Critical Review of Thermal Management Technologies for Portable Life Support Systems

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Thermal management technology is an uncelebrated but nonetheless essential requirement for all spacesuits, spacecraft, and space habitats. During extravehicular activity (EVA), spacesuits must remove metabolic heat produced by the astronaut, residual heat from the suit's electronics, and absorbed heat from the external environment. The contribution of each of these heat sources can vary considerably, meaning a thermal control system must be able to actively adapt to changing heat loads to keep the suit's internal temperature within the narrow band safe for human occupation. Currently, both NASA's Extravehicular Mobility Unit (EMU) and the Russian Orlan spacesuit use water-ice sublimation to provide cooling. This method has proven reliable, but improvements and optimizations will need to be made for future deep space exploration. This system will not operate in a Martian atmosphere and significant mass reductions and improvements in portability must be made to support planetary EVAs. This paper will present a study of current thermal management techniques in development for planetary spacesuits and habitat systems. These include evaporative cooling, phase-change and solid-state heat exchangers, variably emissive electrochromic radiator devices, and variable geometry radiators (mechanical louvers). An analysis of the state of the art and Technology Readiness Level (TRL) of these technologies will be presented. Recommendations will be made for future research and where these technologies would best fit into a lunar or Mars mission system architecture. Analysis is directed towards technologies with potential use in Portable Life Support Systems (PLSS) integrated into next generation spacesuits for planetary surface EVAs on the Moon and Mars.

Nomenclature

PLSS	=	Portable Life Support Systems
EMU	=	Extravehicular Mobility Unit
xEMU	=	Exploration Extravehicular Mobility Unit
LCVG	=	Liquid Cooling Ventilation Garment
ECD	=	Electrochromic device
EVA	=	Extravehicular Activity
SWME	=	Spacesuit Water Membrane Evaporator
SERFE	=	Spacesuit Evaporation Rejection Flight Experiment
SEAR	=	Space Evaporator Absorber Radiator
LCAR	=	Lithium Chloride Absorber Radiator
TRL	=	Technology Readiness Level
ECLSS	=	Environmental Control and Life Support Systems
TEC	=	Thermoelectric Cooler
TEG	=	Thermoelectric Generator
MEMS	=	Microelectromechanical Systems
TVAC	=	Thermal Vacuum
IR	=	Infrared
ISS	=	International Space Station
UV	=	Ultraviolet
MCP	=	Mechanical Counterpressure

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I. Introduction

THERMAL management technology is an essential requirement for all spacesuits, spacecraft, and space habitats. During extravehicular activity (EVA), spacesuits must remove metabolic heat produced by the astronaut, residual heat from the suit's electronics, and absorbed heat from the external environment. The contribution of each of these heat sources can vary considerably, meaning a thermal control system must be able to actively adapt to changing heat loads to keep the suits internal temperature within the narrow band safe for human occupation[1]. Currently, both NASA's Extravehicular Mobility Unit (EMU) and the Russian Orlan spacesuit use water-ice sublimation to provide cooling. The ISS EMU utilizes a base layer called the Liquid Cooling and Ventilation Garment (LCVG) made of nylon and spandex interlaced with flexible rubber tubing for pumping cool water across an astronaut's skin to absorb heat. This garment is shown in Figure 1. Liquid in a feedwater circuit is exposed to a heat exchanger in the Portable Life Support System (PLSS) backpack, creating a thin sheet of ice that sublimates directly into the vacuum of space. Thermal energy is dissipated as the latent heat of sublimation from the water mass, cooling the water in the separate Liquid Transport Circuit that flows through the LCVG[2]. This method has proven reliable, but there are many problems and opportunities for optimization.

The water sublimation method of heat dissipation only works in the hard vacuum of space. New Spacesuit Water Membrane Evaporator (SWME) technology can theoretically operate in pressurized environments such as the Martian surface but uses about the same amount of water as the legacy sublimator and still requires a LCVG[3]. This "open loop" solution requires a significant amount of hardware and disposable water mass. For example, the heat regulation system on the Apollo suits had a mass of about 14 kg[4]. On the EMU, the sublimator itself weighs only 1.6 kg, but a single eight-hour ISS EVA burns through about 3.6 kg of water (approximately 1 gallon), making water the single largest EVA expendable by mass[5]. For long missions to Mars lasting around 575 surface days, water consumed during EVAs could amount to 2,500 kg, or over 30% of the total ECLSS mass[6].

Figure 1. Liquid Cooling Ventilation Garment. *NASA's current EMU uses a consumable loop of cooling water to draw metabolic heat from the skin [Credit: NASA]*

NASA recognizes the need for technological development. The 2015 Space Technology Roadmap noted that:

> Advancements in the PLSS are necessary to enable future missions, such as to planetary environments. An example is the sublimator currently utilized as a part of the ISS EMU to reject heat (metabolic heat plus system-generated heat); it sublimates water and the vapor is released into space. Sublimation is a physical mechanism requiring a hard vacuum environment, and thus cannot be used for Mars surface missions…The PLSS is a prime candidate for infusion of new technologies to significantly reduce or eliminate consumables, improve reliability, and increase crew performance. Significant (order of magnitude) increase in heat rejection performance and provision for closed-loop operations (no venting to environment) are some key advances that would enable future missions...Technical challenges for the PLSS include the development of hardware that can reject heat in a Martian atmosphere while fitting within a small enough mass and volume box to be carried by an astronaut. Radiator approaches seem to hold the most promise, but a radiator must allow adjustment of the heat removal rate, without penalty against other parameters.[7]

Here is presented an update on the latest technological progress in Closed-Loop Heat Rejection Systems with Zero Consumables cited by NASA as crucial for future human EVAs. Specifically identified technologies include the Spacesuit Water Membrane Evaporator (SWME)-Radiator Hybrid (6.2.2.1), Heat Pump Radiator Hybrid, (6.2.2.2), PLSS Radiator (6.2.2.3), as well as lower TRL technologies including variable emissivity radiators[7].

II. Planetary EVA Environments

Next generation spacesuits will need to function in a dynamic range of environmental conditions. Heat sources include environmental radiation, possible atmospheric effects, human metabolic heat, and residual heat from suit electronics.

The lunar environment is characterized by approximately ⅙ Earth g, and surface temperatures ranging from -143°C (-225°F) to +127°C (+261°F) due to direct sunlight or shading in an ambient vacuum. In direct sunlight, radiation can be reflected from the lunar regolith in infrared (IR) range, amplifying the radiative heating. In deep shadowed craters or during the extended night of the lunar 28-day day-night cycle, temperatures can approach absolute zero[8]. Temperatures are also dependent on latitude and local lighting conditions. During a lunar EVA, a crew member will experience sharp transient effects as they move in and out of shadows and change their orientation with respect to the sun[9].

The Martian surface environment is characterized by 0.38 Earth g, atmospheric temperatures from -143°C (-225°F) to +20°C (+68°F) with seasonal variations, and a thin atmosphere of 0.6-1.0 kPa composed of 95% CO_2 and wind gusts of up to 30 m/s that add convective heat loss. Ground temperatures range from -118°C (–180°F) to +29°C (+85°F). Mars has a 24.6 hour day-night cycle, and sunlight is about 43% the intensity experienced on Earth[8]. Overall, conditions vary dramatically depending on specific location, time of the year, and dust content in the atmosphere[10].

Human metabolic heat can fluctuate dramatically depending on activity level. The metabolic heat from a single lunar EVA can vary from 70 to 730 W depending on activity, with extreme peaks of 880 W in emergency contingencies[9]. This heat can be broken down into two categories: sensible heat and latent heat. Sensible heat is transmitted through the skin to the environment via conduction and convection, and generally remains stable over varying activity levels. Latent heat refers to the heat rejected from perspiration and expired water vapor[11]. Latent heat increases rapidly with activity level, as shown in Figure 2. The current LCVG and EMU alter this relationship by adjusting to keep skin temperature constant even at higher work rates so that sensible heat continues to be the dominate heat transfer mechanism. A system that relies on the body's natural transition to latent heat rejection at higher workloads may be more efficient and reduce consumables but will also require more drinking water. It may also require a new mechanism for collecting and filtering latent moisture condensate.

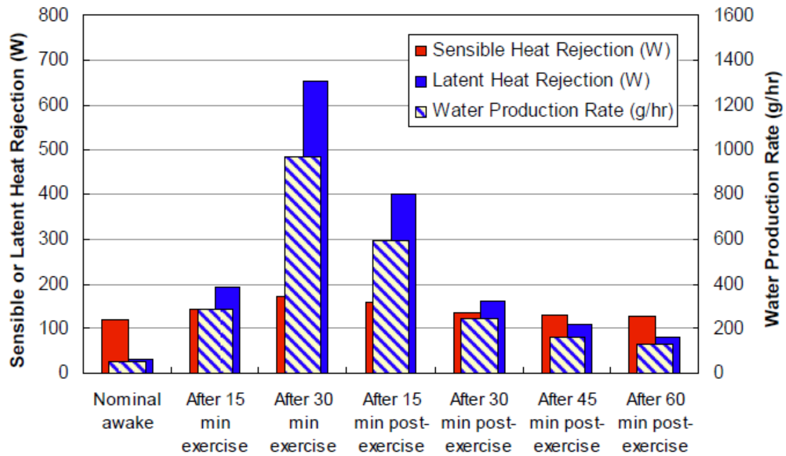


Figure 2. Human cooling mechanisms. *The human body rejects both sensible and latent heat. Latent heat rejection increases with activity level as perspiration and exhalation increase [Image from Ref. 11]*

PLSS electronics heat will likely decrease with technological advancements, but generally runs at a steady 120 W[12]. The current requirement for NASA's next EVA spacesuit, the Exploration EMU (xEMU) is 100 W. In total, this means that a spacesuit must be able to reject between 190 and 850 W. The current EMU has a requirement baseline value of approximately 250 W in steady-state performance for an 8-hour EVA[2]. The Apollo EMU requirement included about 270 W of cooling for an 8 hour EVA with a 19°C internal temperature maintenance, and a 250K heat sink temperature[11]. This represents a conservative baseline for future suit designs.

III. Thermal Management Technologies

Here is outlined the development progress, technological readiness, current identified work, and potential future work for several primary candidate concepts in closed-loop heat rejection application for spacesuits and PLSS. Though many research prototypes combine several different technologies, and a final implementation is likely to include elements from multiple methods of heat rejection, these technologies are subdivided into three categories: evaporators, heat exchangers (solid state and phase change materials), and lower TRL methods including variable-geometry and variable-emissivity radiators.

A. Evaporators

The PLSS built into the xEMU will include several updates from the original Apollo and Shuttle era suits, including the integration of a Spacesuit Water Membrane Evaporator. The SWME utilizes 27,000 thin-walled, hollow, 300 µm diameter polypropylene fibers that provide about 1.1 m^2 open pore. The small pores in the fibers prevent liquid from leaking out while presenting very low resistance to evaporation and vapor flow. The circulating water evaporates due to the low water vapor pressure on the outside of the SWME. The evaporation cools the remaining liquid as it returns to the LCVG. This keeps all contaminants in the cooling line and prevents them from clogging the sublimator, but a periodic scrubbing of the water circuit will be required instead. The heat flux is controllable, and the SWME is pressure independent at start-up, operating over the whole range of suit pressures. The SWME can also degas the thermal loop water to prevent pressure build-up[13]. Testing began in 1999 at the Johnson Space Center, with the first full sheet demonstration in 2009. The Gen2 SWME (shown in Figure 3) was created in 2010 and has demonstrated a capacity of greater than 800 W of cooling capacity with over 200 hours of testing[14]. The SWME is expected to be tested on the ISS for the first time in 2019 as part of the Spacesuit Evaporation Rejection Flight Experiment (SERFE)[15]. Nevertheless, the SWME remains a mass consumable life support system, a limitation for its extensibility to Moon or Mars missions.

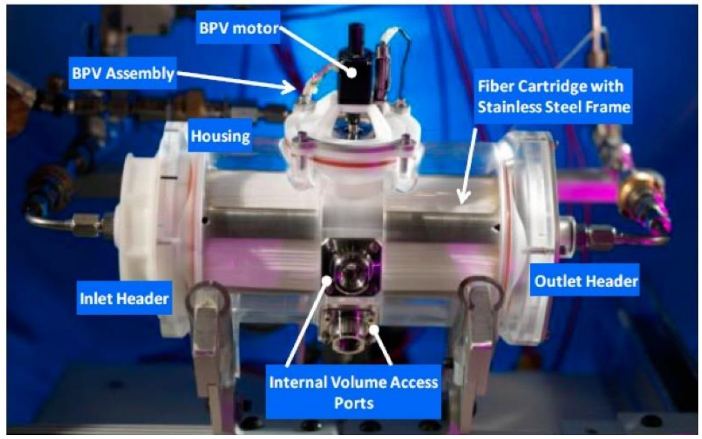


Figure 3. Gen2 SWME. *Lab testing of the Space Water Membrane Evaporator for the xEMU. The unit is less than 50 cm long and would fit inside the PLSS backpack [Image from Ref. 17]*

A critical advancement has been the development of the Space Evaporator-Absorber-Radiator (SEAR), which utilizes a Lithium-Chloride Absorber Radiator (LCAR) to condense and absorb water vapor evaporated through the hollow fibers of the SWME. The lithium-chloride solution is a strong desiccant that maintains a very low vapor pressure even at relatively high temperatures. The heat generated in this process drives up the temperature of a connected exterior surface radiator panel that rejects heat into space. Lithium-chloride solution maintains a low vapor pressure, even at temperatures that are typically 30°C higher than the SWME temperature. This enables the LCAR to operate as a heat pump, rejecting heat at temperatures of about 50°C-60°C which significantly reduces the size of the radiator. The LCAR designers at Creare LLC expect the system to be able to reject 150 to 300 W depending on available radiator surface area and environmental conditions[16].

The lithium-chloride concentration begins at about 95% and slowly dilutes to 45% over the course of an 8-hour EVA, at which point the LCAR ceases to be effective. The absorbed water can be recovered after the EVA by baking the LCAR at 100°C-120°C, which is a high enough temperature to evaporate the water from solution[17]. This could be done using a regeneration oven inside the spacecraft or habitation module. A comparison of the independent SWME and SWME with LCAR systems is shown in Figure 4.

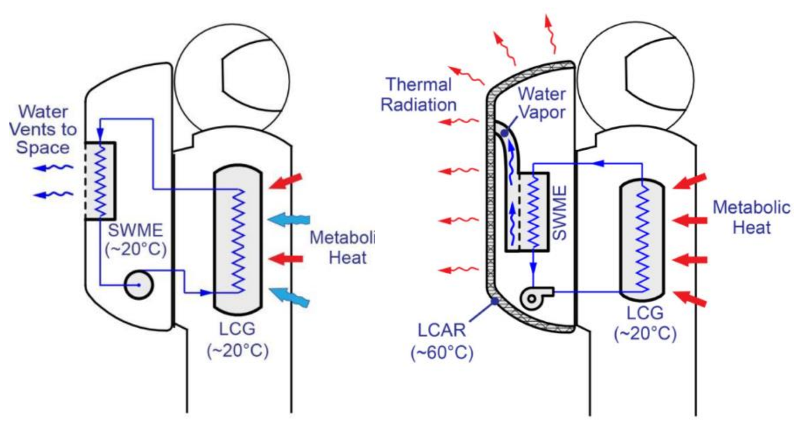


Figure 4. Comparison of heat rejection using SWME and SEAR. *The SEAR system rejects heat by absorbing water vapor and radiating the latent heat, as compared with the SWME independent system that directly vents the water vapor [Image from Ref. 17]*

Additionally, the LCAR radiator itself could be used as a structural shell for the PLSS backpack. When the radiators are engineered into a honeycomb pattern as shown in Figure 5, they demonstrate appropriate stiffness and impact resistance. This dual use may offer additional mass savings.

The LCAR system dramatically reduces water loss as compared with an SWME-only system, but it is not perfectly closed loop. Venting of certain trace non-condensable gases is necessary and results in some water loss, but much less than direct water vapor venting. Venting water may also be necessary to supplement heat loss in hot external

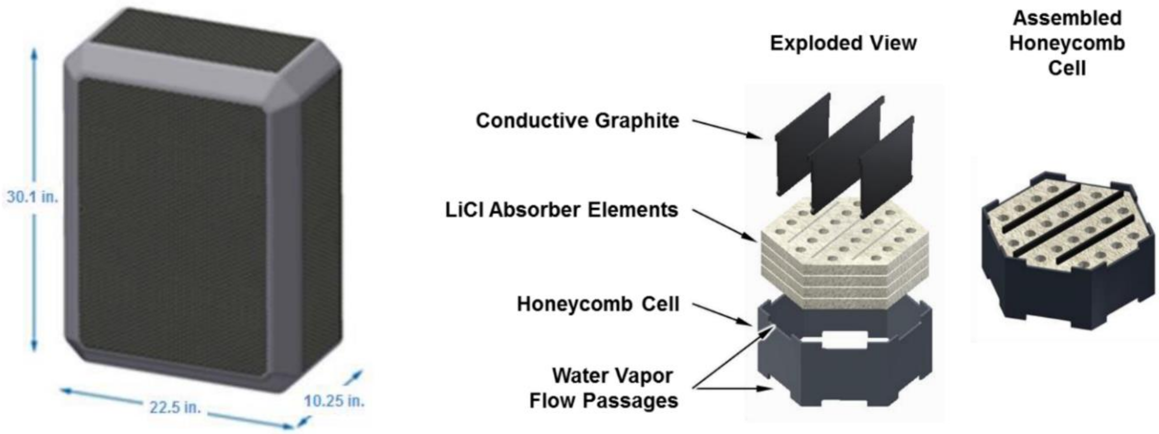


Figure 5. Proposed honeycomb LCAR design for the PLSS backpack. *[Image from Ref. 16]*

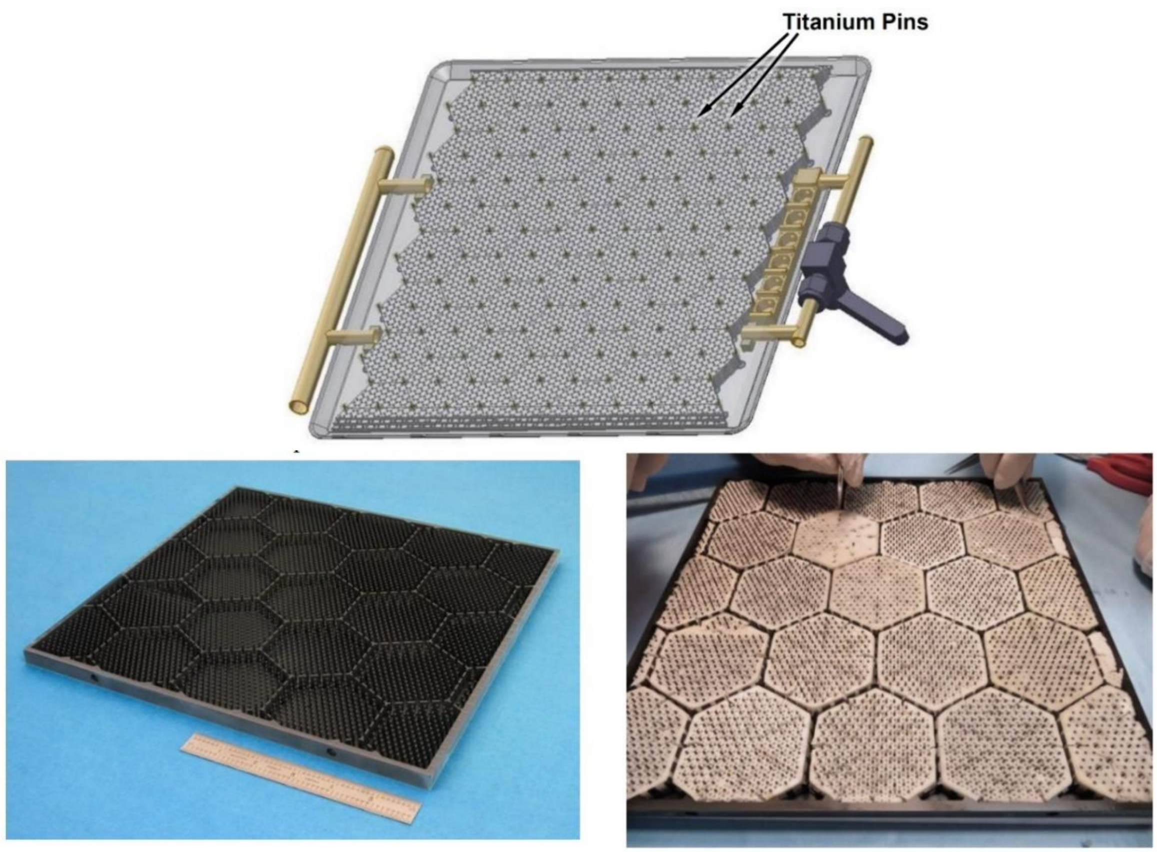


Figure 6. Cutaway view of LCAR titanium and graphite honeycomb module, designed for integration into PLSS shell. *The flight prototype is 1 ft^2 by 0.5 in thick. The front radiating surface (coated in high emissivity aeroglaze) is not shown. This prototype panel exhibited a 19% efficiency improvement over previous iterations during TVAC testing [Images from Refs. 18-19]*

environments, extreme metabolic cases, and at times when the LCAR solution approaches 45% concentration and ceases to absorb water vapor. Thermal vacuum, impact, and pressure tests have verified the performance of LCAR[17,19]. The latest designs include a rigid titanium shell that sandwiches each graphite-reinforced honeycomb LCAR cell, as shown in Figure 6.

Researchers have also started to identify modifications necessary to operate the SEAR and LCAR system on Mars. These steps include a higher average lithium-chloride loading concentration, and a miniature water vapor compressor that could enable the LCAR to operate at significantly higher water vapor pressures and temperatures (up to 80°C)[10].

Next steps in SEAR and LCAR development include prototype flight testing and qualification, assembly and qualification of a flight regeneration oven, improvements in contamination prevention and cleaning, detailed design of LCAR panels that could be used in a full PLSS backpack, and working to ensure the system is compatible with Mars spacesuit concepts[14,17].

B. Heat Exchangers

The most common proposal for solid-state heat exchangers are thermoelectric coolers (TECs). A TEC is a solid state heat pump made of thermocouples that creates a temperature difference across the device when a current runs through it in a process called the Peltier Effect. When a current flows through a junction between two different conductors (from a battery), heating and cooling occur because charge carriers diffuse to opposite sides of the device. Changing the polarity of the current reverses flow direction and switches the temperature gradient[20]. A TEC also has no moving parts, giving it the advantage of simplicity. Traditionally, TECs have been used for cooling small, energy-dense electronic components due to scaling challenges associated with power and mass.

Most research involving heat exchangers for PLSS has focused on rejecting the residual heat from suit electronics, including a new additively manufactured titanium-based liquid-gas heat exchanger for cooling the breathing gas ventilation loop in the next generation EMU. At only 0.39 kg, this small component is less than half the mass of previous prototypes and can reject a higher heat load[21]. Mass reductions will be a key component of future PLSS components, and this demonstrates the potential for future optimization of hardware components. While heat exchanger efforts have focused on small components, there have been several concept studies for using TECs as the primary cooling mechanism for a spacesuit.

Preliminary research using analog EVAs on Earth has shown the potential to provide superior cooling with a lower system mass by using TECs and swappable batteries rather than replaceable ice block coolers in analog spacesuits. Benchtop tests indicate that using five lithium-ion batteries totaling 3.4 kg to power a TEC cooling system would greatly reduce the 60 kg of replacement ice reservoirs needed to keep an analog suit cool over the course of a 175 W, 6-hour EVA. The applications of this work have so far been limited to terrestrial analog EVAs, but future work will examine the feasibility of using the Peltier cooling concept for EVAs on Mars[22].

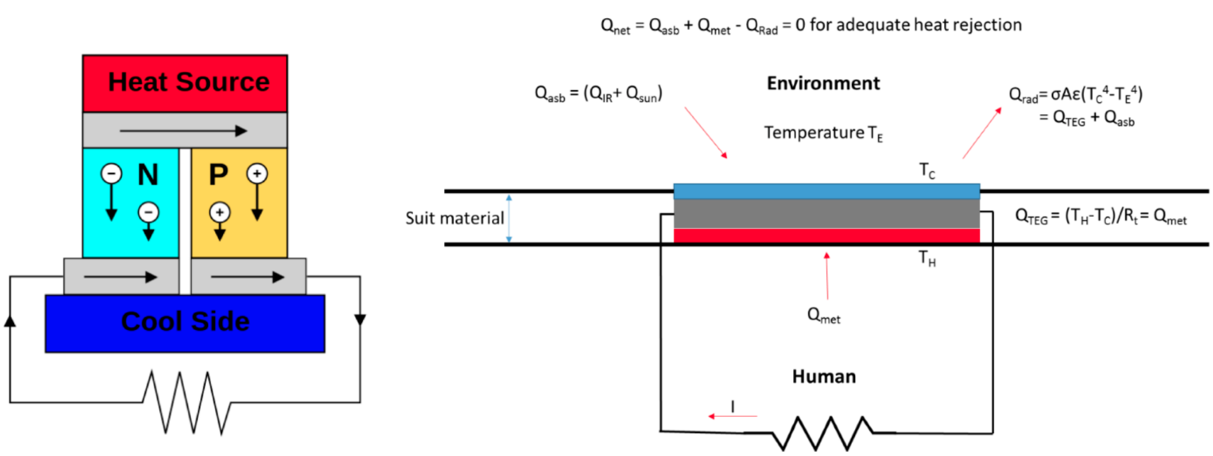


Figure 7. Thermoelectric generator diagram and hypothetical spacesuit implementation. *In a TEG, electrons in the N-type substrate and holes in the P-type substrate migrate away from a heat source, causing a net current flow. In a thermoelectric cooler, the current is run in the opposite direction. In an EVA suit,* Q_{net} *(composed of metabolic heat, radiative heat, and environmental heat) should be zero for maintain a temperature setpoint within the suit [Images from Ref. 23]*

Alternatively, it may be possible to capture metabolic heat using a separate device called a thermoelectric generator (TEG) and recycle the energy to supplement suit power needs. This process, called the Seebeck Effect, is the opposite of the Peltier electrocooler process. In a TEG, a temperature difference across two electrodes produces a voltage. Though they produce little power, TEGs also require no moving parts and can continually operate in an extreme thermal gradient, making them a strong candidate for EVA applications where the surface temperature of the human skin remains relatively constant at a much higher temperature than the surrounding environment and exterior surface of the suit[23]. As long as the cool side of the TEG is at a higher temperature than the environmental heat sink, heat would still be radiated away, keeping an astronaut cool. This radiation could also be modulated using variable emissivity radiator skins (as discussed in the next section).

When the external temperature exceeds the internal temperature inside the suit (as can be the case in direct sunlight on the Moon), the process would be reversed and the generator would be run as a cooler. The power requirements required to drive a network of TECs is unsustainable for a 6-8-hour EVA, but it could still act as an important safety factor in extreme hot case contingencies. It is also worth noting that a TEC can be run with a current in the opposite direction to drive it as a heater, thereby providing backup in case of extreme cold contingencies like a thermal leak in the suit. Currently, a TEG/TEC system would require a mass of about 22.3 kg, well above the 5 kg needed for the current water-cooling support electronics, but there are ongoing efforts to produce lighter and more durable variations of this technology, with some initial successes in flexible TEG substrates[23]. Major improvements in power efficiency will also be needed before this technology becomes competitive.

Additionally, much work remains to be done to qualify these components in space-like environments. All work so far has been first order modeling and approximation. It is also likely that a heat pump system may work more effectively in a Martian rather than lunar environment, as Mars lacks hot case heat sinks and has a small atmospheric convective effect to supplement radiative cooling.

Phase change materials (PCMs) have also been explored for cooling applications in a PLSS. In 2009, Paragon Space Development Corporation built and tested a proof-of-concept prototype cryogenic ice-pack cooler for integration into the EMU. A PCM system can absorb heat for later rejection between EVAs, offering the advantages of no consumables and operation independent of local environmental conditions. In this design, packs would be supercooled in a station or habitat and installed into the PLSS prior to egress to act as a heat sink for the duration of the EVA. A melted pack could swapped out after or midway through the EVA with a fresh, frozen pack. Paragon's PCM demonstrator is shown in Figure 8.

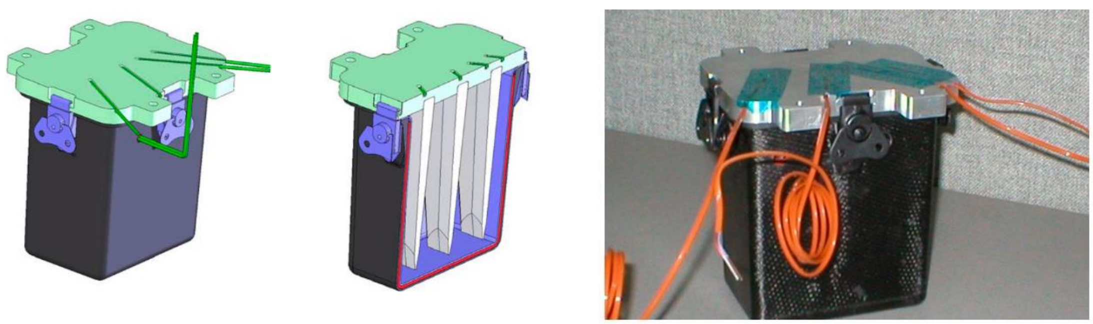


Figure 8. Cryogenic water ice phase change material heat sink demonstrator. *This proof of concept cooling pack is about 16.5 cm x 16.5 cm x 7.3 cm and contains about 1.85 kg of ice. The device includes a carbon composite shell, a foam liner to accommodate for thermal expansion and contraction, and metal fins for enhancing heat transfer [Images from Ref. 24]*

While swappable PCM packs would reduce overall water mass dedicated to thermal management for an extended lunar or Martian campaign, they are not currently mass competitive from an operational standpoint. The Paragon demonstrator was built to handle only 1/8th capacity of the heat loads from a 4-hour EVA. It is estimated that 20-25 kg of water ice would be required to provide cooling for an 8-hour EVA with an average heat load of 400 W. An additional 20-50 kg would be needed for PCM packaging based on current standards. This means that water ice PCM coolers are much too heavy to be the sole cooling source for a spacesuit[24].

C. Radiators

Radiators have been a component of each of the candidate technologies presented so far, but it may be possible to provide cooling using only a passive process. Spacecraft and robotic explorers already use radiators for heat rejection. Radiators reject residual heat via infrared (IR) radiation emitted by a surface exposed to a heat sink with a much lower temperature. These systems are "closed-loop" with respect to mass. Radiators typically provide a steady level of cooling, making them suboptimal for adapting to the dynamic heat loads of a spacesuit application. Additionally, surface area constraints on rigid structures such as the PLSS backpack limit the amount of cooling possible, as seen in the LCAR system[1,19]. However, recent technological developments have reopened the possibility of using a radiator-based approach for EVA thermal control.

Early work investigating the application of passive radiators for zero-consumable heat rejection led to the Chameleon Suit architecture, proposed in the early 2000s. With this approach the thermal control system was envisioned to allow for variable conductance between the skin surface and the surface of the suit using different lofting techniques. The surface of the suit allowed for further adjustment of the heat flow using variable electrochromic radiators along with mechanical modulating of the radiators using MEMS (microelectromechanical system) louvers. Technological advancements in the succeeding decades have made such a concept more viable, but it is still limited by an inability to remove heat when the sink temperature is close to or greater than the desired skin temperature, and it still requires battery power to operate[23,25].

Electrochromic materials may help the problem of environmental temperature variation by allowing for a variably-emissive surface. The optical properties of electrochromic films can be controlled electrically using an applied voltage[26,27]. New technology has also allowed these devices to be installed on a flexible substrate such as Kapton tape or polymer film. When a small bias voltage is applied, the material undergoes an oxidation-reduction reaction, and the surface's IR emission properties change. As shown in Figure 9, the layers of an electrochromic device (ECD) function similarly to the anode, cathode, and electrolyte in a battery[28].

Emissivity is measured on a scale of 0 to 1, where 0 indicated that no IR radiation is emitted (and no heat dissipated), while a 1 indicates that the device acts as an ideal black body and emits radiation at its theoretical limit. Technological demonstrations by Ashwin-Ushas Corporation and Eclipse Energy Systems have demonstrated variable emissive radiators with emissivity values that can be modulated from 0.19 to 0.90[29,30]. The energy emitted is governed by the Stefan-Boltzmann Equation:

$$Q_{rad} = \sigma A \varepsilon (T_s^4 - T_e^4) \tag{1}$$

Where σ is the Stefan-Boltzmann constant, ε is the emissivity, A is the exposed surface area, T_s is the surface temperature, and T_e is the temperature of the environment (heat sink)[1].

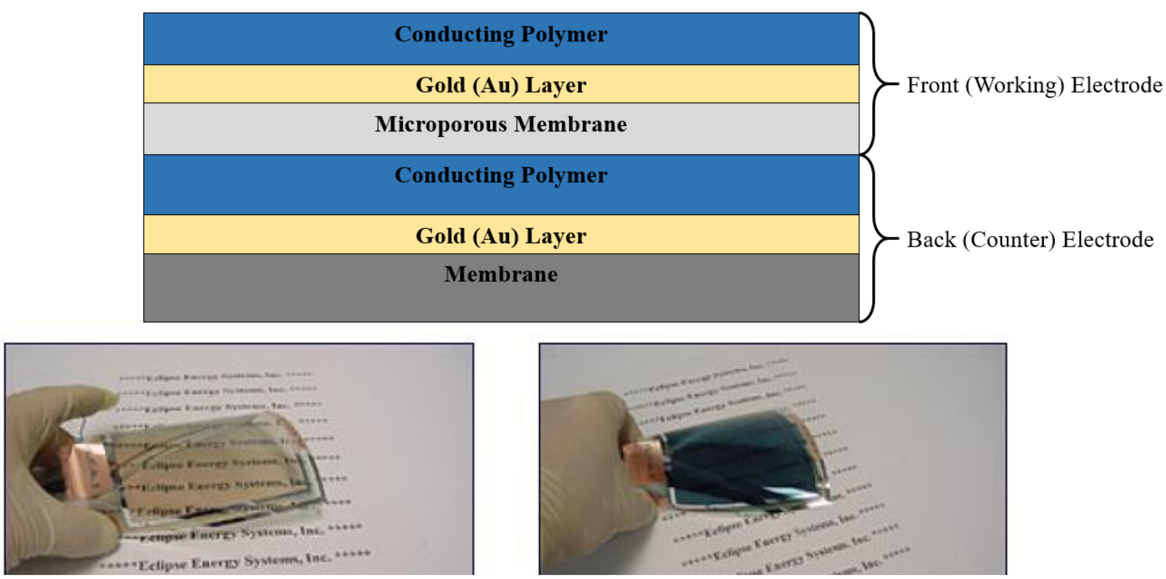


Figure 9. Flexible thin film electrochromic demonstration by Eclipse Energy Systems. *A small applied voltage can darken the color of the material and raise its thermal emissivity [Images from Refs. 28 and 30]*

Variable emissive radiative strategies are appealing due to the large spatial variations in surface temperature of both the human skin and the spacesuit surface. As shown in Figure 10, research in simulated Mars EVAs has shown that surface temperature on the suit may spatially vary by as much as 50°C depending on the astronaut's orientation relative to the sun, and atmospheric effects[4].

Research conducted so far has indicated that alternative heat management technologies such as electrochromic and perspiration pores could significantly offset or eliminate the need for water sublimation in a Martian EVA. Simulations have found that electrochromic radiators could have reduced sublimator water mass usage by 69% across the entire Apollo program, a savings of 68.5 kg[1].

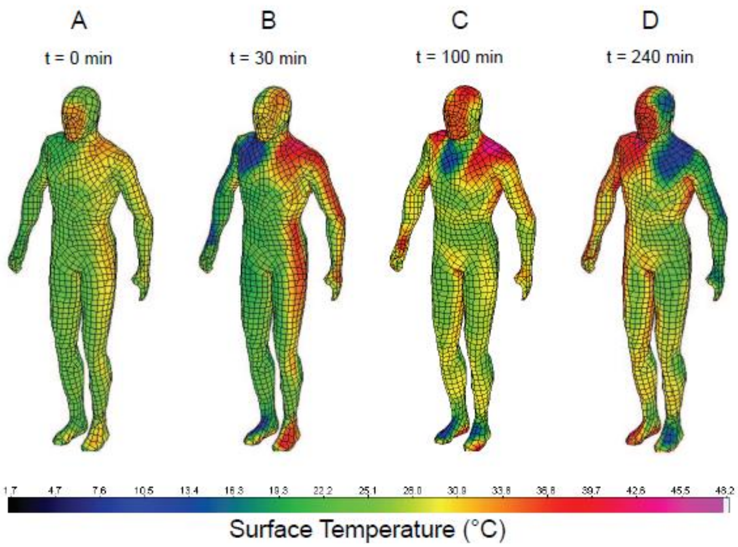


Figure 10. Heat output and suit surface temperature varies throughout a simulated Martian EVA. *[Image from Ref. 4]*

Another consideration is the available surface area to act as a radiator. Most concepts, including the SEAR-LCAR system, only utilize the PLSS shell, which has a surface area of ~0.85 m^2, which limits the total radiative power capacity. Preliminary studies have investigated the concept of using the entire suit surface area as a radiator. This effective area (excluding unexposed spaces like armpits for example) is about 3.9 m^2 for a gas-pressurized suit like the current EMU, or 1.53-2.28 m^2 for an advanced mechanical counterpressure (MCP) design, depending on body type. First order analyses have shown that passive radiation techniques using the full suit surface area could meet a baseline steady state of 300 W cooling power during a lunar EVA, but only in polar or otherwise partly shaded regions. Equatorial EVAs with a more direct incidence angle of solar radiation (and lunar surface reflection) would require additional powered cooling components[31]. This supports similar work simulating a Mars EVA with an MCP suit. It was found that passive radiator cooling by itself was not enough to prevent heat exhaustion by the end of a Martian EVA. If airflow into the helmet is not actively cooled, the headspace is an area of particular concern. However, a supplementary cooling system such as evaporative cooling or TECs would have kept all internal suit temperatures within an acceptable range[4].

Another problem to consider is the automatic controller needed for adjusting emissivity rates depending on human skin temperature. No design work has yet been done to build such a controller.

Less research has been done to refine the concept of internal lofting of pressure garment layers. This concept, proposed in the Chameleon Suit architecture[25], is shown in Figure 11. Implementing active shape change materials such as shape-memory alloys to vary the conductance of suit layers will require power, but little research has been done to develop the concept. It is more likely compatible with a mechanical counterpressure (MCP) suit design or a suit that uses thermoelectric heat transfer rather than traditional LCVG gas-pressurized suits including the EMU.

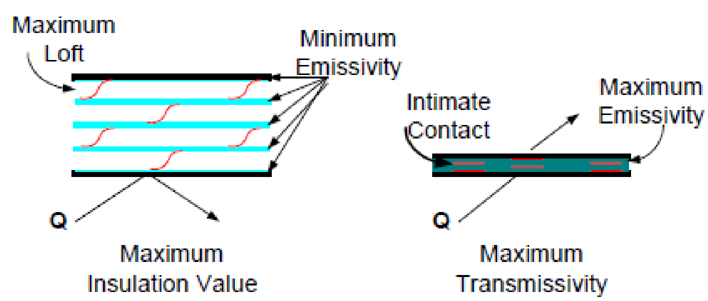
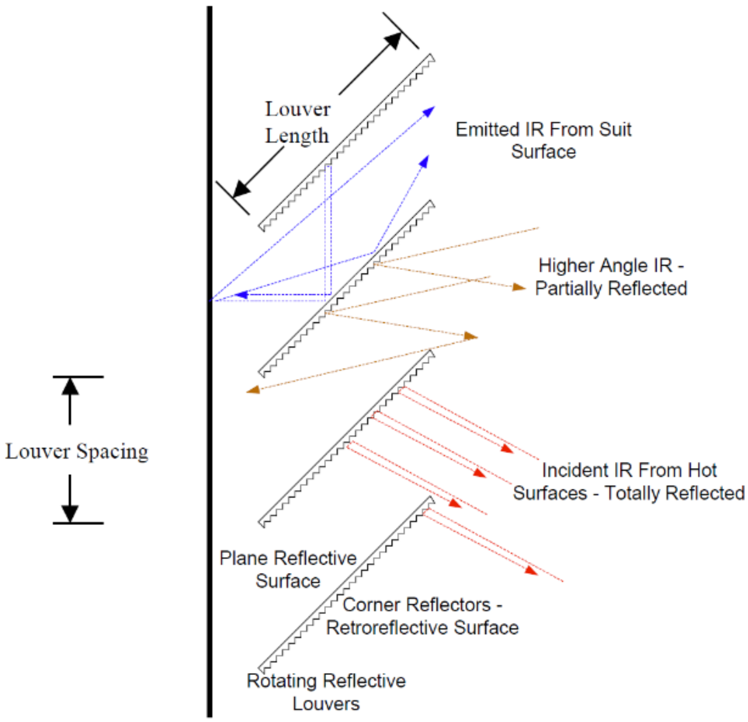


Figure 11. Concept of internal suit lofting for conductive heat transport control. Active shape change materials would alter suit insulation by extending or compressing the suit layers depending on heat rejection needs *[Image from Ref. 25]*



MEMS louvers are also a low TRL technology that would vary radiative capacity by altering the reflectance or absorbency of the suit by adjusting to the inclination angle of solar radiation and changing the exposed surface area. This directional shading concept is shown in Figure 12. This principle has been applied in spacecraft design, but not in a human spacesuit. In the Chameleon Suit concept, these louvers would be very small (~0.1 mm long and 0.04 mm wide), with cornered edges to increase surface area and reflect incoming radiation. The angle of the louver would be adjusted to match the incident angle of incoming radiation[25]. The most likely place to test this approach would be the PLSS shell. A rigid surface would provide the easiest platform to integrate MEMS controllers. Damage and impact tolerance for this concept as well as automatic control mechanisms are largely unexplored.

Figure 12. Concept of directional shading louvers on exterior suit surface. *Small corners reflect both emitted IR radiation from the suit incident IR and UV radiations from the environment back into space [Image from Ref. 25]*

IV. Discussion

Of the technologies discussed here, the SWME is at the highest TRL and is scheduled for an ISS payload flight test in 2019[15]. Proposals have suggested the SWME could be added onto the base of the current PLSS backpack, but this is not presently planned[18]. The SEAR/LCAR system is the state of the art for nearly closed-loop advanced thermal management on next generation spacesuits and could be tested and incorporated into the next generation of the EMUs that will be needed for the potential assembly of a Lunar Gateway station and return to the Moon in the mid to late 2020s. The use of radiators rather than sublimators for heat loss mean SEAR could also theoretically operate on Mars. While the LCAR can operate primarily closed-loop without venting water under ideal conditions, it still requires venting for high metabolic loads. Additionally, current concepts are only able to reject about 130 W of heat for five hours, given efficiency and PLSS surface area constraints[16]. This is less than the current goal of 250-300 W for 8-hour EVA[23]. Furthermore, the system will likely require an eventual redesign of the PLSS backpack housing because the SEAR system is currently too bulky to be practical addition. Another consideration is safety. Despite years of analysis and flight heritage, water used in the EMU suits has leaked into the crewmember helmet on two occasions during EVAs, posing a potentially disastrous risk to the crewmember[23]. The SWME bypasses the fan-pump-separator where the ventilation loop breakdown occurred in these accidents, but the LiCl solution used in the SEAR system has the potential to leak out corrosive salts if not designed properly.

NASA has the goal of accelerating the TRL of closed-loop membrane evaporators from Level 4 (component validation in lab environment) to Level 5 (component validation in relevant environment) within the next 5 years[7,32]. This development appears on schedule and is likely to play an important role in cis-lunar human space development. It remains to be seen whether components can be packaged in a reduced mass format to function efficiently during a planetary EVA. Another series of important tests include the fluid phase change behavior in micro and reduced gravity[19]. It is also an open area of research how the LCAR would integrate with an advanced MCP suit. Evaporator technology is likely to play a large role in spacesuit heat rejection for the next several decades, but ultimately a system with no water mass requirements is ideal for lightweight and efficient Mars exploration.

More research is required to scale heat exchangers and thermoelectrics enough to make the technology competitive in a spacesuit cooling trade. Current TECs and TEGs have such a large power demand that total system mass is likely to be greater than a water-cooling alternative. TECs have a rated TRL of 4, with a desired value of TRL 9 (successful flight proven operations), as they have uses in all spacecraft and habitat systems, not just spacesuits[7,32]. To reach this point, many more advances in materials science, electrical and chemical engineering, and nanotechnology and fabrication will need to be made.

Passive radiator concepts have the least technological heritage of the methods presented here. Variable-emissivity radiators (including electrochromics and thermochromics) currently exist at TRL 3 (analytical proof of concept). Much more work in electrochemical surface coatings, space environment qualification of terrestrial products, integration of flexible films or coatings into fabric materials, and turndown control algorithms must be accomplished before the technology reaches NASA's goal of TRL 9[7,33]. The same can be said of variable-geometry radiators (louvers). This concept currently exists at only TRL 2 (technology concept and application formulation), with a goal of TRL 7 (system prototype development in a space environment)[7,33]. Further research in MEMS and micro and nanofabrication may enable this technology to be incorporated into future spacecraft and spacesuit designs.

Due to lunar environmental conditions, it is likely that any EVA heat rejection system will require active cooling to respond to the extreme hot cases that occur in direct sunlight. Based on simulation, passive radiation alone cannot provide adequate cooling[1,9,31]. For this case, a water evaporator system that greatly reduces consumable mass will perform best. On Mars, the environmental heat sink does not reach such extreme highs, making passive radiator concepts much more appealing and realistic. Modeling work conducted so far suggests that the best system may rely primarily on adaptive radiation with thermoelectric cooling present as a backup for hot case contingencies[4,23].

For all technologies, there are many unanswered questions about integration with an advanced MCP suit, which will restrict the space available for cooling loops across the crewmember's skin. A trade study to compare the advantages and challenges of an MCP suit with respect to heat rejection methods would further inform which technologies and concepts warrant further study and development.

V. Conclusion

A review and analysis of current thermal management technologies shows that three main technological concepts—evaporators, heat exchangers, and radiators—offer the most potential for advanced EVA suit cooling. Of these, evaporative cooling technologies including the SWME, and SEAR with LCAR have the highest TRL and are next in line to be implemented in flight. Heat exchangers including TECs and TEGs will require improvements in scaling and power efficiency before they become practical in suit-cooling, but they offer flexibility and potential mass savings. Phase change materials can reduce consumable mass, but PCM systems studied for EVA cooling so far have been much too heavy for an astronaut to easily support. Advanced radiator concepts including variable-emissivity and variable-geometry radiators are currently at the lowest TRL. It is likely that these technologies will be implemented in spacecraft and habitat designs before spacesuits due to the challenges of "soft" spacesuit fabric materials. Radiators are likely to be a preferable technology for Martian EVA rather than lunar EVA, as Mars does not have ambient temperatures that exceed skin temperature. Radiators may ultimately offer the lowest mass and power demand of any of the heat rejection concepts discussed.

While current plans for the xEMU still include an LCVG with new auxiliary loop cooling, long term exploration sustainability will require improvements in spacesuit heat rejection efficiency. The xEMU is targeting a 2023 flight demonstration[34]. However, this demonstration suit is not currently planned to implement LCAR technology. Therefore, short term research should prioritize improving efficiency and making mass and volume reductions for closed-loop evaporative cooling.

For future lunar and Martian EVAs, it is very likely that active heat exchanging technologies including TECs and TEGs may be coupled with adaptive radiator concepts to provide adequate EVA thermal management at the lowest PLSS mass, improving astronaut safety, mobility, and productivity.

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