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Review of Modern Spacecraft Thermal Control Technologies and Their Application to Next-Generation Buildings

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ABSTRACT

Next-generation buildings and building systems will be designed, installed, and operated with significant improvements in energy efficiency. For instance, the 2010 version of ASHRAE Standard 90.1 increases building energy performance by approximately 30% over existing standards. Realizing high-performance buildings and building systems will be achieved, in part, through technology advances. Although these advances will be the focus of building and building system industries, the spacecraft community is developing exciting technologies that could be applied to next-generation buildings and building systems.

1. INTRODUCTION

Space exploitation provides tremendous opportunities. Since 1957, spacecraft (S/C) have been developed to take advantage of this new high ground by providing communication, scientific observation, weather monitoring, navigation, remote sensing, surveillance, and data-relay services (Gilmore, 2002). However, S/C thermal control subsystems (TCS) present many extraordinary engineering challenges. Overcoming these challenges is the result of carefully designed systems and utilization of modern technologies. In general, S/C TCS technologies have largely been investigated and developed remote from the HVAC&R community. Therefore, much benefit could be gained by bridging the gap between S/C TCS and HVAC&R professionals. Several examples of commercial technologies originally developed for space applications indicate that these collaborations are beneficial.

Out of necessity, S/C of the late 1950s drove solar cell advancements that were ultimately utilized for terrestrial applications. The United States Department of Defense developed the Global Positioning System (GPS) that permeates our society today. Created in 1958, NASA oversaw the development of many technologies that are now widely commercialized, including non-invasive health diagnostics, air-traffic management, precision farming and irrigation tools, engine health-management software, and less-expensive methods of carbon nanotube manufacture (Comstock and Lockney, 2007). Given a long and successful history of spinoffs, opportunities may exist for the transfer of modern S/C TCS technologies to terrestrial HVAC&R applications. This paper investigates those opportunities by reviewing modern S/C TCS technologies and assessing their potential for terrestrial applications.

2. REVIEW OF MODERN S/C THERMAL CONTROL TECHNOLOGIES

The following is a review of modern S/C TCS technologies including those for both traditional and robust S/C design. Insulation, variable heat-rejection, and heat pipe technologies were investigated. For each, an evaluation of its potential for terrestrial applications is provided.

2.1 Insulation

Used to conserve thermal energy and protect satellites from external radiation, insulation is a well-established and extensively utilized S/C TCS technology. Multilayer insulation (MLI), the most common S/C insulation technology, provides an effective method for insulating spacecraft. Combined with a well-established flight history, MLI blankets are effective and highly reliable; however, MLI requires a tedious design and installation process due to its inherent fragility. Aerogels provide an attractive alternative.

According to Lee *et al.* (2009), aerogel materials were first formed in the 1930s by replacing the liquid phase in a silica gel with air. The pore structure of the gel is maintained by drying above supercritical conditions where interfacial tension between liquid and vapor phases are significantly reduced, virtually eliminating capillary forces that typically cause shrinkage and pore collapse. Consequently, aerogels are one of the lightest known solids while exhibiting outstanding thermal and noise insulation properties in both air and vacuum (Sibille *et al.*, 1996).

Trifu *et al.* (2004) evaluated aerogel composite blankets as a potential replacement for MLI. Aerogel composite blankets had similar insulating performance to MLI. An ultra-lightweight (i.e. 0.03 g/cm^3) aerogel blanket achieved a thermal conductivity of 0.74 mW/m-K at 160°C and at moderate vacuum levels. In addition, aerogel blankets can handle up to 200 psi of compression before the thermal performance is noticeably affected. Combined with its ability to handle repeated flexure and handling, the installation costs of aerogel blankets could be significantly less than that of MLI. In addition, aerogel blankets had favorable outgassing characteristics. Compared to MLI, aerogels have limited flight history although recent missions have placed this technology in space. Most notably, the Mars rovers used carbon-opacified silica aerogel to insulate the most sensitive electronic components during cold Martian nights.

Aerogels do not require a high vacuum environment and therefore have great potential to enhance terrestrial products. Due to its extremely low thermal conductivity, aerogels allow for thinner refrigerator and oven walls that increase available volume and/or reduce unit size. In an application comparison of various insulation types for hot-water tanks, Omer *et al.* (2007) found that aerogels were the best insulation in terms of reduced thickness, weight, and quality; however, aerogels were much more expensive than other types. Aerogels are also considered the ‘holy grail’ in glazings although the largest window produced to-date is 1 m^2 (Bahaj *et al.*, 2008). In a study by Schultz *et al.* (2008), an evacuated aerogel glazing provided a 19% reduction in energy compared to an equivalently sized triple-layered argon-filled glazing. Although it currently does not meet the visual quality of conventional glazing systems, it is good enough in many instances. It would certainly meet visual requirements in instances such as skylights or light-transmitting envelopes. Based on performance alone, it is evident that aerogel technologies are well suited for a wide-range of terrestrial applications. However, market penetration will be slowed by its cost. Therefore, leveraging the S/C community – where cost considerations are much less strict – could provide the necessary developments to overcome these barriers.

2.2 Variable Heat-Rejection Surfaces

Variation of heat-rejection capability at the surface of an S/C is one method of providing thermal balance modulation. This can be done by either changing the physical configuration of the radiating surface to alter view factors (e.g. louvers), adjusting the heat conduction path near the surface (e.g. paraffin heat switches), or by changing the optical properties of the radiating surface.

Electrochromic devices (ECDs) rely on chemical processes to vary the emissivity of a surface. The absence of moving parts has obvious advantages for reliability, and ECDs are able to achieve a continuous range of emissivities. ECDs are composed of five main layers, beginning with a reflective electrode (RE) that has a mirror-like reflectance in the infrared and is mounted on the spacecraft skin. The active element, mounted on the RE, is composed of electrochromic (EC), ion conductor (IC), and ion storage (IS) layers. The IC layer conducts ions, but provides electrical insulation between the electrodes of the device. The EC and IS layers are electrochemically active metal oxides that are intercalatable and deintercalatable with electrons and ions. Finally, a transparent electrode with high conductivity and transmissivity protects the device from atomic oxygen.

The ECD operates by applying a small voltage, in the range of ±2 V, to move the ion and electron pairs between the EC and IS layers. When a voltage is applied, one of the active metal oxide layers will experience an increase in absorptivity due to intercalation, while the other active metal oxide layer simultaneously experiences an increase in absorptivity due to ion extraction. When the process is reversed, the emissivity of the active layers will be reduced.
Because maximizing the exposure of the active layer to the environment will provide maximum emissivity variations, it is desirable to have a transparent electrode on the outer surface of the ECD. While some ECDs rely on a grid of opaque electrode material to minimize the area covered by the electrode, Demiryont *et al.* (2008) tested a transparent electrode in their ECD. The ECD not only had a low density of 5 g/m^2, it achieved an average emittance

modulation of 0.3 in a MidStar space experiment and the next generation device achieved 0.7 in laboratory experiments.

ECD technologies similar to those found in S/C TCS have potential for terrestrial applications. In particular, they can be integrated into building windows. Based on the same underlying principles as S/C TCS approaches (i.e. ion conduction), terrestrial applications focus on transmissivity modulation in the visible spectrum for both interior lighting and space-cooling improvements. Lee and DiBartolomeo (2002) investigated the utility of large-area electrochromic windows for commercial building applications and found that they provided reduced lighting energy use in some cases, but were unable to fulfill both energy-efficiency and visual comfort objectives especially during winter when low direct-sun conditions exist. They found that improved switching speed could broaden the use of electrochromics. Switching speed has been shown to slow with increased glazing area, increased cycling, and reduced temperature. In a follow-up study, Lee *et al.* (2006) found two challenges that face electrochromic window technologies: 1) integration of the dynamic window within building systems and 2) development of control algorithms, diagnostic tools, and performance data. For south-facing large-area windows, electrochromics demonstrated 44-59% and 8-23% daily lighting energy savings over 15% and 50% visible transmissivity windows, respectively. In addition, they found that an electrochromic window-lighting system controller maintained work plane illuminance levels within ±10% of requirements. Electrochromic technologies could also be utilized in conjunction with light-guiding devices to direct daylight deeply into buildings. Clear *et al.* (2006) tested 0.9 x 0.9 m electrochromic windows with a visible transmittance range of approximately 3-60%. They found that an increased range would help reduce glare and improve daylight harvesting under low-light conditions. In addition, subjects preferred variable transmittance conditions, but the system used slightly more electric lighting than fixed transmittance types. It was noted that this might be the result of an inefficient control algorithm. Bahaj *et al.* (2008) noted that current switching times of 5 to 10 minutes, glare, color rendering, cost, and lifetime issues must be addressed to enable significant market penetration.

Granqvist *et al.* (2007) focused on space conditioning. Simulations showed that smart windows could reduce space-cooling energy by up to 50%. Achieving widespread use of these devices will require cheap production capability such as web coating allowing roll-to-roll manufacturing. Other barriers include durability, optical switching speed, and size constraints. Although research efforts are being conducted on electrochromic window technologies, the literature did not show any work on electrochromics integrated within building walls. This approach may provide a means of improving both building cooling and heating performance. It is anticipated that cost considerations would be the most significant hurdle in this approach. Variable heat-rejection surfaces, namely electrochromics, have shown much promise for building applications. However, the literature has shown that challenges remain, many of which are shared with the S/C TCS community. These include reduced switching speeds, optimized control algorithms, control range, and diagnostic. Consequently, both building and S/C TCS communities could benefit through collaboration.

2.3 Heat Pipes

Swanson and Birur (2003) claim that two-phase technology, such as heat pipes, are clearly the major spacecraft thermal control innovation of the last decade. First patented in 1942 (Reay *et al.*, 2006), heat pipes are well-established two-phase systems that have proved their usefulness and reliability in many flights. There are several variations making them useful for many applications; the most basic operate by using a wick to draw liquid from a condenser to an evaporator, where the liquid is vaporized before returning to the condenser.

2.3.1 Diode Heat Pipes

Heat pipes can also be designed such that heat can only be transferred in one direction, although some heat will inevitably leak in the opposite direction due to conduction if operation is reversed. Diode heat pipes operate by using a reservoir connected to the heat pipe core to control the amount of liquid and vapor in the heat pipe. Prager *et al.* (2002) describe the operation of liquid-trap, liquid-blockage, and gas-blockage diodes in further detail.

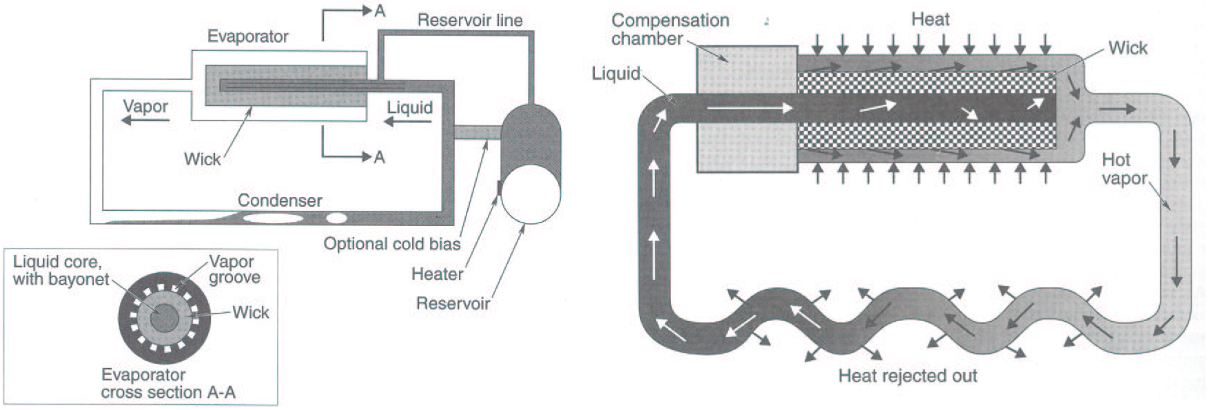
2.3.2 Variable Conductance Heat Pipes (VCHP)

While diode heat pipes use reservoirs containing excess amounts of the working fluid, VCHPs use reservoirs filled with a noncondensable gas to modulate the conductance of the device. As the temperature at the evaporating surface increases, the vapor pressure increases and forces the noncondensable gas into the reservoir, leaving a larger condenser surface area to interact with the two-phase fluid and provide cooling. In this way, the amount of heat removed from the heat pipe can be passively controlled to maintain a device at a relatively constant temperature. Sarraf *et al.* (2008) have also designed and tested a pressure controlled heat pipe (PCHP) with a goal to improve the temperature control of the VCHP while minimizing additional power use, complexity, and response time. They demonstrated that a PCHP that controlled reservoir volume was able to maintain an evaporator temperature within ±0.1 K of a target temperature, while a VCHP experienced a change of ±3.5 K in evaporator temperature under the same conditions. The PCHP also had a shorter response time, taking only 30 seconds compared to the 20 minutes required by a heated-reservoir VCHP having similar power consumption (Sarraf *et al.* 2008). The power consumption of the PCHP averaged around 8 W, but could increase to 32 W when the system was fully loaded.

2.3.3 Capillary Pumped Loops (CPLs) and Loop Heat Pipes (LHPs)

Although conventional heat pipes are useful, well-developed, and reliable devices, they are unable to transport heat long distances. Consequently, S/C component placement is restricted to near-radiator locations; this has a compounding effect of increasing support structure and mass (Hoang *et al.*, 2003). In addition, future S/C will outgrow conventional heat pipe capabilities in terms of heat transport, heat density, and temperature control (Hoang *et al.*, 2003). As a result, capillary pumped loops (CPL) and loop heat pipes (LHP) have been identified as the next generation of heat pipe technology for S/C. Butler *et al.* (2002) estimated that CPLs and LHPs offer at least two orders of magnitude improvement in heat transport capability compared to traditional heat pipes.

CPLs, first presented by NASA in 1966, are currently being used on multiple on-orbit S/C missions and electronics cooling applications (Liu *et al.*, 2008). A single-evaporator CPL flight experiment, CAPL-2, was successfully flown in 1995. Three, single-evaporator CPLs have provided successful and robust operation on NASA's Earth Observing System (EOS) Terra since 1999 (Yun and Bugby, 2007). Similar to conventional heat pipes, CPLs rely on capillary forces to drive vapor from a typically polyethylene evaporator wick to the condenser (Butler *et al.*, 2002). However, they are a significant departure in that they utilize standard, non-wicking tubing in most of the system. In addition, the system relies on a hydro-accumulator (i.e. reservoir), which controls the system saturation temperature and fluid circulation (Figure 1). The reservoir is attached to the CPL liquid line by smooth-walled tubing and can be located remote from the evaporator. The CPL is typically cold-biased, which allows the loop to operate at lower temperatures and provides fine temperature control of ±0.5°C (Hoang *et al.*, 2003). A heater, around 15 W, on the reservoir can be used to control the loop operating temperature, and is also required to pre-condition the loop before start-up (Butler *et al.*, 2002). When heat is applied to the reservoir during pre-conditioning, liquid is pumped through the system, wetting the evaporator wick. This is necessary to avoid vaporization within the liquid core of the evaporator, where vapor bubbles can block liquid flow, causing evaporator dryout and stopping the loop.



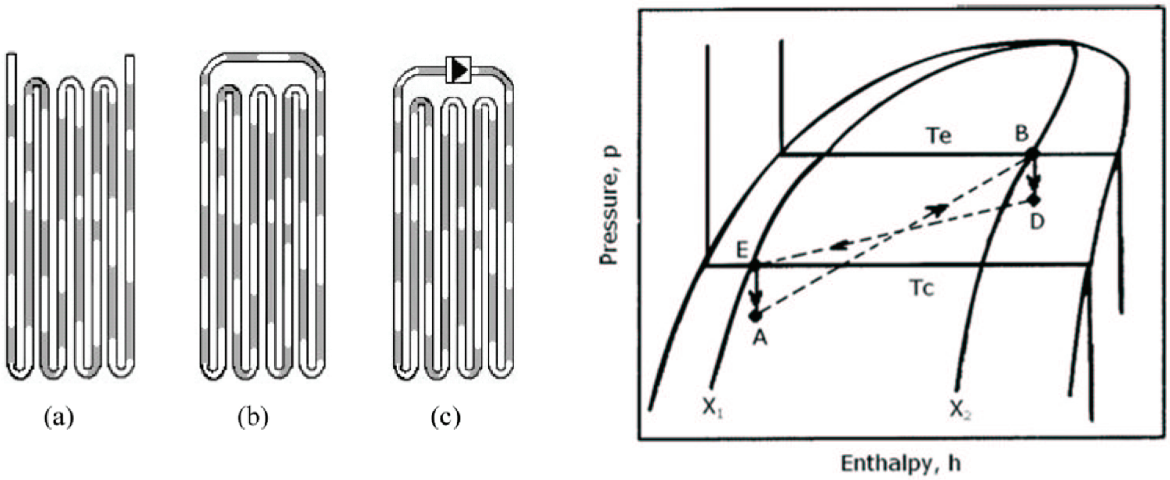
a) CPL b) LHP

Figure 1. Schematic of a CPLs and LHPs (Prager, Nikitkin, and Cullimore, 2002)

First tested in the former Soviet Union in the 1980s, LHPs provide enhanced heat transport capability similar to CPLs and are currently being used on 100s of on-orbit missions (Bugby *et al.*, 2005). LHPs traditionally use sintered powder metallic evaporator wicks and standard, non-wicking tubing for most of the system. The hydro-accumulator in a LHP is called a compensation chamber (CC). As shown in Figure 1, the CC is directly attached to the evaporator and therefore, susceptible to heat leak. A secondary wick connects the CC to the evaporator. LHPs are considered more robust than CPLs due to their ability to operate with vapor bubbles in the evaporator core. Whereas CPLs will deprime, stopping operation, LHPs will autoregulate, adjusting to a higher operating temperature to maintain the necessary subcooling at the CC entrance. This robustness is also evident in the start-up process. While CPLs require a pre-conditioning process to remove vapor bubbles from the evaporator core, LHPs can self-start when a heat load is applied to the evaporator. However, this process is still very slow, and both CPL and LHP systems often employ 35 W to 75 W starter heaters on the evaporator to start vaporization (Butler *et al.*, 2002). Because the CC is quite large, the space required for the combined CC and evaporator assembly may make LHPs more difficult to incorporate than CPLs in certain applications. In addition, the local reservoir makes fine temperature control more difficult although it has been demonstrated in some cases (Baker *et al.*, 2004). A heater, on the order of 50 W, can be used to control the LHP operating temperature if the desired temperature is above the natural equilibrium temperature without heater control (Butler *et al.*, 2002). Although considered more robust than CPLs, in some cases temperature oscillations and instabilities have been witnessed (Ku *et al.*, 2001).

2.3.4 Pulsating Heat Pipes (PHP)

Invented in the 1990s, PHPs utilize a wickless design making them a potentially simple and low-cost technology, especially for electronics cooling (Weislogel, 2002). In a study by Yang *et al.* (2008), heat flux capability of up 1242 W/cm^2 were experimentally verified. The PHP consists of a tube that is small enough in diameter to make surface tension forces dominate gravitational forces and is bent back and forth parallel to itself, as shown in Figure 2. PHPs can be configured either as open or closed loops, depending on whether the ends of the tube are sealed or connected. Closed-loop PHPs can have a combination of oscillating and circulating flow, which seems to improve their performance compared to open-loop systems. Adding a check valve to limit fluid flow to one direction can further improve performance but is not common due to the added cost and complexity.



Three types of PHPs: (a) open-loop (OLPHP), (b) closed-loop (CLPHP), (c) CLPHP with check valve

Pressure-enthalpy diagram of PHP cycle

Figure 2. PHP Overview (Zhang and Faghri 2008)

The evaporator and condenser of the PHP are typically located at the bent ends of the tube, and flow between the two ends is driven by the formation and extinction of vapor bubbles. When a PHP is constructed, the tube is evacuated and then partially filled with working fluid, resulting in a mixture of liquid slugs and vapor plugs. When this mixture enters the evaporating section, it undergoes what Zhang and Faghri (2008) describe as a constant pressure heat addition combined with an isentropic pressure increase due to bubble expansion (i.e. A to B in Figure 2). The simultaneous increase in vapor pressure in the evaporating section and decrease in vapor pressure due to condensation in the cooling section moves the liquid slugs from the heating section to the cooling section providing isenthalpic throttling (i.e. B to D in Figure 2). The motion of the liquid slugs from the heating section to the cooling section leaves a lower vapor pressure in the heating section and causes a higher vapor pressure in the cooling section. This pressure difference will ultimately drive the flow back to the heating section. However, the mixture will first experience a drop in vapor pressure due to condensation as it passes through the cooling section and rejects heat (i.e. D to E in Figure 2). Finally, the mixture undergoes an isenthalpic pressure drop as it returns from the cooling section to the heating section (i.e. E to A in Figure 2).

The absence of a wick not only simplifies the PHP construction, but it also lowers the mass of the device. However, most of the research thus far has studied PHP performance in gravity. In an extensive review of PHP literature Zhang and Faghri (2008) found that most experiments showed a decrease in PHP performance, or even stopped operating, as the PHP inclination angle was varied from vertical to horizontal. Although smaller tube diameters seem to lessen the impact of gravity, increasing the effect of capillary forces, further research is required to determine if this is truly a viable technology for space applications. Gu *et al.* (2004) investigated these effects. Under reduced gravity of ±0.02-g, a PHP made from a thin aluminum showed better operating and heat transport performance than that under normal gravity. In addition, they conducted a theoretical analysis that revealed the possibility of PHPs with channel diameters of up to 5 mm (R114 as a working fluid) could work under microgravity, though they may not work on the ground. Bsibsi *et al.*, 2006 demonstrated that PHPs could be simultaneously be used as heat switches, heat transport devices, and radiators. Breadboard tests demonstrated conductance ratios of 1:40 at a maximum power dissipation of 40 W.

2.3.5 Additional Heat Pipe Technologies

Several other heat pipe technologies are gaining momentum in the S/C community. These include flat-plate heat pipes (Semenov and Burke, 2008) that provide effective thermal conductivities up to 5000 W/m-K; sorption heat pipes (Vasiliev and Vasiliev Jr., 2005) that combine traditional CPLs or LHPs with sorption phenomena; hybrid heat pipes that combine the best attributes of CPLs and LHPs while overcoming their disadvantages (Bugby *et al.*, 2005); and multi-evaporator CPLs and LHPs (Wang *et al.*, 2008).

2.3.6 Terrestrial Applications of Heat Pipes

Reviews conducted by Firouzfar and Attaran (2008) and Vasiliev (2004) found that current and future terrestrial applications of heat pipes include: waste heat recovery, heat pipe embedded clothing, automotive exhaust heat recovery, micro-heat pipes for electronics cooling, PHP for uniform cooling inside refrigerators/freezers, heat pump heat exchangers, enhanced solar collectors, and improved HVAC dehumidification. Yau (2008) found that heat pipe development in the United States is focused on the development of superior heat transfer performance devices for space use. In Western Europe, heat pipes are also used for space applications in addition to heat recovery in flue gas for combustion and industrial processes and air conditioning processes. Yau (2008) investigated HVAC performance improvements achieved using heat pipe energy recovery. Yau (2008) found that heat pipe heat exchangers (HPHX) can be used to enhance dehumidification with resulting reduced energy consumption and peak demand for HVAC systems. Applications included HPHX utilization to pre-cool return air for moisture removal (McFarland *et al.*, 1996). An approach not found in the literature is utilization of advanced heat pipe technologies (e.g. CPL and LHP) for heat load sharing among such devices as refrigerators, dishwashers, and HVAC equipment. This approach could potentially improve overall building efficiencies, but it is anticipated that cost considerations would be a major hurdle. Ochsner (2008) used a 100-meter CO_2 ground-coupled heat pipe in conjunction with a ground source heat pump. Advantages included use in water protection zones and reduced pumping requirements leading to higher seasonal performance values. Varga *et al.* (2002) embedded thermal diode heat pipes within a building structure to allow the building structure to cool during the cooling season. Li et al. (2008) investigated a sorption refrigeration system using heat pipes for heat recovery. They demonstrated a 23% improvement in COP for a regeneration temperature of 103°C and cooling water temperature of 30°C. Yang *et al.* (2009) explored the possibility of embedding PHPs as an integrated structure or heat spreader to improve overall thermal conductance. They achieved successful operation at all orientations with respect to gravity.

S/C TCS heat pipe technology advances have and will continue to provide opportunities for terrestrial systems. CPLs and LHPs will present opportunities to increase the distance between source/sink in addition to allowing for flexible connection lines to be utilized. Miniature heat pipe technologies will provide new opportunities in electronics cooling while PHPs may provide alternative methods for surface isothermalization. It is apparent that S/C TCS heat pipe technologies provide ample opportunities for terrestrial applications.

3. SUMMARY

Traditional and robust spacecraft thermal control subsystems (S/C TCS) are realized through carefully designed systems and utilization of modern technologies. Given a long and successful history of spinoffs, opportunities may exist for the transfer of these technologies to terrestrial applications. Several potential candidates were identified. Aerogels could provide for thinner appliance (i.e. refrigerator and oven) walls and improved glazing and building insulation. Electrochromics provide for the next-generation of glazing technology. Heat pipe technologies including CPLs, LHPs, and PHPs have tremendous potential for improving the performance of existing HVAC&R devices. In addition, next generation systems could be comprised of a combination of these technologies. For example, buildings of the future could be constructed using an aerogel envelope embedded with electrochromic layers allowing improved insulating values and potentially ‘whole-wall’ light penetration for reduced lighting and thermal demands. Realization will require technology advances and cost-reductions; these improvements could be leveraged through S/C TCS development efforts.

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