

Carbon fibers under study include Amoco's K1100, P-100, and P-120 and Nippon's XN-70A (see Crasto and Anderson,[20.15] Shih,[20.16] and Krumweide[20.17]). Crasto and Anderson[20.15] used X-ray diffraction and electron microscopy to examine the microstructure of high-modulus carbon fibers. They found that processing these fibers with lower degrees of graphitization produces fibers with better compressive strengths but with lower axial thermal conductivity (and higher electrical resistivity). Crasto and Anderson[20.15] cited this trade-off between compressive strength and thermal conductivity as an important consideration in the selection of a fiber for a thermal structure application. Users of these advanced carbon fibers have noted that obtaining quality fibers from American suppliers can be difficult and that raising the quality level of domestic fibers to that of Japanese competitors' fibers should be given some priority.

Silverman and Kagohara[20.18] presented the advantages of fabricating radiator-panel facesheets and doublers for use under electronics boxes made of K1100 C-C composite materials in lieu of the conventional aluminum. About 16% weight reduction was shown through the replacement of aluminum heat-pipe radiators with C-C radiators without heat pipes in one particular design. Note that the classic CTE mismatch issue needs to be resolved prior to use in real engineering applications. In addition, the authors suggested that up to 50% weight reduction can be achieved by the replacement of traditional aluminum facesheets and doublers with C-C, in some cases. More recently, Shih[20.16] presented properties of several carbon fibers that are good candidates for thermal doubler and radiator facesheet applications. Shih[20.16] discussed combining high-stiffness fiber composites with compliant adhesives in the construction of PCBs and avionic thermal plane attachments. Such materials would reduce both vibration amplitude and vibration-induced strain. Finally, Krumweide[20.17] presented an investigation of the properties and possible applications of Amoco's K1100X fiber. This investigation discussed K1100X's use in cardguides and cardcages, radiators, conductors, spacecraft bus structures, electronic packaging, and heat sinks.

Future Development Effort for Composite Materials

Composite materials have seen widespread use in structural applications. Loral is currently building GEO (geosynchronous orbit) comsats whose structures are almost entirely composite (the north and south radiator panels of these satellites hold most of the electronics and are not manufactured using composites). The principal impediment to use of composite radiators is the difficulty of attaching heat pipes to the composites because of widely different CTEs of the materials. To date, bonds that are sufficiently compliant to accommodate the resulting relative displacements have had high thermal resistances. The higher resistance drives the use of panel facesheets that are much thicker and thereby eliminates the weight savings offered by the composite.

A second problem is the relatively poor thermal conductivity through the thickness of most composites. While the specific conductivity in the plane of a composite panel may be five times higher than that of aluminum, the conductivity through the thickness may be 300 times lower. For thin panels, the small conduction distance from the surface to the center of the material ensures a low temperature gradient. However, as the thickness increases, the resistance will become substantial, as in the case of thermal doublers.

Additional research efforts should be devoted to the development of technologies for joining low thermal resistance composites and heat pipes, as well as to the improvement of the through-thickness conductivity of composite panels. A possible solution to the joining problem may be development of space-qualified composite heat pipes. The emerging technologies of composite electronics boxes and circuit-card thermal planes present an opportunity for substantial weight savings through the use of stiff, high-conductivity, low-density materials.

Furthermore, materials need to be developed and demonstrated at low and high temperatures. This requirement is important because of the recent development of SiC electronics that can operate at high temperatures. The new materials can be used to decrease the temperature gradients between electronic parts.

Composite material that uses carbon for both the fiber and the matrix material has high thermal conductivity and good strength, and it is lighter than aluminum. It can be used in high-temperature applications (e.g., aircraft brakes, space-shuttle wing leading edges) but has been used with limited application elsewhere to date, primarily because of cost and production lead time. In an era when "faster, better, cheaper" is still a key focus for most space-related projects, the manufacturing process needs further development to obtain ways to reduce the fabrication time and cost.

Diamond Films

CVD (chemical vapor deposition) diamond films offer the potential for up to 3 to 4 times the conductivity of copper. Recent testing using a sample measuring $3 \times 0.5 \times 0.022$ inches has indicated values of 11 W/cm·K at room temperature. Additionally, other forms of advanced composite carbon devices (e.g., annealed pyrolytic graphite) have demonstrated (two-dimensional) conductivities of up to 13 W/cm·K at room temperature. In both cases the conductivity was very dependent on measurement technique (interface resistance, vacuum vs. air, temperature, etc.).

Ultrahigh-conductivity materials such as CVD diamond are also very promising for spreader-type applications where a large area needs to be cooled. Most typically these ultrahigh-conductivity materials could be used as films to collect energy and then could be connected to a more efficient heat-transport mechanism, such as a two-phase device, for transport over long distances.

CVD diamond is a unique substance, which can be used as a heat spreader. It is the hardest known material, with excellent mechanical strength; it is an excellent electrical isolator, and it may be used as a semiconductor. It also has the lowest coefficient of friction and the highest thermal conductivity of any material, which is approximately 4 times that of copper, and it has diffusivity about 20 times that of copper. CVD diamond has a wide range of potential space applications. This material has been selected as a candidate for application as diode heat spreader.

Thermal Control Coatings

Thermal control coatings are used on a space vehicle for various purposes. Solar reflectors, such as second-surface mirrors and white paints or silver- or aluminum-backed Teflon, minimize absorbed solar energy, yet they emit energy as a blackbody does. To minimize both the absorbed solar energy and infrared (IR) emission, polished metal such as aluminum foil or gold plating is used. On the interior of the vehicle, black paint is commonly used to exchange energy with the compartment and/or other equipment. Thus, today's space systems use a wide variety of wavelength-dependent coatings. In-space stability, outgassing, and mechanical adhesion to the substrate are common problems space systems encounter. Because many coatings have been fully qualified, development and qualification of a new coating for a new design has not typically been necessary until very recently. Now, new EPA requirements requiring the elimination of CFCs, electrostatic discharge (ESD) concerns for spacecraft in certain orbits, and other drivers have led to the need for new advanced coatings.

Factors that affect thermal control finishes are charged particles, atomic oxygen (AO), ultraviolet (UV) radiation, high vacuum, and contamination films that deposit on almost all spacecraft surfaces. The general result of these drivers is typically an increase in solar absorptivity with little effect on IR emittance. The degradation of these surfaces is undesirable from a thermal control standpoint because spacecraft radiators must be sized to account for the increase in absorbed solar radiation that occurs as a result of degradation over the mission. These radiators, which are oversized to handle the high solar loads at end-of-life (EOL), cause the spacecraft to operate much cooler in the early years of the mission, frequently necessitating the use of heaters to avoid undertemperature electronic components. The stability of the coating properties is therefore important to minimize radiator size, heater power, and weight.

Future thermal control requirements for space systems are projected to continue to become more demanding: tighter temperature control, higher power dissipation, smaller size and lighter weight, ability to endure longer missions, and more cost-effective designs. Projections suggest that advanced solar reflective coatings and variable-property coatings could provide significant benefits for future space systems. These benefits would lead directly to smaller radiators, lower heater-power requirements, and lighter systems.

One of the most common and critical spacecraft coatings is the solar reflective coating. These coatings are used on external surfaces to minimize absorbed solar radiation while maximizing the amount of energy emitted in the IR wavelengths. A number of these coatings are used in industry. Standard coatings include: OSR quartz mirrors, Silver Teflon FOSR, A276 Organic White Paint, and Z93 Inorganic White Paint.

A number of parameters drive selection of these materials, including protections against AO and ESD, UV/VUV (vacuum ultraviolet) radiation, protons, electrons, manufacturing, cost, and environmental impacts. Primary consideration is given to solar absorptance and IR emittance. Solar absorptivity can significantly degrade in the space environments.

Silvered Quartz Mirrors

Silvered quartz mirrors are a very common type of optical solar reflector (OSR) with a long history in spacecraft thermal control. These OSRs are typically constructed by vapor-depositing a highly reflective metal, typically silver, on the underside of a piece of quartz. The thickness of the quartz (typically 5 to 10 mils) provides a high IR emittance while being transparent in the solar wavelengths. The major advantages are the high α/ε ratios and the stability. However, the mirrors are inherently rigid, brittle materials and are usually manufactured in units approximately 1 square inch in area. The small size necessitates time-consuming "tiling" of large radiator areas. The rigidity and brittleness of the quartz make it difficult to apply these mirrors to anything but nearly flat surfaces. A thin conductive coating is typically needed to meet the ESD requirements for today's space systems. This coating, typically indium tin oxide (ITO), is also a very brittle material. ITO is also very difficult to handle on the ground; it can be rubbed off very easily. Antimony tin oxide (ATO) and indium oxide (IO) are more-durable alternatives under development. Lastly, these mirrors are relatively heavy in comparison to white paints and flexible OSR (FOSR) materials.

OSRs continue to be used in spacecraft when the thermal design requires very high α/ε ratios and stability at the expense of weight, application, and handleability. However, recent advances in micro OSRs are replacing these materials.

Microsheets

Advances in the last few years have led to thinner OSR materials called microsheets. Although the sheet thickness of these materials has been reduced, their optical properties have been maintained. For instance, a 2-mil CMX mirror has approximately the same properties as an 8-mil quartz mirror. In addition, micro OSRs can be manufactured in larger areas than quartz mirrors, 4×4 inches rather than 1×1. The thin OSRs of yesteryear used to break very easily. Getting them to stick was also an issue.

Advanced Spray-On Thin Films

OSR materials offer excellent optical properties and stability in the space environment. However, drawbacks exist in terms of application, weight, brittleness, handleability, ESD protections, etc. Wright Patterson Laboratories is currently funding an SBIR (Small Business Innovative Research) Phase I program to investigate the potential of a novel spray-on OSR process. The concept is to first spray (in air) a silver undercoat directly on the desired surface to provide the solar reflective substrate. Then the high IR emittance and solar-transparent silica coating is sprayed onto the silver. The process is environmentally friendly. Small samples with thin silica layers ($\approx$ 0.5 mils) have been produced as a proof of concept in the SBIR Phase I. The stability of these samples with respect to the space environment remains to be tested. Phase II will investigate the ability to produce films of acceptable thickness to achieve the acceptable optical properties.

Silvered Teflon FOSR

The most common type of FOSR is silvered Teflon. This material provides excellent beginning-of-life (BOL) properties with good application, cleanability, handleability, flexibility, etc. However, certain disadvantages accompany its use. First, it is known to degrade with high levels of electron and proton exposure. Second, Teflon acts as an excellent capacitor for storing electrostatic and bulk charge buildup, which can lead to catastrophic ESDs. At least one lead contractor in industry has internally prohibited using silvered Teflon on any system other than those traveling in low Earth orbit (LEO). The ESD problem has been addressed by using a conductive ITO coating. However, this coating is brittle and susceptible to cracking. Hence handling and cleaning concerns often are very time-consuming and costly. Much of the LEO problem with silver Teflon was found to be in how it was applied. Use of a transfer adhesive and vacuum bag is best and can give an EOL α of ~0.1.

Advanced Metalized Polymer-Based Film

Trident Systems and NASA Langley have been developing clear, oxygen-resistant polymer-based films. The films have been developed and tested for AO erosion. However, the susceptibilities of these films to electrons, protons, and UV/VUV radiation are of concern, based on experience with the parent material, Kapton.

Tedlar Film

Dupont has developed a film called Tedlar. Similar to Teflon, it comes in a number of colors. An oversimplified description of the product is that a Teflon-type clear binder is loaded with various pigments to obtain the desired color. Depending on the pigment loading and thickness of the film, the absorptivity and transmissivity of the film can vary significantly. These films have been shown to be susceptible to UV/VUV degradation. Electrostatic charging could also be of concern, depending on the conductivity of the pigment.

Advanced Coatings

A number of thin-film coatings are available that can be utilized in conjunction with the thin-film products to meet various requirements. OCLI has developed and qualified a proprietary AO/UV/VUV protective coating for white Tedlar films. This coating was developed and qualified for the NASA/Goddard Tropical Rainforest Measurement Mission (TRMM), which was launched in 1997. The coating provides very good AO resistance and good protection of the Tedlar from the UV/VUV degradation. However, this film does not provide a conductive path for protection against ESD events.

At least two coatings are used in industry to protect against ESDs: ITO and Germanium (Ge). Thin ITO films are relatively transparent in both the IR and solar wavelengths. Their application typically increases the solar absorptance by ~0.04 with little effect on the IR emittance. However, ITO can easily be removed from a surface through normal handling. IO and ATO do not appear to have this issue. Germanium, on the other hand, significantly changes both the solar absorptance and IR emittance of the material.

Organic White Coatings—Paints

When describing white paint used in industry, the term "organic" refers to the binder of the paint. In general, these paints tend to degrade very significantly with UV/VUV, electron, and proton exposure resulting from the darkening of the binder. They are also susceptible to charge build-up and AO erosion. The advantages of these coatings are the ease of application, durability, flexibility, and cost. In general, the degradation of the α/ε ratio and the ESD concerns hamper the widespread use of these paints, especially for systems with long mission requirements. Some work is being conducted to produce conductive organic paints to alleviate the ESD concerns. However, the basic degradation of the binder will continue to hinder the use of this paint for future systems. For LEO applications, ongoing research is taking place to utilize AO erosion of the binder material to "scrub" the surface clean and leave the pigment on the outer exposed surface, leading to a low α property.

Inorganic White Coatings—Paints

These inorganic binder paints, also used in industry, are more stable to the space environments than the organic binders. However, they tend to be hard to apply, nonflexible, and not very durable, and they require careful handling. Use of these paints has been very limited because of such issues. Some contractors have "unofficially" banned the use of inorganic paints. As with the organic binder paints, ESD issues remain unresolved.

Advanced Plasma Spray Coatings

A plasma spray process for depositing a ceramic coating on high-conductivity substrates is being funded by Wright Patterson. The advantages are: ease of application; good adhesion properties with C-C, aluminum, and polycyanate composites; possibly a tenth of the cost of traditional inorganic paints; and good AO resistance properties. The disadvantages and remaining concerns are: the ability of different substrates to withstand high-temperature application; the stability of the coating under UV/VUV and electron environments; and the ability to bleed off electrostatic charge build-up. The near-term goal is to optimize the process and identify the pigment powder size that would maximize the optical properties. Environmental testing will also be conducted to address the stability of the coating in the space environments.

Advanced Paints/Coatings

Limited funding is available for developing advanced white paints. The requalification of a number of white paints is being funded to meet new EPA (Environmental Protection Agency) requirements. ITTRI (ITT Research Institute) and Aztek have been able to reformulate a number of the paints to meet the EPA requirements while maintaining equivalent optical properties of the parent paints.

Concepts currently being explored on how to produce conductive paints include doping the paint with conductive pigments, encapsulating conductive pigments, and using conductive binders. All the approaches produce concerns involving the stability of the paint in space environments. The NASA SEE (Space Environments and Effects) Program is currently funding efforts to investigate this area.

The inorganic paints are more attractive than organic paints because of their better stability when exposed to UV/VUV radiation. However, adhesion, flaking, and handling concerns have significantly limited their use. A project has been funded to develop an inorganic white paint and a reliable process for coating any type of material. The preliminary samples have produced flexible inorganic white paints possessing good BOL properties ($\alpha < 0.15$, $\varepsilon > 0.85$). The process utilizes an intermediate conversion coating between the paint and the substrate. This conversion coating can be made conductive in an effort to reduce the ESD concerns. However, ESD concerns still exist with the paint itself.

Similarly, an effort has been funded to develop low-solar-absorptance coatings. Preliminary samples had measured BOL properties of $\alpha \approx 0.04$ and $\varepsilon \approx 0.90$. These types of coatings could offer a tremendous advantage to future space systems. However, ESD continues to be a major concern.

NASA/GSFC has been working with Aztek to develop Aztek White Low Alpha (AZW LA-II) paint (BOL: $\alpha = 0.07$ with $\varepsilon = 0.91$ for a 10-to-13-mil-thick coating). This paint is proving to be very difficult to apply in such thickness in a uniform manner, especially for nonflat surfaces. However, its properties are so good that NASA is compromising and going to an ~8 mil thickness, which is providing an α of 0.10. NASA/GSFC is currently applying this paint to the radiators for the BAT (Burst Alert Telescope) and XRT (X-ray telescope) instruments that will fly on the SWIFT mission in 2003.

Variable-Emittance Technologies

Minimizing heater power requirements and thermal control hardware weight in future space systems is highly desirable. The heater power and thermal control hardware weight can vary significantly depending on mission requirements. In the design of today's space systems, approximately 5–7% of the satellite power is typically allocated for heater power and 2–10% of the satellite dry weight is allotted for the weight of the thermal control subsystem.

An emerging technology that could significantly reduce these allocations is variance of the optical properties of the thermal radiator finishes. A number of types of surface treatments might produce variable properties: MEMS (microelectromechanical systems)-based minilouvers, electrochromic (EC) devices, and electrophoretic, electrostatic, and thermochromic devices. EC devices are polymer based and hence employ a "wet" chemistry. All previous attempts have demonstrated the difficulty of developing such EC devices that survive a vacuum. Ashwin-Ushas has very recently provided some samples that appear to have resolved this issue, but many questions remain. The same can be said of all the other candidate technologies. The electrophoretic concept didn't survive vacuum, and was dropped; a mechanical/electrostatic concept has replaced it. The other two are still in the infancy stage and have been assessed to have a number of significant concerns (contamination and stability, etc.) associated with their applicability to space systems.

Solid-state EC materials provide the capability to vary the optical properties of a surface by the application of a small voltage potential across the material. EC materials can behave thermally as mechanical louvers without complicated moving mechanical assemblies, bimetallic strips, solar trapping, or annoying hysteresis. This material characteristic would lead directly to more economical and reliable space systems. However, these advantages have not been quantified. The information in the following sections is based on an article by Cogan[20.19] presented at The Aerospace Corporation's seventh Thermal Control Technology Workshop.

EC Principles

EC devices operate on the principle that an EC material changes its reflectance in IR wavelengths by the addition or removal of ions or electrons. When a small biased voltage (less than 2 Vdc) is applied, the charged ions are either collected or removed from the EC layer of the device, resulting in a change in the IR reflectance of the device. The EC process is a reversible, solid-state reduction-oxidation (redox) reaction. The prototypical EC materials are transition metal oxides that undergo reversible redox reactions. Two types of optical modulation are obtained depending on whether the EC material is crystalline or amorphous.

Crystalline EC materials develop a broad reflectance band in the IR (2–40 μm) and become increasingly reflective as the concentration of inserted alkali increases. The reflectance is the result of an increase in free-electron density, which causes the crystalline material to undergo a controlled transition between an IR-transparent wide-band gap semiconductor and an IR-reflective metal. In principle, crystalline EC materials exhibit a reflectance edge that moves to shorter wavelengths as the alkali concentration increases, and they are transparent at wavelengths shorter than the reflectance edge. In practice, the reflectance edge is broadened by free-electron scattering, and some absorption is observed at wavelengths shorter than the edge.

An amorphous EC material develops a broad absorption band from 0.4 to 2.0 μm upon alkali insertion. The absorption band is usually centered in the near-IR (≈ 0.8–0.9 μm) and increases in intensity with increasing alkali insertion.

Thin-Film Devices for IR Modulation

An alternative approach is to use thin-film technology. In this approach, a thin film of tungsten oxide is used as the active material with lithium as the ion carrier. The materials offer potential advantages of a large number of switching cycles and increased IR-emittance modulation. A method for producing a low solar absorptance value is uncertain but may be possible using a dielectric mirror.

This technology is a spin-off of the development for terrestrial applications using variable solar-transmissive devices with amorphous tungsten oxide. A large number of cycles has been demonstrated on similar solar-transmissive materials used for terrestrial purposes. Thin-film devices to vary the transmissivity in the solar wavelengths are being actively pursued for terrestrial applications. This technology could provide devices that modulate the solar-absorptance property. The applicability of these devices in space systems would be much more specialized and not of general interest. However, this technology provides a good foundation for developing variable-emittance devices.

Polymer-Laminate Devices for IR Modulation

Dornier has actively been pursuing electrically controlled, low-absorptance, variable-emittance devices for spacecraft. The approach Dornier is taking is to develop a variable-emissivity, low-α, EC device. In this approach, conductive polymers are used as the active materials. However, of concern is the number of switching cycles. The details of this work have not yet been obtained. A potential flight test of these materials aboard ASTRO-STAS has been rumored.

Some basic EC device requirements are:

- minimum high emittance (0.8) and maximum low emittance (0.2)
- time duration to switch states (60-sec goal but 300 acceptable)
- survival and qualification temperatures (–110 to 90°C)
- maximum power consumption (0.14 W·hr/m^2)
- maximum weight per unit area (1 kg/m^2)
- stability in electrons (1 MeV, 2×10^{15} electrons/cm^2) and protons (10 MeV, 1.0 $\times 10^{13}$ protons/cm^2)
- stability to UV radiation
- vacuum compatibility with low outgassing
- minimum number of thermal cycles (10,000)
- minimum number of switching cycles (10,000)
- ESD (must be unsusceptible to damage)

Variable-Emittance-Coating (VEC) Applications

Designs

A VEC design is composed of a variable-emittance coating that comprises a series of vacuum-deposited thin films with an overall thickness of ~1.5 mm. The emittance is modulated by application of a voltage between the electronic contacts. The magnitude and polarity of the applied voltage determine the reflectance of the crystalline EC layer. IR-emittance modulation is obtained by contrasting this reflectance against an emissive (IR-absorptive) substrate. The following schematic is EIC Laboratories' approach for developing a variable IR-emissive thin-film EC device. The variable transmissive device is somewhat similar but uses an amorphous WO_3 (tungsten trioxide) as the active layer.

Devices

In the area of variable-emittance devices and thermal switches, two specific technologies are being investigated. One is based on an inorganic material such as WO_3, and the other is an organic material based on conducting polymer (Chandrasekhar[20.20]). EC devices are being evaluated for their variable-emissivity property for replacing thermal control louvers on future spacecraft. The cost and mass of EC devices are an order of magnitude lower than those of the mechanical louvers currently used on spacecraft.

EC devices based on conducting polymers are currently undergoing tests at JPL and GSFC for their performance and also for their reliability in the space environment for long-term operation. (A sample of such an EC device fabricated by Ashwin-Ushas of New Jersey is shown in Fig. 20.5.) A change in the IR emissivity from 0.39 to 0.74 has been measured on these devices so far. Development and test efforts are currently underway to broaden this change to 0.3 to 0.8. This improvement will give an emissivity range of 0.5, which is similar to what is currently obtained from mechanical louvers. Further, these EC devices weigh less than 400 g/m^2, whereas the louvers weigh 5 kg/m^2.

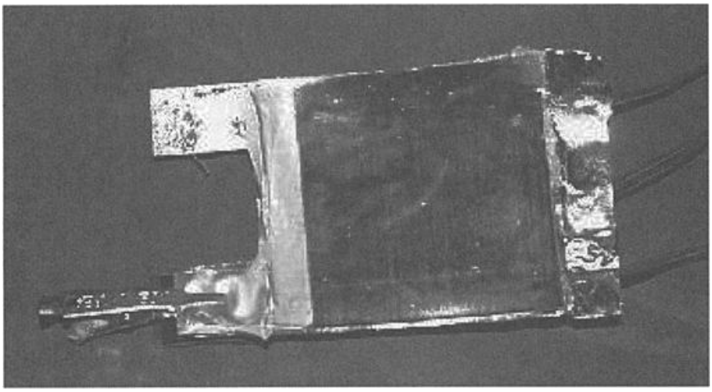

Fig. 20.5. Variable-emittance EC device (Ashwin-Ushas[20.21]).

Surface Treatments

Variable-emittance surface treatments (coatings) have been identified as perhaps the next major technological innovation in thermal control. Analytical system studies have demonstrated power savings of more than 90% and/or weight savings of more than 75% over conventional technologies for representative applications.[20.22] Three of these variable-emittance technologies are slated to be flight demonstrated on the ST-5 spacecraft that is to be launched in 2004. It is anticipated that one or more of these technologies will eventually demonstrate an emittance change of 0.6 to 0.8 and operate reliably in a space environment.

Current variable-emittance surface-treatment concepts under development include the use of MEMS-scale thermal louvers; thin flaps of insulation that can be held close to, or off of, a surface by utilizing an electrostatic effect; and polymer devices utilizing the EC effect. Thermochromic films have also been proposed. These treatments offer the potential to replace traditional techniques (mechanical louvers, variable-conductance heat-pipe arrays, or electrical heaters for make-up heat) that are used to shut down or reduce the effective capability of a radiator for a variety of safe-hold or operational modes. The MEMS microlouvers, electrostatic flaps, and EC polymer devices will be flight demonstrated on NASA Goddard's ST-5 spacecraft, now scheduled for launch in 2004.

The first of these three VEC concepts (microlouvers) has demonstrated, in a laboratory environment, a change in emissivity of approximately 0.3 to 0.4, with the potential of even greater changes. None of these concepts require more than a few tenths of a watt to operate, although they do need controllers. Survival in the space environment (with all of its difficulties, including UV, hard vacuum, wide temperature changes, AO, solar wind, micrometeroids, etc.) is expected to be the major technical challenge for these devices.

MEMS-Scale Thermal Louvers. Microscale mechanical louvers that function very similarly to conventional louvers have recently been developed. Current MEMS-based microlouvers contain shutters that measure 6 μm by 150 μm. A microphotograph is shown in Fig. 20.6.

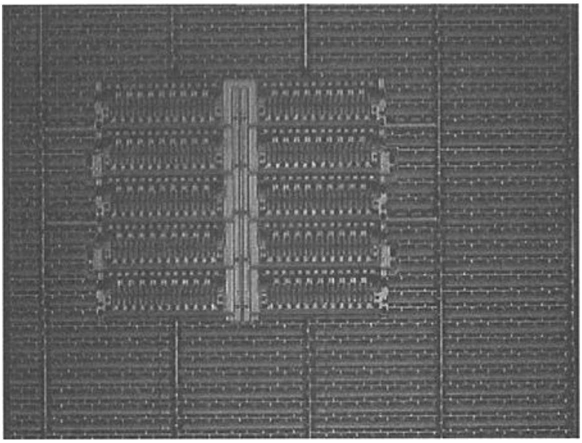

Fig. 20.6. MEMS microlouvers for variable emissivity.

These devices are currently under development and are at a NASA Technology Readiness Level (TRL) of about 5. Prototype devices have been fabricated by the DOE's Sandia National Laboratory for NASA Goddard/Johns Hopkins University Applied Physics Laboratory (JHU APL) and tested in a relevant environment, and they demonstrated an effective emittance change of about 0.4. Improved packaging designs should increase this change. Because these MEMS devices are made from solid silicon chips with a gold coating, they appear to be largely immune from space environmental effects. The major technical concern at this time appears to be contamination and ground handling.

Electrostatic Flap and EC Polymer Device. The electrostatic flap can be scaled to a wide variety of sizes and shapes. It is a very simple device but does require (in its current design) a few hundred volts dc potential to actuate. However, power consumption is negligible. The concept behind this device, currently being developed by Sensortex for GSFC, is illustrated in Fig. 20.7. The conducting polymer concept employs the EC effect that allows reflectance to be tuned over a broad IR wavelength (2 to 40 μm). The device may be considered a composite of several films bonded together. It is very flexible and can be applied over a curved surface.

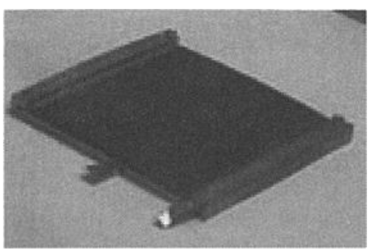

Fig. 20.7. Electrostatic flap.

Single-Phase Heat-Transport Devices

Mechanically Pumped Loop

The mechanically pumped cooling-loop technology that was successfully demonstrated on the Mars Pathfinder is being further developed for longer-life missions (Birur *et al.*,[20.23] Birur and Bhandari[20.24]). The pump used was a centrifugal pump driven by a brushless dc motor. The pump capacity was 0.75 liters per minute (l/min) of Refrigerant 11 with a 27 kPa differential head in the temperature range of –20 to 30°C. The pump consumed about 10 W of power. The pump assembly unit, which weighed about 8 kg, was installed into the cooling loop on the spacecraft. The cooling loop operated continuously for more than seven months on the Mars Pathfinder during its cruise. In a life-test setup, the pump has been successfully tested for a continuous operation of 14,000 hours.

A bearing- and seal-free pump is being developed under a NASA Small Business Innovative Research contract for space applications that require reliable long-life pumps. This pump technology was developed by Advanced Bionics Inc. for artificial heart applications. A prototype of this pump is currently being life-tested at JPL Thermal Technology Laboratory. The pump uses Refrigerant 11 as the working fluid and produces a pressure head of 27 kPa at a flow rate of 0.95 l/min. As of October 31, 2001, the pump had been operating for over 5000 hours without any change in performance.

Electrohydrodyamics (EHD) Devices

EHD devices contain cooling technologies embedded with sensors, electronic chips, or other devices. EHD is an emerging technology for pump single-phase fluids. It can be scaled to small sizes and directly integrated with sensors and other electronic components for spot cooling applications. While the EHD concept was originally demonstrated decades ago, it has only recently been developed to the point where significant pumping heads (in the thousands of Pascals) can be developed. Most recently an EHD system using liquid nitrogen was demonstrated. Although the power needed for pumping is negligible, for conventional-scale applications (e.g., 3-cm-diameter pumps) very high voltages (tens of thousands of volts) are needed. This requirement can be an issue, especially for space applications. However, at micro or MEMS scales the voltage level is reduced dramatically to hundreds or even tens of volts. This technology holds promise for spot electronic cooling, but significant development remains to be done.

MEMS-Based Pumped Cooling Loop

The current interest in micro- and nanospacecraft for future science missions by NASA has necessitated developing MEMS-based thermal control technologies for removing heat from very-high-power-density electronics, lasers, and sensors. The main reason for this is that even with the lower power levels of these spacecraft, the electronics-package power densities have increased because of the shrinking size of the spacecraft. Some of the future micro- and nanospacecraft that are being investigated have dimensions as small as 10 to 15 cm on the side and 5 to 10 cm in height. These systems, called systems-on-a-chip, could have power levels of 20 to 50 W and package avionics, propulsion, and thermal control all as a single unit. The power densities in future microspacecraft are expected to be as high as 25 W/cm^2.

A MEMS-based liquid-pumped cooling system is being investigated at JPL.[20.25] In this technology, a single-phase liquid removes heat from high-density electronics and rejects it at a heat exchanger. The liquid is pumped through microchannels etched in silicon substrate that is attached to the electronics package. The heat removed by the liquid is rejected at another heat exchanger, which is heat-sunk to the spacecraft cooling system. A schematic of this concept along with a picture of the actual microchannel device is shown in Fig. 20.8.

Two-Phase Heat-Transport Devices

Heat Pipes[20.26]

The earliest known description of a heat pipe (the Perkins tube) was published in 1892.[20.27] After the heat pipe was independently reinvented at Los Alamos National Laboratory, intensive development of the device began in the mid-1960s, with experiments continuing into the 1990s. Much of the research was funded by several NASA centers and performed by large aerospace firms.

Research is still being performed in optimization of grooved heat pipes, and in the performance penalties associated with single-sided heat input and removal. While the feedback-controlled heat pipe seems to be the leader in flight applications to spacecraft thermal control, the use of gas-controlled switches and diodes has recently been proposed.

The axial-groove heat pipe is the favored design because of its low cost and uniformity. Designs that can transport more heat over a given distance and withstand a larger adverse tilt are possible with composite or arterial wicks, but the additional capability has not been needed. As the power dissipated by components increases, thermal control systems no longer have the margin that they once did, and limitations (such as the reduction in performance resulting from single-sided input into a grooved pipe) are becoming a factor in design.

The heat-pipe operating-temperature ranges depend strongly on the working fluid. At –32°C, the vapor pressure of ammonia is about one atmosphere. As the saturation temperature decreases below this point, the pressure drop in the flowing vapor can become a significant percentage of the total pressure. A temperature drop exists corresponding to this pressure drop. In addition, any noncondensable gases present at the processing temperature have expanded significantly at this colder temperature, blocking off a noticeable part of the condenser. Above 90°C,

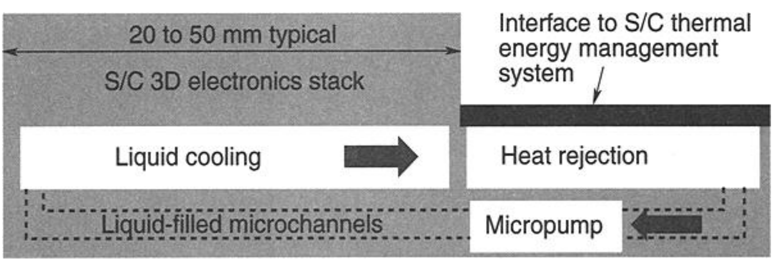

Fig. 20.8. MEMS-based pumped-liquid cooling system for micro/nano sciencecraft.

time-related failures that appear to be metallurgical in nature have been reported, although the ammonia pressure at this point is high.

A cryogenic heat pipe will reach a very high internal pressure if allowed to warm to room temperature. If the pipe walls are designed to be thick enough to withstand this pressure, the pipe is heavy and (if the pipe is to be a diode) conduction along the thick walls becomes significant, even when the pipe is shut off. If an expansion chamber is used to provide additional volume, some means of accommodating the additional volume must be found in the design.

The simplest variable-conductance heat pipe (VCHP) uses the difference in rate of change of pressure with temperature between a saturated vapor (high rate of change) and an ideal gas (low, linear rate of change) to provide temperature control. When a heat pipe that contains noncondensable gas starts up, the gas is swept toward the condenser and collects there. A VCHP has a reservoir to hold the gas at the end of the condenser. A VCHP can also be used as a thermal diode and a thermal switch. The thermal diode transports heat in one direction only, and shuts off if the "condenser" becomes warmer than the "evaporator." A conventional heat pipe would simply reverse—it transports heat as well in "reverse" as it does in the "forward" direction. A thermal switch is a heat path that can be turned on or off in response to an external signal. Because the noncondensable gas drifts in the heat pipe in the direction of vapor flow, if the heat flow is reversed (and if heat is applied to the reservoir as well as the condenser and if the reservoir has liquid in a wick on its wall), the gas will be swept back to the original evaporator, blocking it. However, since the volume of the evaporator is usually much smaller than the volume of the reservoir plus the condenser, a very long gas plug results, causing complete blockage quickly in the shutoff process.

The only heat-pipe envelope materials that have demonstrated long life are metallic. Unfortunately, metallic envelopes tend to have CTEs very different from those of composite structures. Because composite structures are generally cured at temperatures in excess of 90°C, and such structures (particularly radiator panels) can reach very cold temperatures (on the order of –73°C), the thermal stresses developed can crack the structure. One proposal is to allow a very thin metallic wall to flex.

In recent years, other new heat-pipe developments have included "flexible" and "inflatable" heat pipes. Flexible heat pipes generally have such stiff envelopes that they could more properly be considered bendable. Inflatable heat-pipe structures have been built for lunar applications with a single deployment and a small gravity assist in both deployment and operation, but they were not intended for long-term space operations. Some of the walls used were plastic, and flexing of the walls as the internal pressure changes and the generation of noncondensable gas remain potential problems.

The concept of a micro heat pipe was first proposed in 1984 by Cotter[20.28] to improve thermal control for semiconductor devices. A micro heat pipe was defined as one "so small that the mean curvature of the liquid-vapor interface is necessarily comparable in magnitude to the reciprocal of the hydraulic radius of the total blow channel." The sizes of micro heat pipes range from 1 mm in diameter and 60 mm in length to 30 mm in diameter and 10 mm in length. An overview of micro heat-pipe research and development is found in an article by Peterson.[20.29]

Other heat-pipe technology development efforts are still required for future thermal control applications. These include new control schemes, new wick designs, new materials, composite heat pipe, plastic heat pipe, and flat-plate heat pipe.

Loop Heat Pipes (LHPs)

LHPs are two-phase passive heat-transfer devices that use capillary action of a wick structure to pump liquid from a condenser to an evaporator. Unlike fixed-conductance heat pipes, in which the capillary grooves or wick are located along the entire length of the pipe, the LHPs have a main wick located only in the evaporator. The LHP consists of four major elements:

- the evaporator, where the working fluid, changing its phase from liquid to vapor, collects heat
- the condenser, where the vapor condenses and releases heat
- a compensation chamber (CC), where the excess working fluid is stored
- the transfer tubes that carry the vapor from the evaporator to the condenser and carry the condensed liquid back to the evaporator through the CC

LHPs are increasingly being used in Earth-orbiting spacecraft and communication satellites (Maidanik *et al.*,[20.30] Ku[20.31]). They were originally developed in the former Soviet Union and since have flown in several Russian spacecraft. A miniature variable-conductance LHP (VCLHP) is being investigated at JPL for the Mars Rover battery thermal control application. The VCLHP was designed and fabricated by the Dynatherm Corporation of Hunt Valley, Maryland, for JPL in June 1999 (Fig. 20.9). It is currently undergoing tests at JPL (Birur *et al.*[20.32]). The VCLHP has two condensers; one is on the battery and the other is the external radiator. The variable-conductance function for the LHP is provided by a passive thermal valve integrated in the LHP. This valve allows the external radiator to be bypassed when the evaporator temperature drops below a certain level. The VCLHP is designed for heat-transfer applications with power levels of 60 W or below. The battery thermal application being investigated is for power levels less than 10 W.

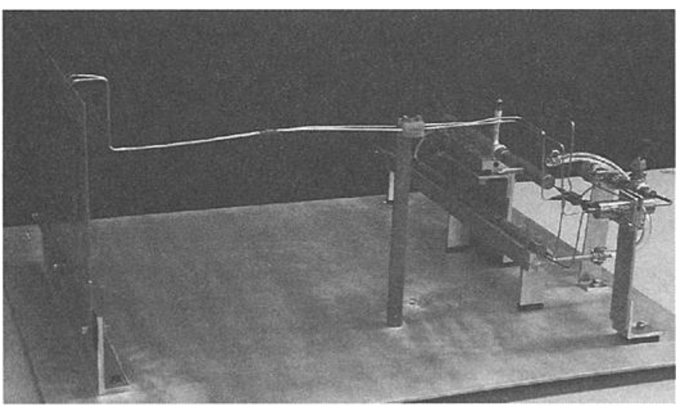

Fig. 20.9. Miniature variable-conductance loop heat pipe.

Capillary Pumped Loops (CPL)

CPLs are two-phase heat-transport devices capable of isothermalizing very large structures. Multi-evaporator CPL systems are now being developed that will allow multiple heat loads to be cooled simultaneously with the potential of heat-load sharing. In the heat-load sharing concept, waste heat from one or more loads is directed toward other loads that need make-up heat to stay warm. Implementation of this concept (which offers the potential of significant energy savings) is possible with multi-evaporator systems. A recent flight experiment, NASA/GSFC's CAPL-3, on STS-108 in December 2001, successfully demonstrated this idea.

Over the course of the flight, CAPL-3 (Fig. 20.10) was able to accomplish all of the minimum required tests, and most of the secondary tests also. The total operating time for CAPL-3 was more than 200 hours, and the longest period for continuous operation was 58 hours. Despite tight energy budgeting, numerous tests were performed, increasing our knowledge and understanding of CPL performance in a space environment. These tests included start-ups, low power operation under various conditions, steady power operation at various power levels, saturation temperature change tests, variable- and fixed-conductance transitions, heat-load sharing demonstrations, variable heat-load tests, single-pump and multiple-pump high-power tests, and pressure priming tests under heat loads. Many of these tests were performed at various operating temperatures and were repeated several times.

Mini-CPLs and -LHPs

Mini-CPLs and -LHPs (Fig. 20.11) are miniaturized thermal control devices suitable for microsats and nanosats. Current technology utilizes ~1.0-inch-diameter evaporators. Miniaturized two-phase heat-transport loops, with 0.5-inch-diameter evaporators and short transport lengths, have been demonstrated in the lab. The goal is to get down to ~0.25-inch diameters.

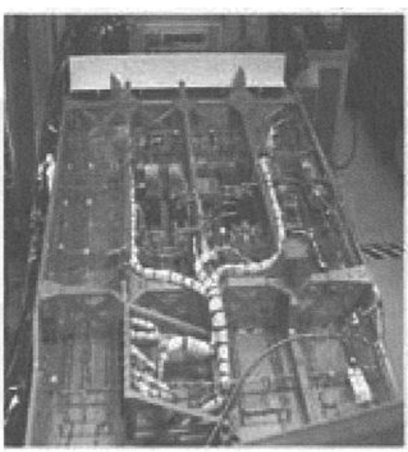

Fig. 20.10. CAPL-3 flight experiment.

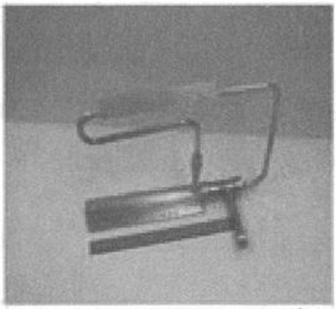

Fig. 20.11. Minicapillary pumped loop/loop heat pipe.

Cryogenic Two-Phase Heat-Transport Devices

Two-phase heat-transport devices capable of operating at deep cryogenic temperatures for sensors, optics, and electronic instruments, such as cryogenic, capillary pumped, two-phase devices (CPLs and LHPs) for heat transport, have been demonstrated both in the laboratory and in space.[20.32] These devices offer a major benefit by providing a greatly improved means of cooling sensors, optics, and electronics at cryogenic temperatures. Use of these devices enables engineers to locate the sensor/optics/electronics remotely from the cooling source (mechanical cryocooler, passive radiator, etc.), thus greatly reducing vibration and EMI and improving packaging design.

A CPL system using nitrogen as a heat-transfer fluid (operating in the 80–100 K range) flew on STS-95 in October 1998 as a flight experiment.[20.33] It successfully demonstrated reliable startup and operation with heat loads of 0.5 to 3.0 W. This CPL is depicted in Fig. 20.12.

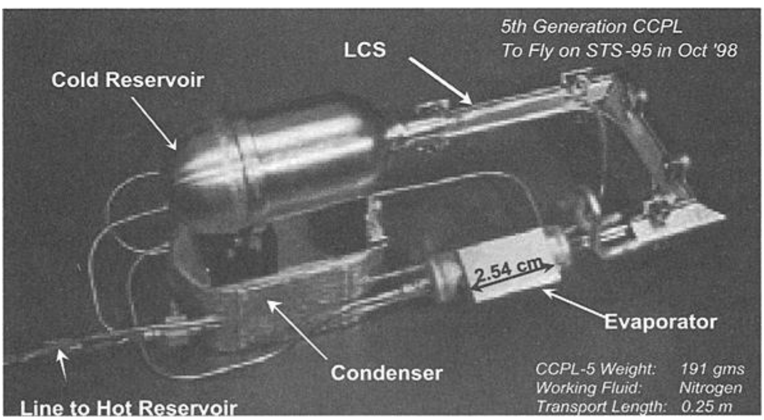

Fig. 20.12. CPL for sensor cooling.

IR&D/CCPL
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A similar cryo-CPL was charged with neon and successfully operated in a laboratory environment at GSFC. It successfully demonstrated over 2 W of heat-transport capability in the vicinity of 30 K. Recently, a more advanced design demonstrated successful operation (start-up, temperature control, heat transport, etc.) using hydrogen as a heat-transfer fluid in the vicinity of 20 K.

Management of parasitics and effective startup are the major issues with this technology, but successful designs have been developed for devices that operate under temperatures as low as the vicinity of 20 K. Development of devices that operate in the 2–4 K range may also be possible by using helium as an operating fluid, but this technology has not yet been developed.

Heat-Storage Devices

Phase-Change-Material (PCM) Devices

PCM devices are heat-storage devices that utilize PCMs to greatly increase the effective "thermal capacitance" of a device, which will improve thermal stability under changing thermal loads/environments. PCMs absorb or discharge a great amount of energy when melting or solidifying. A PCM device for NASA's Vegetation Canopy Lidar mission is shown in Fig. 20.13.

PCM Storage Units

A PCM thermal storage unit was designed and fabricated for use with the VCLHP. The PCM is dodecane, which has a melting point of –9.6°C with a heat of fusion of 217 kJ/kg and a density of 720 kg/m^3. A thermal storage enclosure containing this PCM was designed so that the batteries can be housed inside. Energy Science Laboratories Inc. (ESLI) of San Diego, California, designed and built the unit in late 1998 to JPL's specifications. Typical challenges in using PCM thermal storage are the poor thermal conductivity of the PCM in its solid phase, containment of

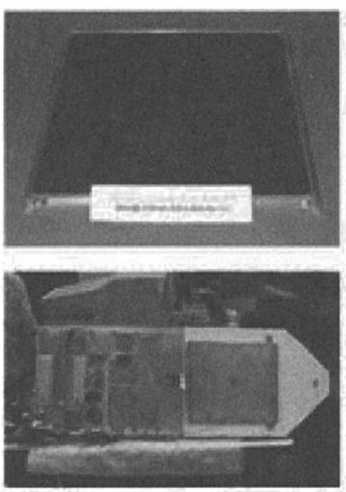

Fig. 20.13. PCM device for NASA's Vegetation Canopy Lidar mission.

the PCM in a leak-tight container that can handle expansion and contraction during the freeze-thaw process, and minimization of the PCM system mass. Several novel features were used in the design and fabrication of the PCM storage unit. A carbon-fiber core, used to provide the PCM with a good thermal conductivity in its solid phase, also provided structural strength to the module. Thin-walled aluminum sheets were used to build the container. In construction of the unit, structural epoxies were used to bond the various container parts. The PCM thermal storage unit is shown in Fig. 20.14. The PCM unit was 350 mm long and 95 mm in diameter. The various components of the unit and their masses are: carbon-fiber core, 80 g; dodecane PCM material, 530 g; and aluminum wall material, 175 g.

Spray Cooling Devices

Spray cooling devices are capable of absorbing very high heat fluxes (hundreds of W/cm^2) from lasers, electronic chips, power converters, and similar high-energy devices. Spray cooling is a relatively new concept now being investigated for ground applications. This technology involves impingement of a fine spray directly onto the surface to be cooled. Laboratory experiments have demonstrated the ability to cool fluxes in excess of 100 W/cm^2. While this concept offers considerable promise for cooling lasers and other high-flux situations, very little work has been done to address space applications of this technology. For example, the collection and condensation of the vapor could be a significant issue in zero gravity. Figure 20.15 is a schematic diagram for a spray cooling device.

Heat Rejection through Advanced Passive Radiators

Heat-rejection technology that makes use of advanced passive radiators is in need of rejuvenation. Many of the specialists who developed expertise in this area are no longer working, and existing designs are prohibitively expensive. A newer concept

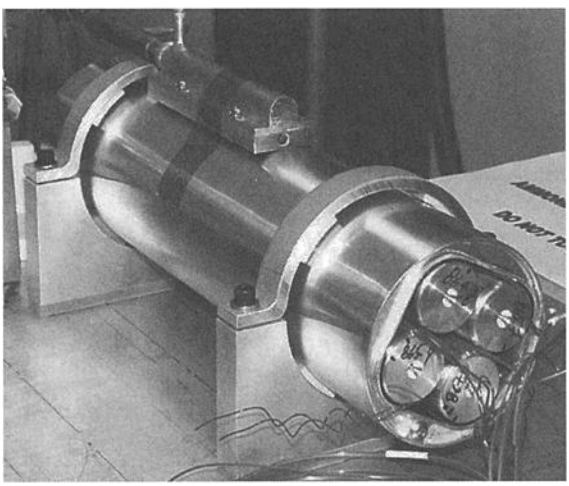

Fig. 20.14. PCM thermal storage system for battery thermal control.

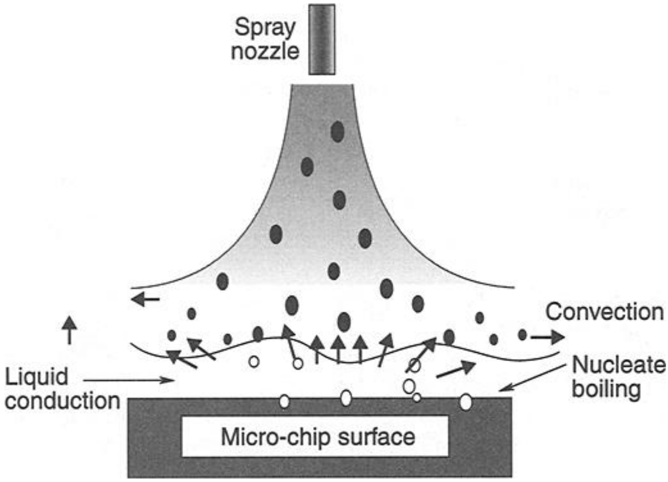

Fig. 20.15. Spray cooling device for thermal control.

currently being developed at GSFC involves the use of flat composite panels coated with a highly specular film and assembled in such a fashion so as to simulate a parabolic shape. This concept is modular and low cost, and it avoids the elaborate machining needed to fabricate a more conventional reflector.

Lightweight Thermal Insulation

High-performance lightweight thermal insulation is another technology that is very important for future spacecraft, especially for future Mars landing missions. New types of insulation, in which aerogel and carbon dioxide are the insulation media, are currently being examined (Tsuyuki *et al.*[20.34]). These new types reduce the mass by 50% compared to the battery thermal insulation currently used for Mars surface landers. In a thermal insulation concept using carbon dioxide as a thermal insulation medium, the insulation is fabricated using two layers of aluminized Kapton separated 4 cm by Mylar stand-offs. The gap between the two layers is filled with carbon dioxide. In the Martian surface operation, the gap is automatically filled by the 8-torr carbon dioxide that exists naturally in the environment. A thermal conductivity of 0.022 W/m·°C at –25°C, which is comparable to that of the batt insulation, has been measured in tests.

Mechanical Heat Switches

Mechanical heat switches have not been extensively used for spacecraft thermal control applications in the past, because of low performance (on/off heat-transfer ratio) and the large switch mass needed to conduct heat. Heat switches based on gas-gap technology are being investigated for situations where the heat-transfer rates are small. Heat switches based on bimetallic mechanisms have been occasionally used in the past but only for low heat-transfer rates. Wax-actuated heat switches are currently being investigated for spacecraft thermal control applications at JPL. Starsys of Boulder, Colorado, which has developed the wax-actuated heat switch for space applications, is modifying a design created for JPL for application to Mars surface conditions. Those conditions, where an 8-torr carbon-dioxide atmosphere exists, require that the gap in the switch be substantially larger than that used in space. The current Starsys actuator, which weighs about 100 g, provides a heat-transfer rate of 0.7 W/°C and has a ratio of 100:1 for on/off operation (Lankford[20.35]). The heat switch for Mars application is expected to weigh about 60 g and have conductance of 0.45 W/°C and a closed-and-open-position heat-transfer ratio of 25:1.

A miniature heat switch is being developed for future microspacecraft applications under the NASA SBIR program. This technology, developed by ESLI, is expected to reduce the heat-switch mass by an order of magnitude compared to the switch mass in current state-of-the-art technology. The heat switch uses a PCM-based actuator to obtain high heat-transfer rates with low switch mass. A switch based on this technology has demonstrated a performance of 0.12 W/°C with an open/close ratio of 18:1, a weight under 8 g, and a contact area of less than 6 cm^2. The current development plan has goals for enhancing the performance by an order of magnitude.

Heat Pumps

Heat pumps allow radiative heat rejection when the temperature of the thermal sink is near or above the desired control temperature. This condition may occur in several situations, such as planetary/lunar applications, positions in which a radiator is forced to look at the sun, and very low orbits (possibly including balloon applications). Analytical studies[20.36] have demonstrated that a heat pump may be beneficial from a systems-level weight perspective if the effective thermal sink is within 50°C of the source. This assumes near-term technologies (with respect to efficiency and weight) that appear to be achievable; however, no funding has been available to effect the necessary improvements and system design. Some researchers have expressed a concern for the effects of zero gravity on existing designs, but others have suggested wicking schemes and forced convective flow to overcome those effects.

Summary

Advanced thermal control technologies are needed to meet the requirements of future space missions, and many are presently under development at various organizations. Thermal control applications include maintaining spacecraft equipment within allowable temperature limits, minimizing the spacecraft survival power, providing dimensional stability for large spacecraft structures, and providing thermal control for micro- and nanospacecraft. Some of these efforts are improvements on recently demonstrated technologies, such as mechanically pumped cooling loops and LHPs, whereas others are new technologies, such as EC devices for variable-emittance properties and MEMS-based devices for thermal control. At the current level of research and developmental efforts, some of these technologies are expected to be ready for flight applications in two to five years.

Improved thermal control technology is ultimately driven by need and created by the imaginations of thermal engineers. In addition to providing improved performance, many of the new technologies identified in this chapter are robust and flexible in their applicability. These qualities can significantly enhance a designer's options in the development of a thermal control concept for a given spacecraft.

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