Space Evaporator Absorber Radiator (SEAR) for Thermal Storage on Manned Spacecraft

Michael G. Izenson,[1] Weibo Chen,[2] and Ariane Chepko[3]
Creare LLC, Hanover, NH

Grant Bue[4]
NASA Lyndon B. Johnson Space Center, Houston, TX

and

Gregory Quinn[5]
UTC Aerospace Systems, Windsor Locks, CT

Future manned exploration spacecraft will need to operate in challenging thermal environments. State-of-the-art technology for active thermal control relies on sublimating water ice and venting the vapor overboard in very hot environments, and or heavy phase change material heat exchangers for thermal storage. These approaches can lead to large loss of water and a significant mass penalties for the spacecraft. This paper describes an innovative thermal control system that uses a Space Evaporator Absorber Radiator (SEAR) to control spacecraft temperatures in highly variable environments without venting water. SEAR uses heat pumping and energy storage by LiCl/water absorption to enable effective cooling during hot periods and regeneration during cool periods. The LiCl absorber technology has the potential to absorb over 800 kJ per kg of system mass, compared to phase change heat sink systems that typically achieve ~50 kJ/kg. This paper describes analysis models to predict performance and optimize the size of the SEAR system, estimated size and mass of key components, and an assessment of potential mass savings compared with alternative thermal management approaches. We also describe a concept design for an ISS test package to demonstrate operation of a subscale system in zero gravity.

Nomenclature (Lynne, please alphabetize)

PCM	=	Phase-change material
SEAR	=	Space evaporator absorber radiator
LCAM	=	Lithium chloride absorber bodule
SWMX	=	Space water membrane exchanger
ECLS	=	Environmental control and life support
TCS	=	Thermal control system
LLO	=	Low Lunar orbit
PGW	=	Propylene glycol /water mixture
SHReD	=	Supplemental heat rejection device
EVA	=	Extravehicular activity

[1] Principal Engineer, 16 Great Hollow Road, Hanover, NH 03755.
[2] Senior Engineer, 16 Great Hollow Road, Hanover, NH 03755.
[3] Project Engineer, 16 Great Hollow Road, Hanover, NH 03755.
[4] Aerospace Technologist, 2101 NASA Parkway, Houston, TX, 77058/Mail Stop EC2.
[5] Staff Research Engineer, 1 Hamilton Road, Windsor Locks, CT 06096-1010/Mail Stop 1A-2-W66.

IFHX	=	Interface heat exchanger
BVAD	=	Baseline values and assumptions document
ISS	=	International space station
TEC	=	Thermoelectric cooler

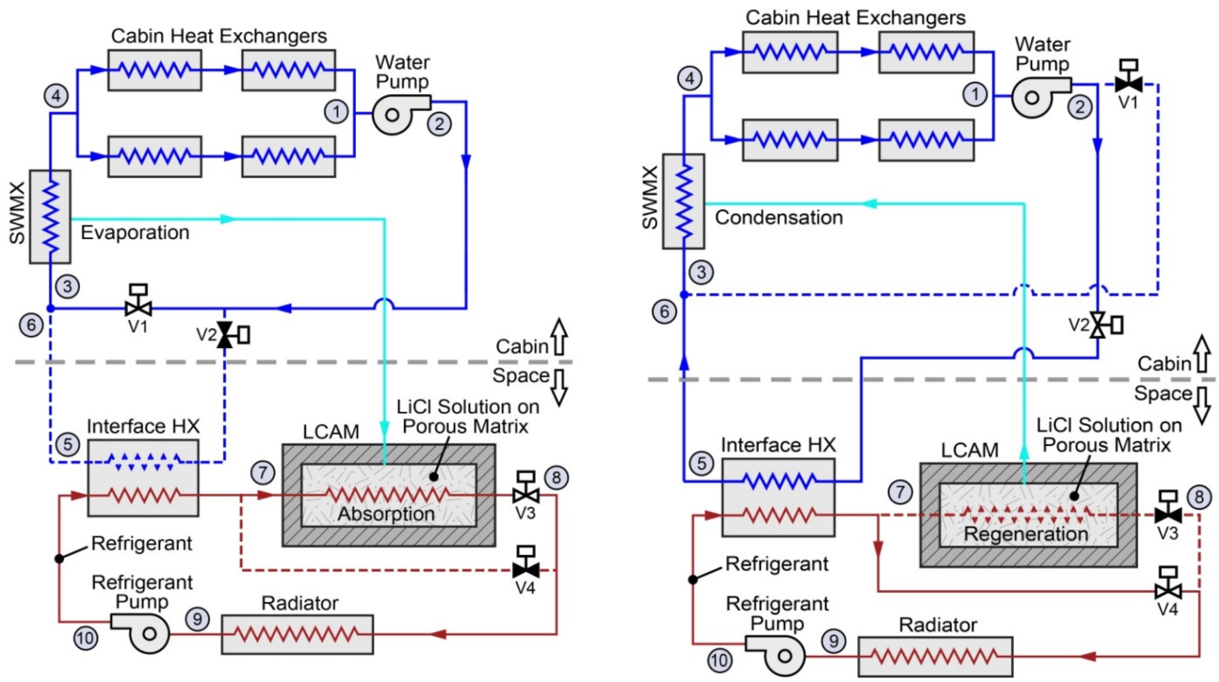
I. Introduction

Future manned exploration spacecraft must be designed to operate for long durations in extreme thermal environments. Repeated orbital cycling between hot and cold heat sink temperatures present severe challenges for spacecraft thermal control systems. Existing approaches to handle these large swings in heat rejection capacity include large radiators sized for peak loads, heavy heat sinks or phase change material (PCM) heat exchangers, or water-sublimators. These options lead to system designs that are heavy and/or vent a large amount of water to maintain controlled cabin temperatures. This paper describes an innovative thermal storage system based on non-venting space evaporator/absorber/radiator (SEAR) technology. The objectives of the SEAR system are to manage thermal loads in extreme environments and provide significant mass savings over traditional PCM heat exchangers and sublimators, enabling a large reduction in expendables (hundreds of kg for some missions).

The SEAR system uses evaporation, condensation, and absorption of water in lithium chloride solution to boost temperatures for heat rejection and to store thermal energy (Figure 1(a)). The SEAR system uses two novel components: a compact lithium chloride absorber module (LCAM) (Figure 2) coupled with a space water membrane exchanger (SWMX) (Figure 3). For cabin thermal control during high heat sink temperature conditions, cabin cooling water flows through the SWMX where it cools by evaporation and circulates back to the cabin heat exchangers. The evaporated water flows to the LCAM where it is absorbed by the lithium chloride (LiCl) solution in an exothermic process. The LCAM is cooled by the spacecraft's external cooling loop, in which circulating refrigerant picks up heat in the LCAM and cools in the spacecraft radiators. The LiCl solution in the LCAM is a very powerful desiccant and can absorb water vapor at temperatures that are 30°C warmer than the SWMX. As a result, the SEAR provides heat pumping and raises the radiator temperature to enable heat rejection from the spacecraft even when the radiation environment is very hot. During low-temperature heat sink conditions, the LCAM is regenerated by heating to drive the absorbed water back into the flow system and using heat stored in the LCAM to help maintain spacecraft temperatures (Figure 1(b)).

The components of the SEAR system are based on advanced technologies developed for spacesuit themral contlrol configured to create a spacecraft thermal control solution. The LCAM is built from modular components that build on the LiCl absorber radiator (LCAR) technology that has previously been integrated with the SMWE and undergone extensive ground testing (refs). A critical step to enable use of SEAR technology is testing in an operational microgravity and thermal environment. This paper describes the first step in a program to develop a conceptual design for a thermal management system for manned spacecraft based on the SEAR, conduct a ground test program that aims to develop and demonstrate the key SEAR components, design and qualify a flight test SEAR prototype, and finally demonstrate the SEAR prototype system onboard the International Space Station (ISS). The proposed ISS test will enable significant advancements in the SEAR TRL to support development of future spacecraft life support and habitation systems, in particular developing technology that will help enable a closed-loop Environmental Control and Life Support (ECLS) system.

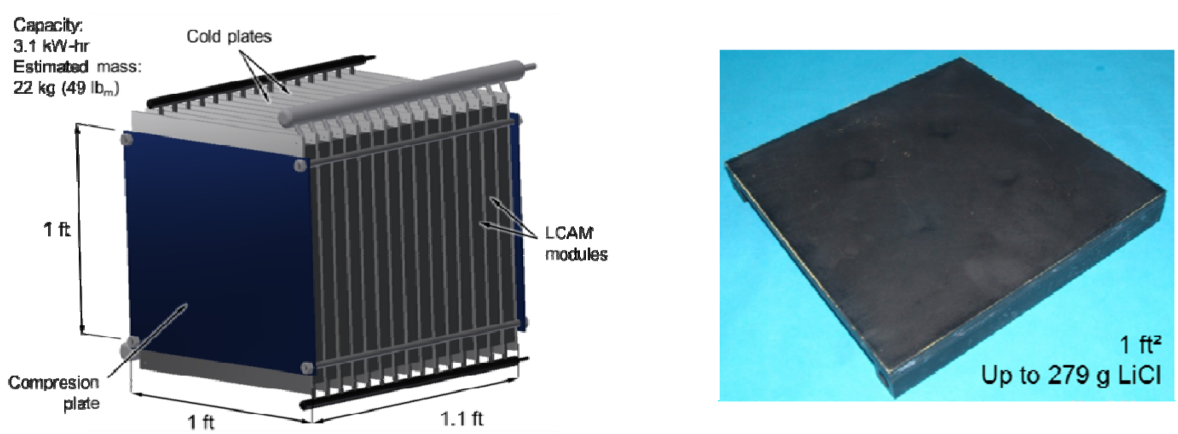
This paper focuses on the initial feasibility study, in which we developed a conceptual design for a spacecraft thermal management system that uses the SEAR to minimize ECLS size, weight, and use of consumables. Design requirements for the system were based on published information concerning future exploration spacecraft design and flight environments. We analyzed the performance of the SEAR system and sized the key components, then compared the size and weight of ECLS systems with and without the SEAR. We found that the SEAR system had the potential to reduce TCS mass by over 200 lb_m compared to a baseline system based on the Orion TCS. Based on this spacecraft system design, we produced a conceptual design for the ISS experimental package.



(a) Absorption Mode for Hot Radiation Environments

(b) Regeneration Mode for Cold Radiation Environments

Figure 1. Thermal Control System With Space Evaporator Absorber Radiator (SEAR) for Peak Loads in Hot Environments.



(a) Concept design for 3.1 kW-hr LCAM

(b) The LiCl absorber is assembled from modular units based on Creare's LiCl absorber/radiator technology

Figure 2. Lithium Chloride Absorber Module (LCAM) for SEAR Thermal Control System

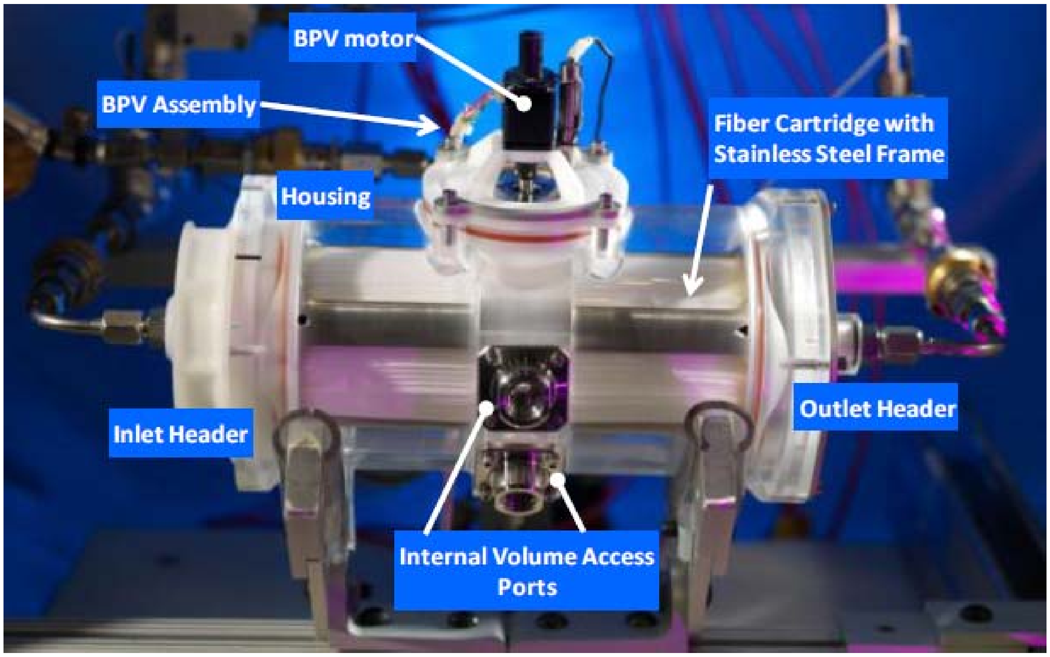


Figure 3. The Space Water Membrane Exchanger (SWMX) builds on NASA's SWME technology[6]

II. The Need for Improved Thermal Storage Technology

Future, manned exploration spacecraft must be designed to control cabin temperatures in extreme and highly variable thermal environments. Low Lunar orbit (LLO) is one of the key challenges, in which the heat sink temperature can vary from 60 to 300 K every ~2 hours (Figure 4). Spacecraft heat loads vary from ~5 to 6 kW. The thermal control system must maintain cabin temperatures in an acceptable range even under the most adverse conditions. Existing designs call for sublimators to reject heat by venting water vapor in hot environments.[7] The total amount of water vented overboard in these designs is quite large—over 200 kg for LLO operations, descent, and lunar surface operations.

The thermal control system for the Altair Lunar Lander represents state-of-the-art technology for the thermal control system. Figure 5 shows a simplified schematic. The system comprises an internal propylene glycol/water (PGW) loop coupled to an external loop that uses a freeze-tolerant refrigerant (R245a). The PGW loop collects heat from the cabin and airlock and transfers heat via an interface heat exchanger to the external loop. Heat is normally rejected from the external loop by radiation from the external R245a loop, but the PGW loop includes a supplemental heat rejection device (SHReD) to reject heat when the radiation heat sink temperature is very high. The SHReD comprises a pair of sublimators that reject heat by vaporizing water ice.

Another approach to thermal load-leveling that has been used on past space missions are PCM heat exchangers. The Lunar Rover Vehicle used wax PCM heat sinks to absorb heat during EVA sorties. A pentadecane wax heat sink was baselined for use on the Orion Crew Exploration Vehicle. Current state-of-the-art PCM modules can achieve a packing ratio of ~30% PCM within the heat exchanger structure.[8] The designs are challenged by the low thermal conductivity of most PCMs, requiring additional fins and features to accomplish effective heat transfer, and the additional structure required to accommodate the density changes of the materials between solid and liquid

---

[6] Bue, G., et al., "Long-Duration Testing of a Spacesuit Water Membrane Evaporator Prototype," 42nd International Conference on Environmental Systems, 15–19 July 2012, San Diego, California, AIAA 2012-3459.
[7] Stephan, R. A., "Overview of the Altair Lunar Lander Thermal Control System Design and the Impacts of Global Access," 41st International Conference on Environmental Systems, July 2011, Portland, Oregon, AIAA 2011-5001.
[8] Quinn, G., Hodgson, E. and Stephan, R., "Phase Change Material Trade Study: a Comparison Between Wax and Water for Manned Spacecraft," 41st International Conference on Environmental Systems, July 2011, Portland, Oregon, AIAA 2011-5229.

phases. Another limitation of PCM systems is that thermal control designs hinge around the phase change temperature of the material. Finally, the relatively low energy storage capability of liquid/solid phase change limits the energy storage density of PCM heat exchangers. For example, the latent heat of the solid-liquid transition for pentadecane wax is 162.8 kJ/kg. With a 30% PCM-to-system mass fraction, a pentadecane heat sink provides ~48.8 kJ of heat absorption per 1 kg of system mass, which is about 1/50th the heat of evaporation of water (and roughly an order of magnitude lower than projected for the LCAM).

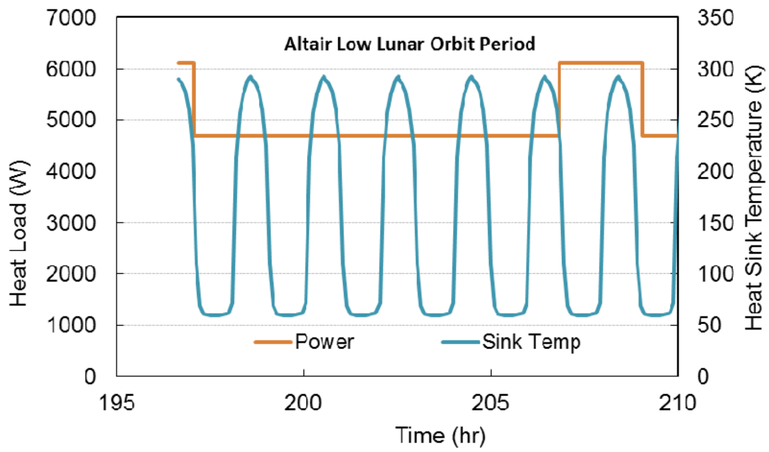


Figure 4. Typical Thermal Environment and Heat Rejection Requirements for Lunar Exploration Spacecraft.[7]

III.

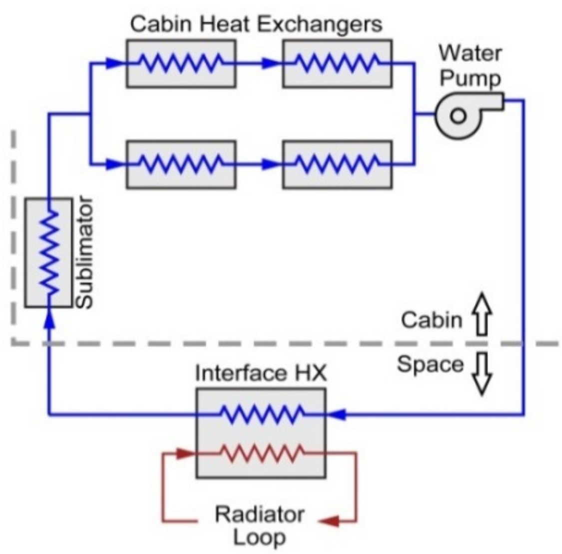


Figure 5. Simplified Schematic of Thermal Control System for a Space Exploration Vehicle

IV. SEAR Thermal Storage Based on LiCl/Water Absorption

The SEAR system will provide future spacecraft with a compact and efficient way to store heat, control temperatures, and reject heat in hot environments without venting water overboard. It offers significant advantages over other thermal control approaches by using LiCl as an energy storage medium, taking advantage of water's very high heat of condensation and solution. Compared to thermal storage in paraffin, the LiCl absorber can provide over an order of magnitude improvement in energy storage density (kJ/kg).

Lithium chloride (LiCl) solutions are a powerful desiccant with a much lower vapor pressure than pure water at the same temperature. The SEAR system exploits this phenomenon and builds on prior hardware demonstrations to enable chemical energy storage and heat pumping to help reject spacecraft heat to hot environments.

Basic Principle of Operation. Figure 6 shows equilibrium properties of LiCl/water solution, including pure water (0% concentration), and Figure 7 illustrates the basic absorption and regeneration processes used in a SEAR TCS. Figure 6 shows, for example, that the vapor pressure of 20°C water in the SWMX will be greater than the vapor pressure of 40% solution in the LCAM, even if the LCAM temperature is 50°C. The equilibrium temperature difference is even higher for more concentrated solutions. Therefore, water vapor generated in the SWMX will flow to and be absorbed in the LCAM even when the LCAM is considerably hotter than the SWMX.

To regenerate the LCAM, heat must be added to drive water vapor out of solution. The water vapor produced during regeneration condenses in the SWMX (Figure 7). Regeneration is typically performed at a relatively high temperature (up to 120°C), mainly due to kinetics inside the absorber. Evaporation of water results in high LiCl concentrations near the vapor/solution interface that exceed the solubility limit. Temperatures must be high enough to enable water diffusion through the thin solid layer.

Prior papers (refs) describe the SWMX, which comprises a bundle of porous, hydrophobic hollow fibers built into a shell-and-tube configuration. Liquid water flows inside the fibers and water vapor fills the shell side. The pores in the fiber walls are very small and capillary forces prevent the liquid water from seeping out. The open area fraction of the fiber surface is very high (typically 40%) and provides a very large contnact area between the liquid inside the tubes and the vapor in the SWMX shell. As a result, the liquid and vapor in the SWMX equilibrate and the unit can function as either an evaporator or condenser depending on the pressure of the vapor relative to the vapor pressure of the water in the fibers. Note that operation of the SWMX in condensing mode has not yet been demonstrated and will be a key element of future development.

SEAR Integration With a Spacecraft Thermal Control System. An LCAM can be used as part of a SEAR system to enhance heat rejection from a spacecraft thermal management system as shown in Figure 1(a) and 1(b). Figure 1(a) shows how the SEAR provides heat pumping in a hot environment. In this mode, valves V1 and V3 are open and valves V2 and V4 are closed. Warm water from the circulating pump flows through the Space Water Membrane Exchanger (SWMX) and cools by evaporation.[9] The water vapor produced in the SWMX flows into the LCAM's absorber bed, which operates at a temperature roughly 30°C warmer than the SWMX outlet. The heat generated by condensation and absorption in the LCAM is absorbed by the refrigerant loop that flows through the spacecraft's external radiators. Because the LCAM temperature is substantially higher than the cabin, operating in this mode enables the spacecraft to reject its heat in very hot environments without venting water or using heavy PCM-based thermal storage units.

Figure 1(b) shows how the LCAM regenerates during periods when the spacecraft is in a very cold thermal environment. During regeneration, valves V1 and V3 are closed and valves V2 and V4 are open. Warm circulating water from the cabin flows through the radiator interface heat exchanger, where it cools to a relatively low temperature (as close as practical to 0°C) due to the cold thermal environment. At the same time, heat is added to the LCAM to evaporate water and reduce its concentration in preparation for the next absorption phase. Vapor from the LCAM flows to the SWMX, where it condenses into the circulating water through the pores in the hollow fibers. Condensation heats the cold circulating water back to a suitable temperature for cooling the cabin.

[9] The SWMX functions as an evaporator (SWME) during absorption and as a condenser (SWMC) during regeneration.

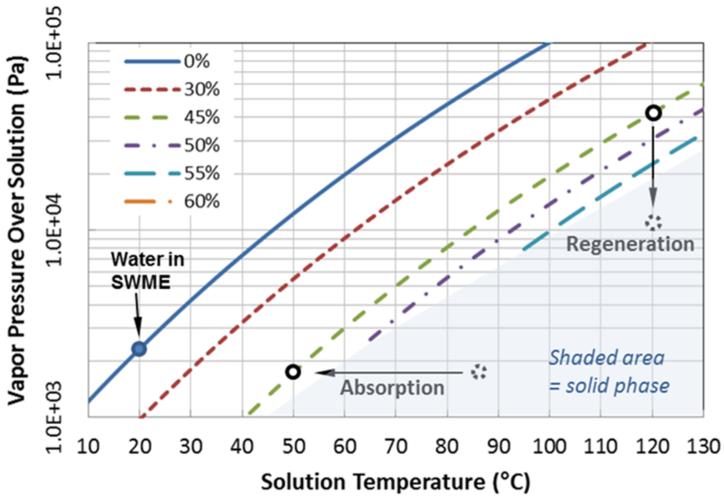


Figure 6. LiCl is a Powerful Desiccant that Enables the Absorber to Operate 30°C or More Warmer Than the Evaporator.[10]

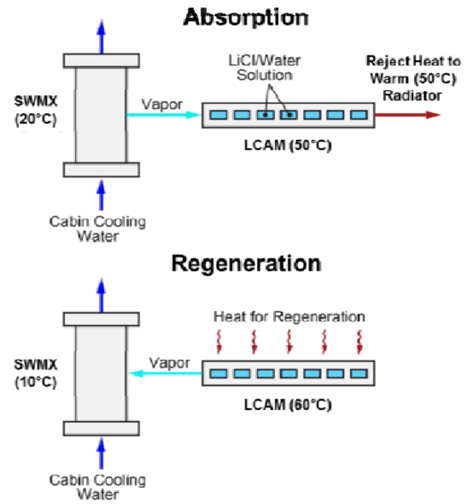


Figure 7. Absorption and Regeneration in a SEAR TCS.

Adopting a SEAR-based thermal control system does not need to remove any of the current capabilities that are built into existing designs. For example, if the SWMX is isolated from the LCAM, then the system will operate just like more conventional systems: the water circulating loop will transport heat from the cabin and external heat exchangers to the interface heat exchanger to transfer to the refrigerant loop and radiation to space. Also note that the SWMX could be equipped with a vacuum vent, enabling the system cool by venting in the event of beyond-design heat loads in a hot environment.

Using the LLO as an example, we can see that the SEAR mass will be very small compared to the potential savings in vented water mass. The TCS system described by (ref) requires venting about 1.7 kg of water per orbit.[11] Our mass estimate for a non-venting LCAM system sized for LLO is 22 kg (Section 5). NASA reports that a SWME capable of 800 W of cooling has a mass of about 1.8 kg, so the mass of a 6 kW SWMX would be about 14 kg. Therefore, the mass of the primary components in the SEAR system will be about 36 kg, which is much smaller than the 115 kg of water that would be vented from sublimators during LLO operations.

V. Modeling and Design of a SEAR Thermal Control System

We have shown the feasibility of a SEAR-based TCS for manned spacecraft through system design, performance analysis, comparison of overall system mass with more conventional technologies, and concept design for an ISS flight experiment. We formulated design models that enable us to predict the performance of a SEAR TCS in a time-varying thermal environment. We used these models to analyze performance of the SEAR TCS in LLO and calculated the key parameters needed to size the system. The system maintains cabin temperatures in an acceptable range without the need for PCM thermal storage or venting water. Based on the specifications for the TCS, we developed a conceptual design for an LCAM sized for a manned spacecraft in LLO. The LCAM is built from modules that can be demonstrated at smaller scale. We compared the predicted mass of the SEAR TCS with the mass predicted for a baseline TCS sized for the Orion spacecraft, and found that mass savings greater than 200 lb_m are possible. Finally, we developed a conceptual design for an ISS flight experiment to demonstrate operation of a SEAR system built using prototypical LCAM modules.

A. Design Models

The SEAR TCS design model predicts TCS temperatures, heat transfer, and water transfer as a function of system design parameters, the external thermal environment, and key operating parameters like cabin coolant and

[10] "1997 Fundamentals Handbook," American Society of Heating, Refrigeration, and Air Conditioning Engineers.
[11] Stephan, R., "Overview of the Altair Lunar Lander Thermal Control System Design and Impacts of Global Access," 41st International Conference on Environmental Systems, July 2011, Portland, OR, AIAA 2011-5001.

radiator loop flow rates. The design models are based on a first-order thermodynamic analysis of the heat and mass flows in the system schematic illustrated in Figure 1. Table 1 summarizes the design model inputs and outputs along with the values used for simulation operation in LLO.

Table 1. Design Model Inputs and Outputs	
INPUTS	
Sink Temperature Profile Over One Orbit Period (Temperature vs. Time)	60–290 K (for LLO)
Cabin Heat Load	4,800 W
Cabin Inlet Temperature (target)	10 C
Cabin Inlet Temperature (maximum excursion)	18 C
Cabin Outlet Temperature	28 C
Radiator Area	30 m^2
Radiator Fluid	HFE-7,000
Radiator Emissivity	0.9
Effectiveness of LCAM Heat Exchanger	0.9
Concentration of LiCl	>0.46
OUTPUTS	
System Temperatures	
System Heat Transfers: -Heat Rejected Via Radiation -Heat Required for Regeneration -Heat of Absorption of LiCl	
System Flow Rates: -Cabin Water Loop -LCAM / Radiator Loop	
Mass of Water Absorbed/Desorbed in LCAM	

Key assumptions. The model is based on assumptions related to LiCl properties and some elements of TCS hardware.

- *LiCl Properties*. The model computes the system temperatures and heat balances at each point in the orbit. It assumes that the system equilibrates at a time scale that is short compared to the orbital period, so it operates at essentially steady state for each sink temperature. The model also assumes that the LiCl solution concentration remains in equilibrium in the monohydrate, crystalline state and is greater than ~0.46. This corresponds to an equilibrium vapor pressure lower than the water in the SWME at 10°C. Over the course of the absorption cycle, the vapor pressure over the mostly solid LiCl can be assumed to be constant. Rate limitations due to diffusion of water into the LiCl solution were not included in this analysis; we assume that LCAM has been designed with enough vapor/absorber contact area for rapid diffusion, based on our past experience with these systems. Because available correlations of the enthalpy of absorption of water into LiCl are not valid beyond the crystallization line, the heat of absorption was assumed to be 17% of the heat of condensation, based on the maximum absorption enthalpy at higher temperatures on the crystallization line.
- *Spacecraft Hardware*. The LCAM heat exchanger that transfers heat to the spacecraft's external refrigerant loop is modeled as a condenser with an effectiveness of 0.9. For simplicity, we calculated radiation heat rejection using an average radiator temperature assumed to be the mean of the radiator fluid hot and cold temperatures.

Calculation Methods. For each point in the orbit sink temperature profile, the SEAR system is determined to be in one of three operating modes, as summarized in Table 2. System flow rates, temperatures, and heat transfer quantities are determined at each time step in the orbit.

- *Absorption Mode*: During absorption mode, the model uses an optimizer to determine the minimum flow rate in the radiator loop that will achieve all of the system heat rejection requirements (the cabin heat load and the LiCl heat of absorption). As the sink temperature rises, the radiator flow increases to raise the average radiator temperature, up to a user-supplied maximum flow rate (20 LPM in the LLO scenario). At the maximum radiator loop flow rate, if the system cannot meet the heat rejection requirements, the cabin inlet temperature is allowed to increase. By increasing the cabin inlet temperature (and therefore the vapor pressure in the SWME and LCAM), the LCAM solution temperature and average radiator temperature can increase to achieve the needed heat heat rejection rates.

- *No SEAR Mode*: As the sink temperature drops and the LCAM absorption is no longer needed to achieve cooling, the system switches into a "normal" operating mode, where the cabin heat load is rejected via the IFHX to the radiator loop. At each sink temperature, the available extra cooling capacity of the radiator is determined, and when sufficient capacity exists, heat is applied to the LCAM to begin regeneration.
- *Regeneration Mode*: The total time of the orbit that is spent with a sink temperature low enough to regenerate the LCAM is determined and used to calculate the average input power needed for LCAM regeneration. In the LLO scenario, more time is available for regeneration than is needed for absorption, thus the average thermal power input for regeneration is lower than the average heat absorption power. Once the extra cooling capacity of the radiator exceeds 100 W, the LCAM regeneration rate is ramped up according to the available capacity. The temperature of the water loop exiting the IFHX is constrained to be greater than 4°C to prevent freezing. To absorb the heat of condensation in the SWMX and maintain a cabin inlet temperature of 10°C, the cabin loop flow rate must increase. The rate of water evaporation from the LCAM is calculated based on the average thermal power needed for regeneration.

  As the sink temperatures drop, the flow rate in the radiator is either (1) maintained in balanced flow with the IFHX, which allows the average radiator temperature to drop; or (2) increased to limit the radiator exit temperature from dropping below -5°C to prevent freezing the water side of the IFHX. Increasing the radiator loop flow rate means the average radiator temperature is higher than necessary to reject the full heat load (cabin and LCAM regeneration heat), and over-cooling would occur. Allowing the radiator temperature to drop to remain balance with the heat load may lead to cold radiator exit temperatures (-20°C).

Table 2. SEAR Operating Modes

Mode	Use	SEAR Operation
Absorption	T_{sink} > 250 K	SWMX: Evaporates water to chill cabin circulating loop from 28 to 10°C LCAM: Absorbs water at ~50°C, concentration falls Radiator loop: Rejects heat at ~40–50°C
Regeneration	T_{sink} < 170 K	SWMX: Condenses water at 10°C to control cabin temperature LCAM: Electrically heated. Desorbs water at 70°C, concentration rises Radiator loop: Rejects heat at 22°C
No SEAR	170 K < T_{sink} < 250 K	SMWX : Absorption is finished, but environment not cool enough to enable regeneration. Cabin water loop rejects heat through IFHX. Radiator Loop: Rejects cabin heat load at ~15°C

B. Predicted Performance of SEAR in LLO

We analyzed the performance of a manned spacecraft in LLO using our SEAR TCS analysis models. We found that the SEAR TCS can control cabin temperatures within acceptable bounds without the need for additional thermal storage or water venting.

The radiation heat sink temperature during one period of the Altair LLO is shown in Figure 8. With the spacecraft parameters listed in Table 1, the normal heat rejection mode cannot reject the cabin load above a heat sink temperature of 250 K, setting the point when Absorption Mode with the SEAR system must be activated. The thermal control system design requirements used in the SEAR analysis were based on the Orion TCS specifications and generalized requirements for spacecraft thermal control. The key requirements were to:

- Reject a cabin heat load of 4,800 W.
- Maintain the cabin inlet temperature at 10°C when possible, with a maximum excursion to 18°C.
- During regeneration, maintain water outlet temperature of the IFHX ≥ 4°C to prevent freezing.

Additional constraints and parameters were imposed to ensure physical feasibility, narrow the design space, and balance competing performance goals. These include:

- Selecting a cabin exit temperature of 28°C. This parameter defines the flow rate through the cabin heat exchangers during absorption mode, but has little effect on the system performance. A value was chosen that has a heat capacity close to the Orion baseline radiator loop flow for operation in the No SEAR Mode with the IFHX. The value of 28°C reflects cooling of electronics and other loads that can operate at warmer temperatures.
- Limiting the maximum radiator flow rate to ≤ 20 L/min. The Orion baseline flow rate is 3.3 L/min. Higher radiator flow rates allow for higher radiator temperatures and greater heat rejection but consume additional pumping power.
- Limiting the minimum radiator exit temperature to ≥ -5°C to prevent freezing the water side of the IFHX. This results in higher-than-needed radiation at the lowest sink temperatures.

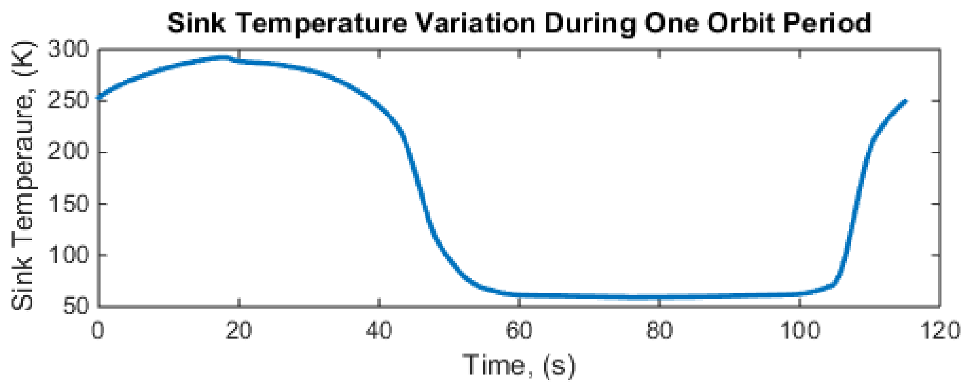


Figure 8. Altair LLO Sink Temperature Profile for One Orbit Period

Figure 9 and Figure 10 show the predicted thermal performance and required flow rates in the SEAR-TCS in LLO. During Absorption Mode, the SEAR system is able to reject the full cabin heat load within the specified temperature and flow constraints. As the system switches out of Absorption Mode, there is a short period when the regeneration heat ramps up to full power (while the sink temperature drops to provide more heat rejection capacity). Achieving full heat rejection at the highest sink temperatures requires that the system operate with a high radiator flow rate (at the 20 LPM maximum) and allowing the cabin inlet temperature to rise from the target goal of 10°C up to 17°C. Figure 12 shows the cabin inlet temperature variation required during Absorption. The small increase in cabin flow during the cabin temperature excursion (from 10–30 mins) is an effect of performing the calculations assuming a constant cabin outlet temperature—alternatively, the outlet temperature could increase and the flow rate remain constant. The flow rate in the radiator loop increases from the No Sear Mode to ~12 L/min during regeneration to maintain an outlet temperature of -5°C.

The total mass of water absorption in the LCAM that is required to achieve the heat rejection performance is 4.5 kg. Figure 12 shows the rate of water absorption and desorption in the LCAM during one orbital period. Because more time is available for regeneration in the LLO scenario than is required for absorption, the average regeneration power (and evaporation rate) is lower than the heat of condensation during Absorption Mode.

Figure 13 and Figure 14 show the system state temperatures as the sink temperature varies during Absorption Mode and Regeneration Mode, respectively. (Ariane, instead of showing all the state point temperatures in this format, it might be better to pick a few key temperatures and plot them along with the cabin inlet temperature as in Figure 13: SWMC inlet, cabin outlet, average radiator, anything else?)

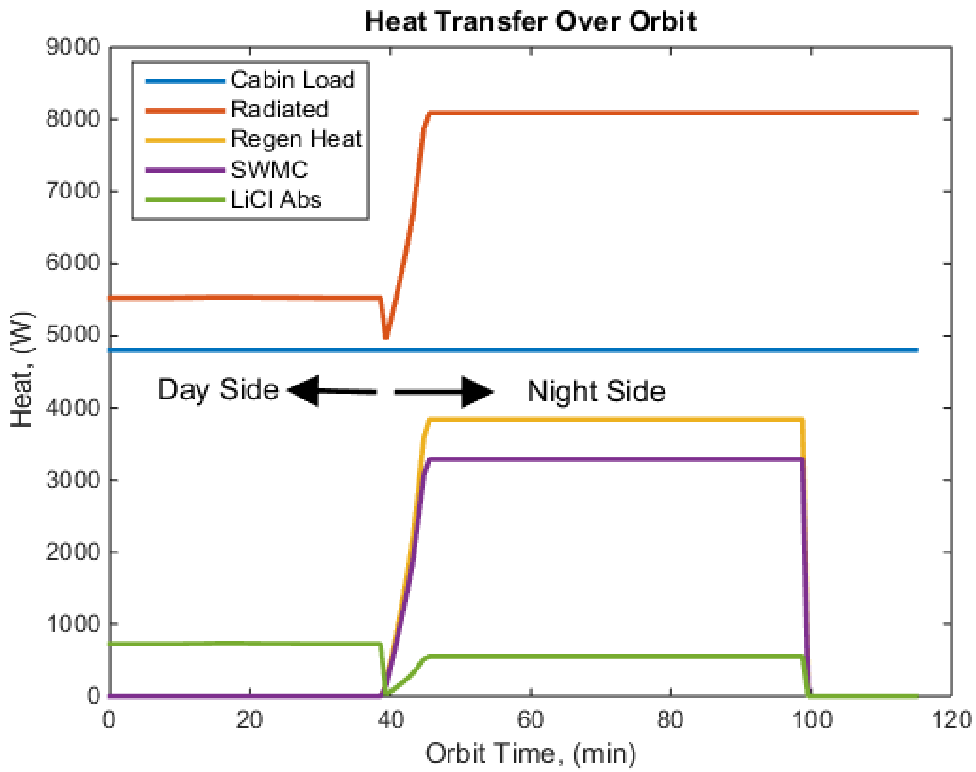


Figure 9. Thermal Performance of SEAR System Over One Orbit Period in LLO

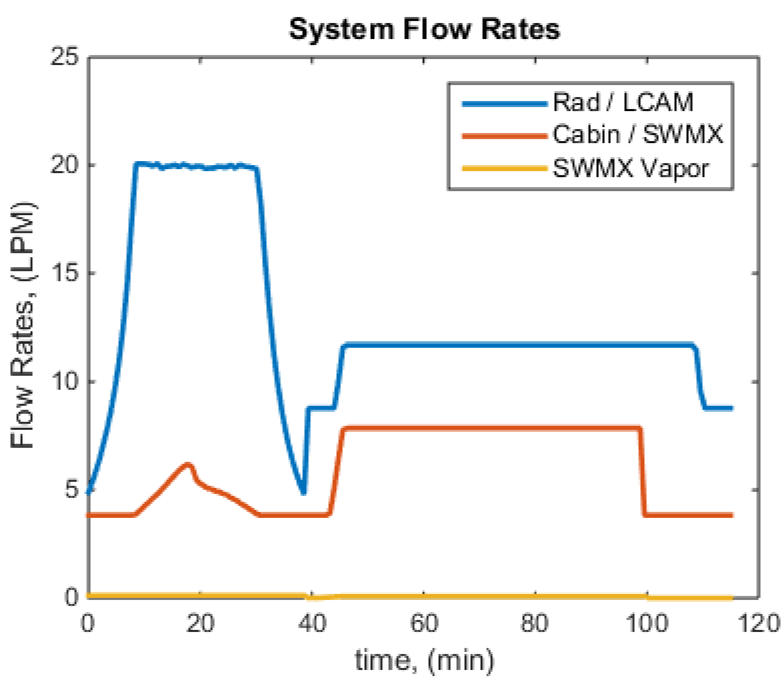


Figure 10. Flow Rates in SEAR TCS System Over One Orbit Period in LLO

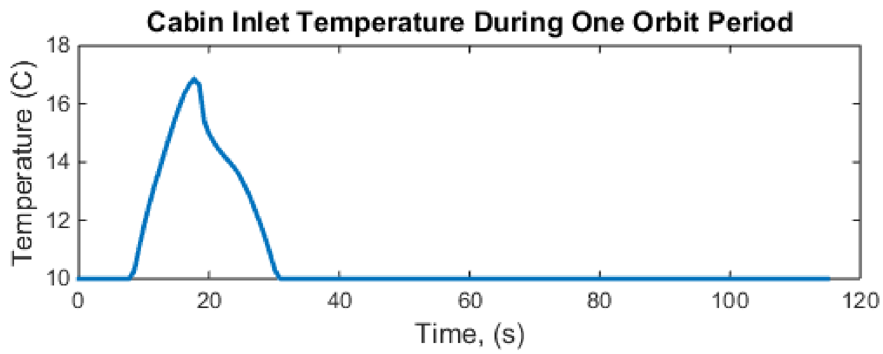


Figure 11. Variation in Cabin Inlet Temperature at the Highest Sink Temperatures (T_{sink} ≥278 K)

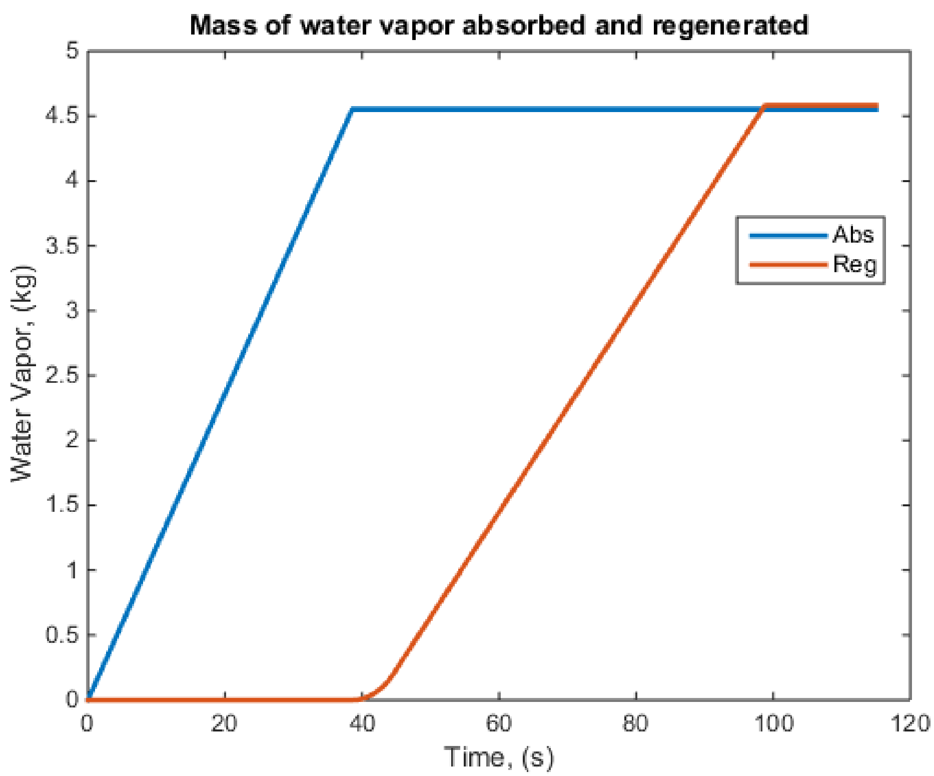


Figure 12. Water Vapor Absorption and Regeneration from LCAM Over One Orbit Period in LLO

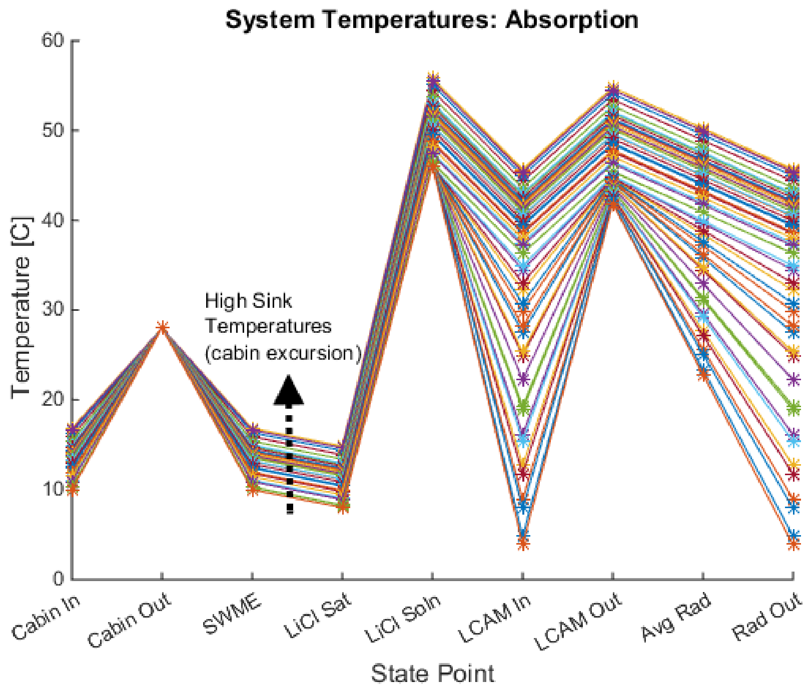


Figure 13. System Temperatures during Absorption With Varying Sink Temperatures

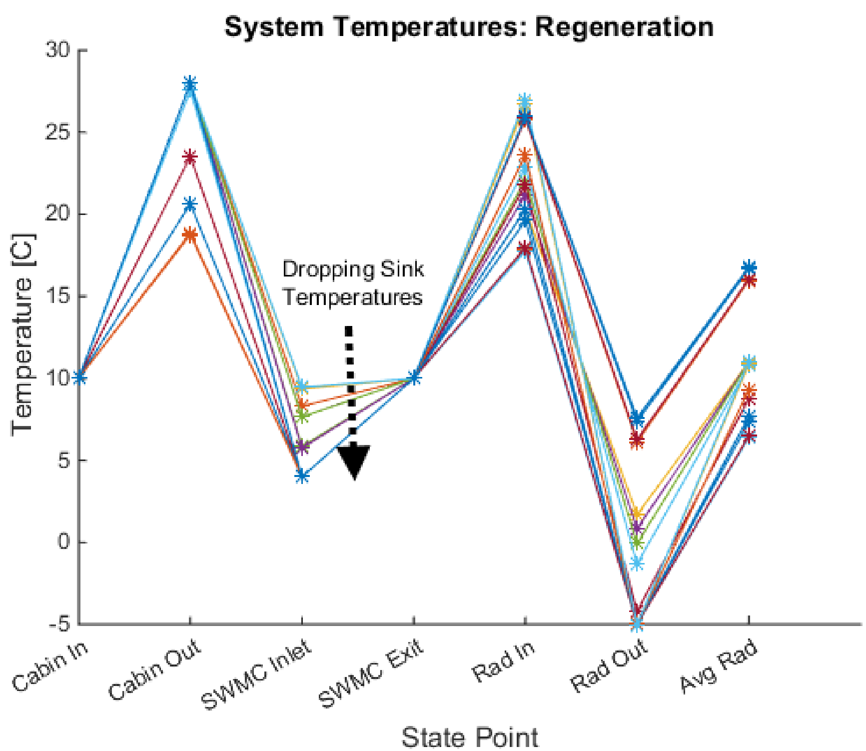


Figure 14. System Temperatures during Regeneration With Varying Sink Temperatures

C. Design of a Spacecraft LCAM

We have developed a conceptual design of an LCAM sized to meet the performance requirements for future manned exploration spacecraft that must operate in LLO. The design is scaled up from Creare's LiCl Absorber/Radiator (LCAR) technology, with modifications designed to enable rapid (one hour) regeneration. The design comprises an assembly of identical modules, which will enable testing and demonstration of prototypical modules at a small scale that could be suitable for demonstration flight testing on the space station.

Module Design. Figure 15 illustrates the overall design of a single LCAM module. Each module consists of a graphite shell that encloses an array of absorber sponges. The graphite shell comprises a cover plate and a pin plate. The pin plate is machined with an array of honeycomb cell features for strength and an array of pins perpendicular to the heat transfer surface. The pins provide a low-resistance path for heat to conduct from the absorber sponges to the heat transfer surface. The cover plate is machined with a regular array of embossments that line up with about 1/3 of the heat conduction pins. When the cover plate is bonded to the pin plate, the perimeter forms a seal and the pin bonds provide internal strength to support the plates against pressure loads.

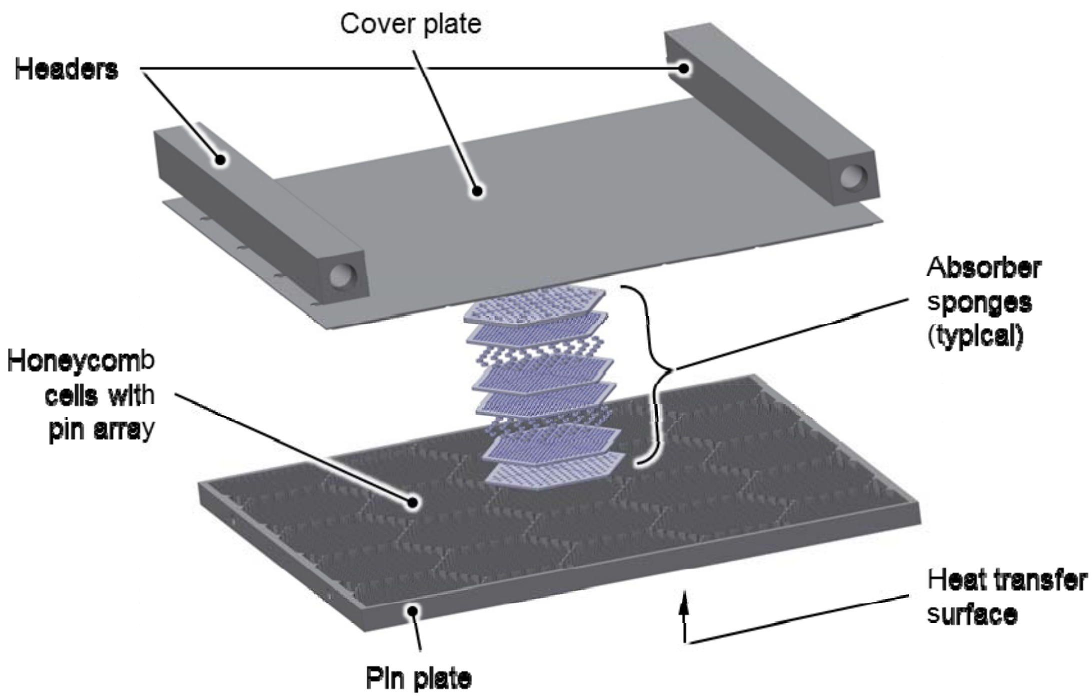
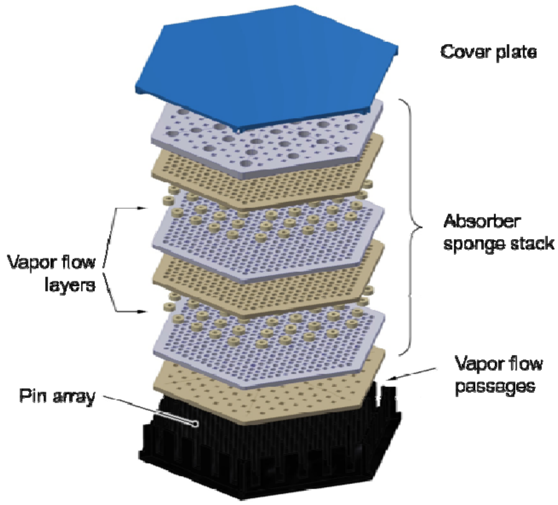
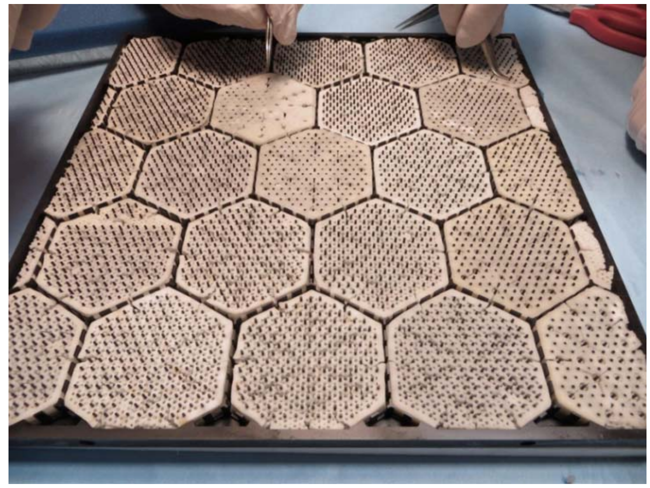


Figure 15. Basic Construction of a LiCl Absorber Panel

Figure 16(a) shows details of a single honeycomb cell in the LCAM. The sponges are made to fit inside the honeycomb cells and are designed with an array of flow passages and mounting holes. They are installed in the pin plate by aligning the mounting holes with the pin array. Several of the sponge layers comprise an array of small "washer" sponges that leave space for water vapor flow between the larger sponges. The walls of each honeycomb cell are made with castellations that enable water vapor to flow laterally between adjacent honeycomb cells. Figure 16(b) shows a honeycomb LiCl absorber/radiator during assembly, with all sponges installed but before the cover plate has been bonded.



(a) Absorber sponge stack-up enables vapor flow throughout the module.



(b) 1 ft² honeycomb absorber panel during assembly.

Figure 16. Design of LCAM Internals

Overall Size and Shape of a Spacecraft LCAM. Figure 2(a) has illustrated the overall size and shape of an LCAM designed for a SEAR TCS sized for the Orion spacecraft in LLO. Based on the current design of Creare's LiCl absorber radiator (LCAR), one 1 ft × 1 ft absorber module in the LCAM can hold roughly 280 g of LiCl. To absorb the 4.5 kg of water that must evaporate during the hot portion of each orbit for cabin cooling requires 16 of these panels. The LCAM design calls for 16 absorber modules stacked with alternating cold plates. Refrigerant flows through the cold plates to absorb heat generated by water vapor condensation and absorption in LiCl solution. The cold plates and LCAR are held in thermal contact by compression plates and tie rods that provide axial compression force. Thermal interface material such as Grafoil will be used to minimize thermal resistance between the cold plates and the absorber modules.[12] The structure is fault tolerant and cannot leak refrigerant into the SEAR system due to a single leak in either the absorber modules or the cold plates. Each LCAM module is thicker than the current design LCAR in order to provide more vapor/solution contact area for rapid regeneration (as described later).

LCAM Mass Calculation. Table 3 shows the mass calculation for the LCAM. The amount of LiCl needed is based on an assumed concentration swing from 45% to 90% for each orbital cycle and a total water absorption capacity of 4.5 kg. The amount of LiCl needed in this case is then 0.45 kg. The "dead water mass" is the amount of water that stays permanently in the LCAM at the end of a regeneration cycle when the concentration peaks at 90%. The mass of graphite structure is estimated from the current design of Creare's LCAR. The mass of the water vapor headers is computed as a fraction (10%) of the module mass, and the cold plate ("coolant passage") mass was estimated by UTAS as part of their mass comparisons based on their past experience designing and building spacecraft heat exchange equipment.

The table shows that adding together all the elements of the LCAM results in a total mass of 21.9 kg (48.2 lb_m). The energy absorption capacity of the unit can be computed from the energy equivalent of 4.5 kg of water (3.1 kW-hr). The absorption capacity of the LCAM is then 515 kJ/kg, which is roughly an order of magnitude larger than can be achieved in a typical PCM heat exchanger.

Table 3. Calculation of LCAM Mass for Manned Spacecraft TCS

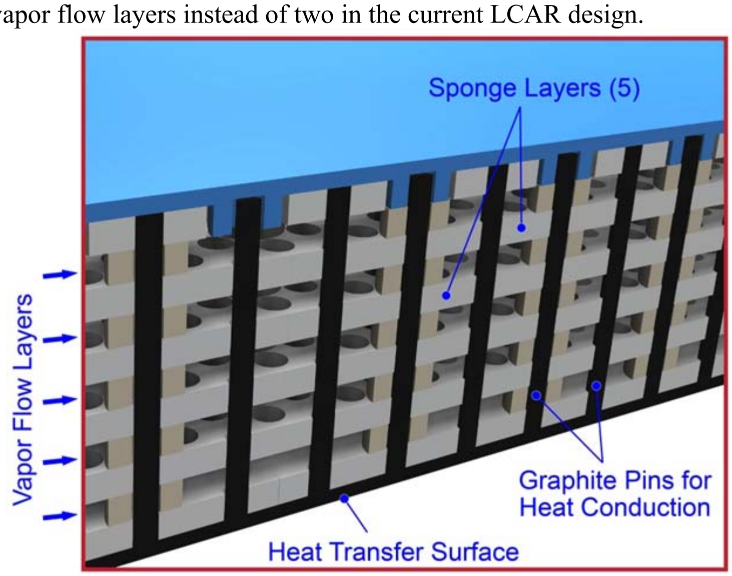
---

[12] Previous demonstration tests at Creare under contract NNJ06JD55C ("Liquid-Liquid Heat Exchanger With Zero Interpath Leakage") have shown that Grafoil can provide a low thermal resistance interface between heat exchanger layers while operating in a vacuum.

LCAM Mass Calculation				Scaling from LCAR:	
Water absorption requirement	4.50 kg			Graphite	279 g
Max concentration	90%			Sponge	62 g
Min concentration	45%			LiCl	279 g
Mass LiCl	4.05 kg			TOTAL	620 g
Dead water mass	0.45 kg				
Graphite + sponge mass (scaled from LCAR)	4.95 kg				
Vapor header percent	10%				
Vapor header estimated mass	0.50 kg				
TOTAL LiCl panel mass	14.45 kg				
Coolant passage estimate from UTAS	7.4 kg				
TOTAL LCAM MASS	21.9 kg	=	48.2 lbm		
Energy absorption capacity	1.13E+07 J				
	3,125 W-hr				
Energy absorption density	143 W-hr/kg				
	515 kJ/kg				

Modified LCAR Design for Rapid Regeneration. The LCAM design is based on Creare's current LCAR design[13], but modified to enable more rapid regeneration. The LCAR is designed to minimize overall thickness and does not have a requirement for one-hour regeneration. In contrast, the LCAM must regenerate in about one hour (compared to four hours for the LCAR) and is not as constrained in overall thickness. As a result, the LCAM modules are thicker than an LCAR and provide a larger area for vapor/solution contact.

Figure 17 shows the design proposed for the LCAM. The LCAM must regenerate in about ¼ the time of current-generation LCARs. The process that controls the rate of regeneration is diffusion of water through the layer of solid LiCl that forms at the vapor/absorber interface during regeneration. Since diffusion distance varies as $(D\ t)^{0.5}$, where D is the diffusion coefficient for water in crystalline LiCl and t is time, reducing the regeneration time by a factor of four requires a factor of two reduction in diffusion distance. For the same volume of solution, this is equivalent to doubling the vapor/solution contact area. Figure 17 shows that the LCAM design doubles the contact area by providing five vapor flow layers instead of two in the current LCAR design.



[13] Reference the EMU SEAR ICES PAPER

Figure 17. The Absorber Sponge Array in the LCAM Provides a Large Surface Area for Rapid Regeneration.

D. Comparison of SEAR TCS Mass With Baseline System Mass

We performed a differential mass analysis to estimate the possible weight savings that could be gained using a SEAR TCS instead of a baseline TCS that uses more conventional technology. By eliminating heavy PCM heat exchangers and the need for sublimating water, the SEAR TCS has the potential to reduce spacecraft mass by over 200 lb_m. To achieve these weight savings on an Orion-type spacecraft, a lightweight solar panel technology must be used to generate the power needed for regeneration.

Baseline System and Mission Design. We believe that the Altair vehicle thermal profile is the most appropriate thermal environment to use to assess TCS designs for a manned spacecraft. We conducted a preliminary study to compare the SEAR TCS mass to the published mass of the Orion TCS. The baseline architecture for the study comes from the paper by Ochoa & Ewart (2009)[14] which contains mass estimates of vehicle's the two-loop architecture. Creare's freezable radiator TCS metrics were also included in the system comparison, and are reported in Chen, et.al. (2013)[15]

Differential Mass Analysis. To assess possible advantages of the SEAR TCS compared to the baseline, we compared the two systems, removed elements from the baseline that would not be present in the SEAR system, then added elements from the SEAR system that are not present in the baseline system. We then calculated the net addition or loss of mass for the SEAR compared to the baseline.

To make the comparison on the same basis, we assumed that the SEAR TCS would require two redundant loops just like the Orion baseline TCS. The power level and radiator adjusted for consistency between the Altair thermal profile and the radiator design described by Ambrose et al.[16], which is sized for a larger heat load.

Figure 18 illustrates how the baseline TCS design would be modified to produce a SEAR TCS, highlighting the elements that need to be removed an added. We estimated mass of the PCM and heat sink design based on results of a UTAS internal study in 2009 on PCM heat sinks. The mass of sublimation water was also derived from this earlier analysis. All the other components (cabin heat exchangers, pumps and valves for the redundant loops, external radiator system) were all assumed to be identical for the baseline and SEAR systems.

[14] Ochoa, D. A., Ewert, M., "A Comparison Between One- and Two-Loop ATCS Architectures Proposed for CEV" SAE ICES Paper 09ICES-0353, 39th International Conference on Environmental Systems,. July 2009.
[15] Chen, et.al., "A Multi-Environment Thermal Control System with Freeze-Tolerant Radiator", AIAA 2013-3354, 43rd International Conference on Environmental Systems, July, 2013.
[16] Ambrose, et al., "Flow-Through Radiator Development for Orion Crew Exploration Vehicle," 41st International Conference on Environmental Systems, July 2011, Portland, Oregon; AIAA 2011-5081.

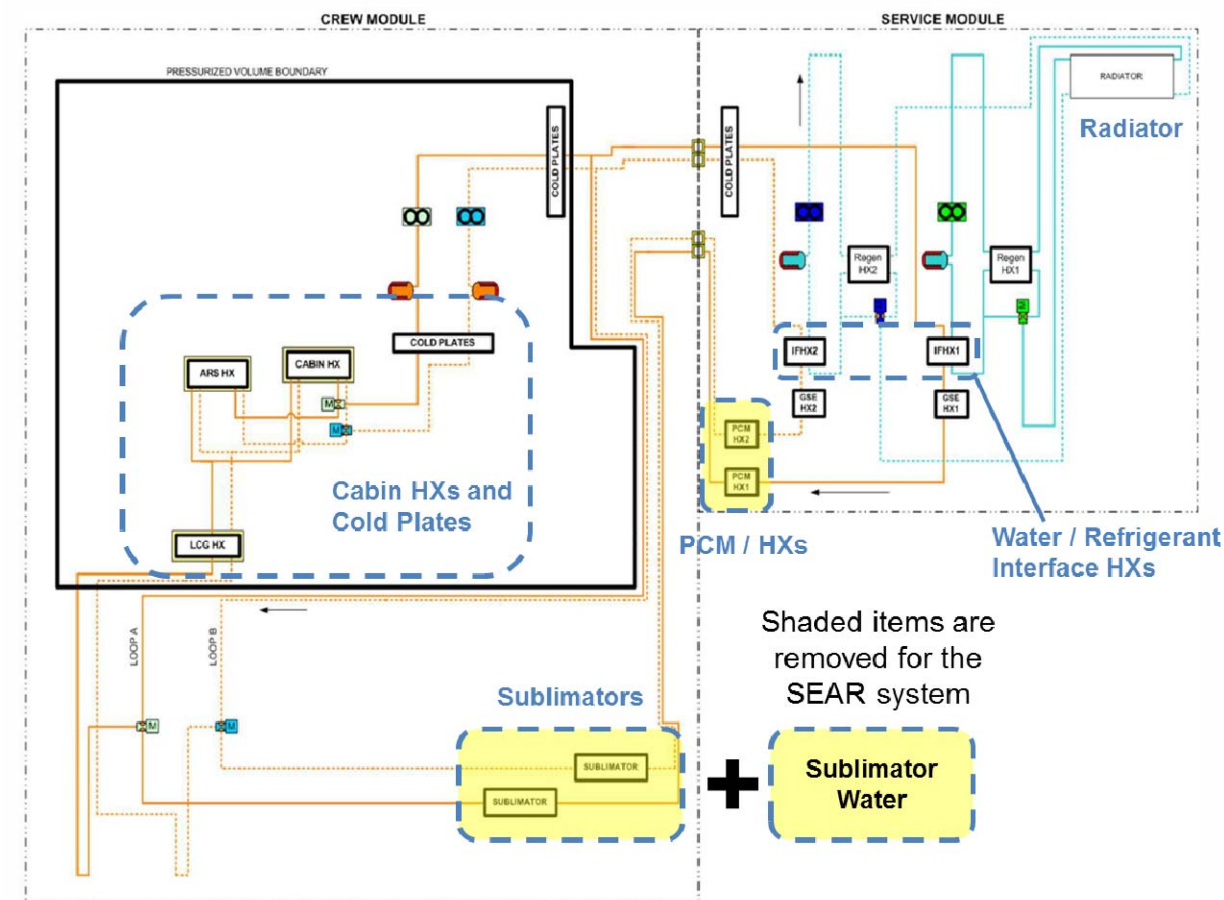


Figure 18. Baseline TCS Design for Orion Highlighting Components Not Present in SEAR TCS[17] (will be modified and combined with the SEAR schematic)

For the SEAR system, the LCAM mass is estimated based on the LiCl concentration swing and water absorption requirements as described earlier. We also estimated the change in pumping power, based on the switch in cabin coolant from viscous PGW to an aqueous coolant (a benefit for SEAR) and the higher flow rates needed for the refrigeration loop (a penalty for SEAR). These effects nearly cancel each other, and the net change in pumping power turns out be very small (a 13 W reduction in pumping power for the SEAR TCS compared to the baseline).

Additional power generation and energy storage are needed to generate additional power on the sun side of the obit and store the energy for use to heat the LCAM during regeneration on the cold side of the orbit. Details for the mass estimates made to account for the additional power and energy storage are shown in Table 4. The batteries need to store 3.45 kW-hr of energy for regeneration on a battery charging efficiency of 93%, the solar panels will need to generate 3.71 kW of power during the one-hour hot portion of the orbit. UTAS estimated battery mass using an energy density of 180 W-hr/kg, which is standard for military batteries but exceeds the recommendations in the Baseline Values and Assumptions Document. Solar panels were sized based on advanced, lightweight solar panel technology (also lighter than recommended in the BVAD. UTAS assumed a flexible solar panel configuration with a specific mass of 5 kg/kW, corresponding to the UltraFlex solar array system produced by ATK. These panels have been space flight qualified and used in flight programs that include the Mars 01 Lander, the Mars Phoenix Lander, and the Orbital CRS.

[17] Ochoa, D. A., Ewert, M., “A Comparison Between One- and Two-Loop ATCS Architectures Proposed for CEV” SAE ICES Paper 09ICES-0353, 39th International Conference on Environmental Systems, July 2009.

Table 4. Solar Panel and Battery Mass Needed for Regeneration			
Solar Panel and Battery Mass			
Mass of water	4.5 kg		
Ratio of h.abs to h.fg	0.15		
Stored energy needed to regenerate	12.4E+6 J	=	3,450 W-hr
Batter charging efficiency	93%		
Energy input to batteries	13.4E+6 J	=	3,710 W-hr
Time available to generate energy	3600 s		
Additional power needed to regenerate	3,710 W		
Additional power SEAR vs baseline	-13 W		
Net additional power needed	3,697 W		
Solar panel specific mass	5 kg/kW		
Additional solar panel mass needed	18.48 kg	=	40.7 lbm

Table 6 and Figure 19 summarize the differential mass analysis, showing that the SEAR TCS has the potential to save over 200 lb_m in system weight compared to the baseline system. LCAM, SWMX, solar array, and battery components are the major mass additions in the SEAR system, contributing 40 to 50 lb_m each. These offset the substantial masses of the PCM heat exchanger (about 200 lb_m) and the sublimator and sublimator water (also about 200 lb_m). The net result is a mass savings of about 200 lb_m for the SEAR system.

Table 5. Differential Mass Comparison Between SEAR and Baseline TCS.

Components	Qty	Mass (lbm)	Total (lbm)
Added for SEAR System			
LCAM mass (90% LiCl)	1	49	49
SWMX mass	2	19	37
Evaporation water (4.5 kg)	1	11	11
Extra accumulator mass	1	6	6
Valves	5	1	3
Larger solar arrays (5 kg/kW)	1	41	41
Battery mass (180W*hr/kg)	1	42	42
Removed for SEAR System			
Subtract PCM mass *	1	-223	-223
Subtract Sublimator Mass*	1	-101	-101
Subtract Sublimator Water Mass	1	-90	-90
Net mass increase for SEAR TCS			-226

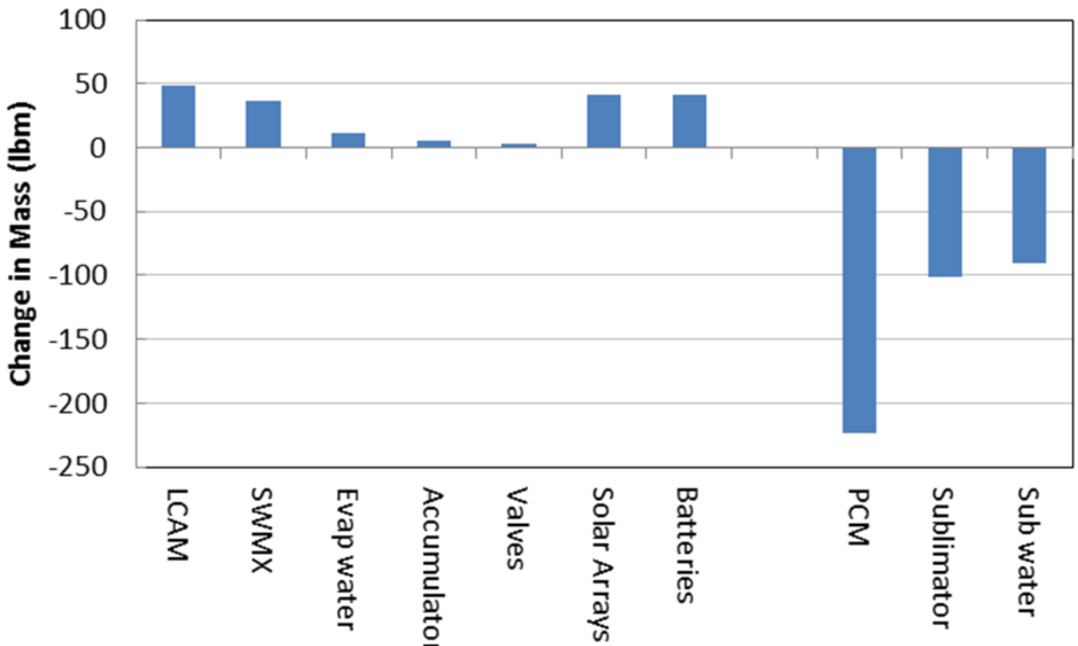


Figure 19. Differential Mass Comparison between SEAR and Baseline TCS

E. Design of an ISS Flight Experiment

We have developed a conceptual design of a SEAR TCS flight experiment that meets the high-level requirements for testing in an EXPRESS rack on board the space station. The proposed system will fit within the 4 ft^3 volume available in a dual bay EXPRESS rack with power and cooling requirements that are well within the available range.

Key Requirements for ISS Demonstration. Demonstration of a SEAR TCS on board the space station requires scaling the system down to fit within the size available in standard experimental accommodations while not exceeding power, cooling, and other limitations. A dual-bay in an EXPRESS rack will provide roughly 4 ft^3 of volume, up to 1,000 W of electric power, and up to 1000 W of cooling from the ISS moderate temperature water loop. Standard ISS vacuum interfaces will provide outlets for noncondensible gas from the LCAM and the SWMC capillary vents. These ISS capabilities will enable testing of an 800 W-hr LCAM at simulated power levels of 800 W, leaving 200 W for LCAM equipment and instrumentation. The 800 W heat load also corresponds to the sizes of NASA current generation of SWME's developed for space suit cooling, so current SWME designs can be adopted directly for the SWMX in the SEAR flight experiment. The system has inherently long time constants and can easily be monitored and controlled via telemetry. No significant crew time should be needed to support the experiment.

System Schematic for the Flight Experiment. The SEAR ISS experiment will consist of a circulating water loop with a LCAM, SWMX, and set of heaters and heat exchangers (Figure 20). Heaters will simulate the heat load that would come from a spacecraft cabin heat exchanger, warming the circulating water to about room temperature. Operation of the ISS experiment is very similar to the SEAR TCS, except that the radiator is simulated by a thermoelectric heat exchanger coupled to an ISS coolant supply. This heat exchanger comprises two cold plates with an intermediate array of thermoelectric coolers (TECs). By controlling the polarity of the TECs, they can pump heat in either direction between the streams flowing to and from the simulated radiator interface heat exchanger. The system will be designed to provide temperature cycling that will simulate thermal loads that correspond to a future manned exploration spacecraft. Although the TEC modules cannot produce temperatures as low as the cold radiation environment in LLO, they can remove heat from the circulating water in a way that simulates the radiator interface heat exchanger.

The LCAM and SWMX capillary vents connect to the ISS vacuum interface. The system includes a "pressurizer" that is coupled to the cabin atmosphere. This device maintains a constant loop pressure and provides a way to measure the circulating water inventory. Changes in bellows position during a test will show how much water is absorbed by (or recovered from) the LCAM. Longer-term changes can indicate excessive water loss from the LCAM and SWME capillary vents.

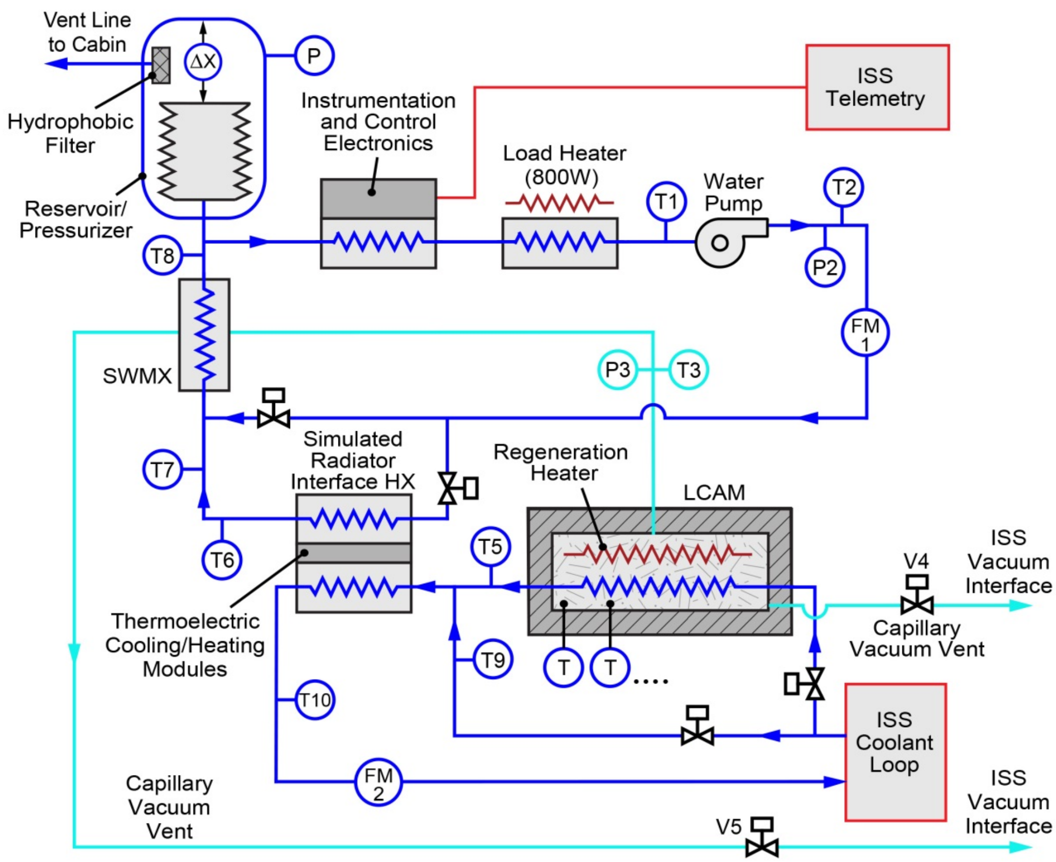


Figure 20. Major Components in SEAR Test Package for Flight Testing on the Space Station

Flight Experiment Conceptual Design. Creare's current design for the LCAM absorber modules derive from the current design for the LiCl absorber/radiator. Our 1 ft² radiator prototypes are designed to hold enough LiCl (280 g) to absorb about 310 g of water, equivalent to 778 kJ or 216 W-hr. Therefore, four of these panels will have a heat-absorbing capacity of 864 W-hr. As described above, this capacity is well-sized to match operation on the ISS.

Our subscale LCAM design for the ISS flight experiment therefore comprises four of these panels, which are identical to our current LCAR except for design features (described above) that increase the number of vapor channels to boost the vapor/absorber contact area for rapid regeneration. The four absorber modules will be stacked alternately with thin cold plates for heat removal, just as in the spacecraft design (Figure 2). Therefore, the ISS flight experiment will be able to demonstrate operation of a very high fidelity model of a future spacecraft LCAM.

Figure 21 illustrates the conceptual layout of the flight experiment within the 4 ft^3 envelope available in a dual bay EXPRESS rack. The layout shows that all the major components of the test facility can fit within the available volume with plenty of room to lay out tubing connections.

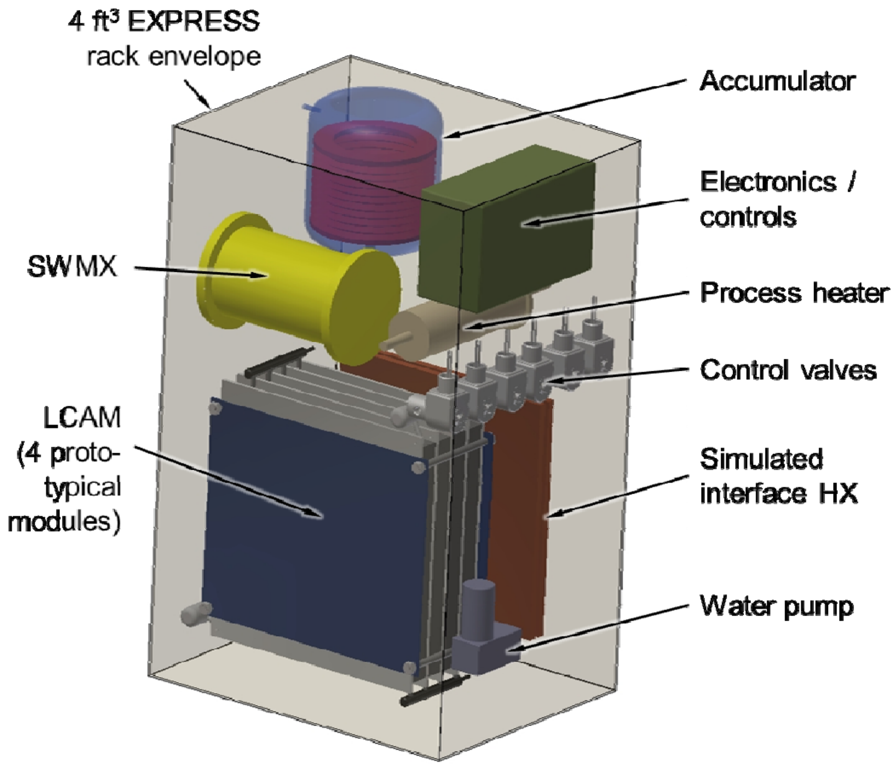


Figure 21. Concept Design for SEAR TCS Experimental Package for Testing on the Space Station

VI. Conclusions

The results presented in this paper support the technical feasibility of using a SEAR system for spacecraft thermal control:

SEAR system design for future spacecraft. We have developed an overall design of the SEAR TCS that minimizes the number of components in the system. We also developed a modular design for the LCAM that builds on prior LiCl absorber radiator technology and designs for test units at small scale that are high-fidelity models of full-scale absorbers.

Quantitative benefits of using a SEAR. Our analysis showed that a SEAR system can enable spacecraft thermal control in the very extreme LLO environment without venting water or requiring a PCM heat exchanger. Compared to the baseline Orion TCS, the SEAR system has the potential to save over 200 lb_m in spacecraft mass.

Design of an ISS flight test unit. We have sized all the major components for an 800 W-hr system that will fit in a dual-bay EXRESS rack on the space station. The flight test unit will use four prototypical LCAM modules and will be subjected to two-hour simulated orbital cycles to simulate operation in LLO.

Acknowledgments

The authors gratefully acknowledge the support of the Crew and Thermal Systems Division at NASA Lyndon B. Johnson Space Center and the NASA SBIR program.

References

The following pages are intended to provide examples of different reference types. When using the Word version of this template to enter references, select the "references" style to automatically format your references. If you are using a print or PDF version of this document, all references should be in 9-point font, with reference numbers inserted in superscript immediately before the corresponding reference. You are not required to indicate the type of reference; different types are shown here for illustrative purposes only.

Periodicals

[1]Vatistas, G. H., Lin, S., and Kwok, C. K., "Reverse Flow Radius in Vortex Chambers," *AIAA Journal*, Vol. 24, No. 11, 1986, pp. 1872, 1873.

[2]Dornheim, M. A., "Planetary Flight Surge Faces Budget Realities," *Aviation Week and Space Technology*, Vol. 145, No. 24, 9 Dec. 1996, pp. 44-46.

[3]Terster, W., "NASA Considers Switch to Delta 2," *Space News*, Vol. 8, No. 2, 13-19 Jan. 1997, pp., 1, 18.

All of the preceding information is required. The journal issue number ("No. 11" in Ref. 1) is preferred, but the month (Nov.) can be substituted if the issue number is not available. Use the complete date for daily and weekly publications. Transactions follow the same style as other journals; if punctuation is necessary, use a colon to separate the transactions title from the journal title.

Books

[4]Peyret, R., and Taylor, T. D., *Computational Methods in Fluid Flow*, 2nd ed., Springer-Verlag, New York, 1983, Chaps. 7, 14.

[5]Oates, G. C. (ed.), *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1984, pp. 19, 136.

[6]Volpe, R., "Techniques for Collision Prevention, Impact Stability, and Force Control by Space Manipulators," *Teleoperation and Robotics in Space*, edited by S. B. Skaar and C. F. Ruoff, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1994, pp. 175-212.

Publisher, place, and date of publication are required for all books. No state or country is required for major cities: New York, London, Moscow, etc. A differentiation must always be made between Cambridge, MA, and Cambridge, England, UK. Note that series titles are in roman type.

Proceedings

[7]Thompson, C. M., "Spacecraft Thermal Control, Design, and Operation," *AIAA Guidance, Navigation, and Control Conference*, CP849, Vol. 1, AIAA, Washington, DC, 1989, pp. 103-115

[8]Chi, Y., (ed.), *Fluid Mechanics Proceedings*, SP-255, NASA, 1993.

[9]Morris, J. D. "Convective Heat Transfer in Radially Rotating Ducts," *Proceedings of the Annual Heat Transfer Conference*, edited by B. Corbell, Vol. 1, Inst. Of Mechanical Engineering, New York, 1992, pp. 227-234.

At a minimum, proceedings must have the same information as other book references: paper (chapter) and volume title, name and location of publisher, editor (if applicable), and pages or chapters cited. Do not include paper numbers in proceedings references, and delete the conference location so that it is not confused with the publisher's location (which is mandatory, except for government agencies). Frequently, CP or SP numbers (Conference Proceedings or Symposium Proceedings numbers) are also given. These elements are not necessary, but when provided, their places should be as shown in the preceding examples.

Reports, Theses, and Individual Papers

[10]Chapman, G. T., and Tobak, M., "Nonlinear Problems in Flight Dynamics," NASA TM-85940, 1984.

[11]Steger, J. L., Jr., Nietubicz, C. J., and Heavey, J. E., "A General Curvilinear Grid Generation Program for Projectile Configurations," U.S. Army Ballistic Research Lab., Rept. ARBRL-MR03142, Aberdeen Proving Ground, MD, Oct. 1981.

[12]Tseng, K., "Nonlinear Green's Function Method for Transonic Potential Flow," Ph.D. Dissertation, Aeronautics and Astronautics Dept., Boston Univ., Cambridge, MA, 1983.

Government agency reports do not require locations. For reports such as NASA TM-85940, neither insert nor delete dashes; leave them as provided by the author. Place of publication *should* be given, although it is not mandatory, for military and company reports. Always include a city and state for universities. Papers need only the name of the sponsor; neither the sponsor's location nor the conference name and location are required. *Do not confuse proceedings references with conference papers.*

Electronic Publications

CD-ROM publications and regularly issued, dated electronic journals are permitted as references. Archived data sets also may be referenced as long as the material is openly accessible and the repository is committed to archiving the data indefinitely. References to electronic data available only from personal Web sites or commercial, academic, or government ones where there is no commitment to archiving the data are not permitted (see Private Communications and Web sites).

[13]Richard, J. C., and Fralick, G. C., "Use of Drag Probe in Supersonic Flow," *AIAA Meeting Papers on Disc* [CD-ROM], Vol. 1, No. 2, AIAA, Reston, VA, 1996.

[14]Atkins, C. P., and Scantelbury, J. D., "The Activity Coefficient of Sodium Chloride in a Simulated Pore Solution Environment," *Journal of Corrosion Science and Engineering* [online journal], Vol. 1, No. 1, Paper 2, URL: http://www.cp/umist.ac.uk/JCSE/vol1/vol1.html [cited 13 April 1998].

[15]Vickers, A., "10-110 mm/hr Hypodermic Gravity Design A," *Rainfall Simulation Database* [online database], URL: http://www.geog.le.ac.uk/bgrg/lab.htm [cited 15 March 1998].

Always include the citation date for online references. Break Web site addresses after punctuation, and do not hyphenate at line breaks.

Computer Software

[16]TAPP, Thermochemical and Physical Properties, Software Package, Ver. 1.0, E. S. Microware, Hamilton, OH, 1992.

Include a version number and the company name and location of software packages.

Patents

Patents appear infrequently. Be sure to include the patent number and date.

[17]Scherrer, R., Overholster, D., and Watson, K., Lockheed Corp., Burbank, CA, U.S. Patent Application for a "Vehicle," Docket No. P-01-1532, filed 11 Feb. 1979.

Private Communications and Web Sites

References to private communications and personal Web site addresses are generally discouraged. Private communications can be defined as privately held unpublished letters or notes or conversations between an author and one or more individuals. Depending on the circumstances, private communications and Web site addresses may be incorporated into the main text of a manuscript or may appear in footnotes.

Unpublished Papers and Books

Unpublished works can be used as references as long as they are being considered for publication or can be located by the reader (such as papers that are part of an archival collection). If a journal paper or a book is being considered for publication choose the format that reflects the status of the work (depending upon whether it has been accepted for publication):

[18]Doe, J., "Title of Paper," Conference Name, Publisher's name and location (submitted for publication)

[19]Doe, J., "Title of Paper," *Name of Journal* (to be published).

[20]Doe, J., "Title of Chapter," *Name of Book*, edited by… Publisher's name and location (to be published).

[21]Doe, J., "Title of Work," Name of Archive, Univ. (or organization) Name, City, State, Year (unpublished).

Unpublished works in an archive *must* include the name of the archive and the name and location of the university or other organization where the archive is held. Also include any cataloging information that may be provided. Always query for an update if a work is about to be published.