Thermal Control System Architecture and Technology Challenges for a Lunar Surface Habitat

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***Abstract*— NASA's current plans for exploration of the Lunar South Pole region include a Surface Habitat (SH) to provide up to 60-day habitability for a crew of four. The SH concept is comprised of several elements including an inflatable volume for the habitable space and a metallic airlock for access to a pressurized rover and other surface assets. A conceptual architecture for the SH Thermal Control System (TCS) is presented. A TCS dual loop design is utilized with a water/propylene glycol mix for the internal crew spaces and an external loop with low temperature coolant. The internal loop is partitioned into low and moderate temperature service with a sublimator available for operational scenarios prior to thermal radiator deployment (or redeployment). Waste heat is rejected through thermal radiators contained in the external loop. Optimization of the thermal radiator geometry/orientation as well as the TCS internal/external loop architecture is accomplished via analytical models of the system. Low mass, dust tolerant, deployable/retractable thermal radiators (in partial gravity) and thermal control surfaces, along with accommodating infrequent eclipse periods lasting up to 100 hours, present the major technology challenges. Mitigation strategies to reduce the energy needed to maintain the SH and associated systems above survival temperature limits during the eclipse period are considered in the paper. Options include retractable radiators, re-generable heat exchangers, temperature excursions, thermal energy storage and optimized inflatable optical properties. TCS sensitivity to potential SH Electrical Power System (EPS) growth is also a consideration for both operational and dormant mission phases.**

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1. INTRODUCTION

The NASA Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Area Announcement (BAA) for Habitation (Appendix A) was released in April 2016, with a focus on developing a habitation capability in cis-lunar space through multiple commercial partnerships [1].

As part of an overall habitation formulation strategy, NASA has developed a Lunar Surface Habitat (SH) Reference Architecture.

A Thermal Control System (TCS) conceptual design for the SH based on the government design reference is presented with a focus on thermal radiator design, Survive-the-Night considerations and growth potential.

2. SURFACE HABITAT REFERENCE DESIGN

The Lunar Surface Habitat (SH) is assumed to be comprised of an inflatable volume, an airlock and a propulsive transfer element. After insertion into a Near Rectilinear Halo Orbit (NRHO), the SH is deployed to the Lunar South Pole via the lander element. The habitat is designed to support 2-4 crew for 30-60 days with a 15-year life. The SH will normally accommodate 2 crew with 4 crew during changeover periods between the SH and a habitable pressurized rover. The rover may conduct multiple sorties lasting up to 15 days in duration between visits to the SH when resupplied with essential consumables.

Electrical power is assumed to be provided by a deployable solar array (10-15 kW), with heat rejection via deployable thermal radiators. Both the solar array and thermal radiators are articulated from the top of the SH as shown in Figure 1. Regenerative fuel cells will provide up to 3 kW of power during eclipse periods lasting up to 100 hours at the South Pole. Total mass is constrained to 12 mT and the internal pressure is baselined at 10.2 psia but may be reduced to 8.2 psia to facilitate Extra Vehicular Activity (EVA). The Environmental Control and Life Support System (ECLSS) is baselined to be fully regenerable to reduce logistics resupply but varying degrees of loop closure are possible pending system trades.

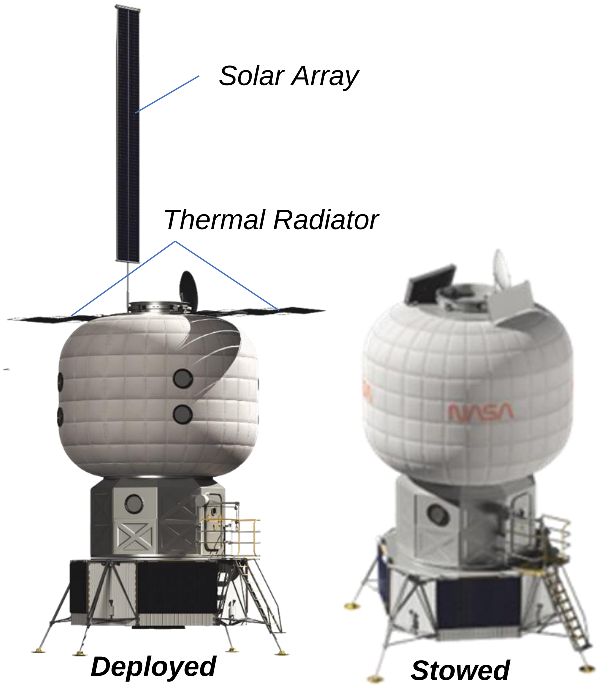

Figure 1. Lunar Surface Habitat Reference Design

3. THERMAL CONTROL SYSTEM DESIGN

The Surface Habitat (SH) Thermal Control System (TCS) is designed to reject >15 kW of heat under peak summertime conditions at the Lunar South Pole with 48 m^2 of radiator surface area (double sided). The two-sided deployable thermal radiators are derived from the International Space Station (ISS) design utilizing a honeycomb core and embedded flow paths with slightly thicker face-sheets.

The TCS has two loops with NOVEC 7200 as the working fluid externally and a 60/40 water/propylene glycol mixture for the internal fluid as shown in Figure 2. Two interface heat exchangers transfer heat collected in the internal loop to the external loop. For clarity, only one internal/external loop is shown in the figure but there are redundant loops with hardware mounted both internal and external to the habitat. Each loop contains a pump package with redundant pumps for two fault tolerance system wide.

The internal TCS loop is subdivided to provide both low and moderate temperature capability, analogous to the ISS ATCS, through the two interface heat exchangers designated for the Low Temperature Loop (LTL) and Moderate Temperature Loop (MTL). Temperature control, through a mixing valve, is maintained via a bypass on the internal side of each heat exchanger. The LTL heat exchanger is located first on the external loop to receive the coolest return from the radiators. The low temperature service is intended primarily for Life Support System (LSS) loads (i.e. condensing heat exchanger) as well as any other payloads that may require it.

All of the internal flow is ultimately routed through the MTL but only a fraction is diverted through the LTL due to the disparity in loads between the two loops. It is anticipated that the valve controlling the LTL flow fraction won’t be maintained dynamically but set by mission phase. The regenerative heat exchanger shown on the internal loop prevents carryover of MTL loads into the LTL loop as well as mitigating potential condensation on the LTL return line.

The external loop circulates through the two interface heat exchangers, external cold-plates, and is split into parallel paths through the two thermal radiator arrays. Each array is subdivided into four panels, with the flow split in parallel through each panel. Fluid entering each radiator panel via a manifold is split further into a number of radiator flow tubes. A balance between the spacing of the tubes and radiator efficiency is desired. Return temperature from the radiators is controlled via a mixing valve and bypass through a regenerative heat exchanger on the external loop. The external regenerative heat exchanger is added to thermally manage (i.e. minimize) parasitic heat loss during dormant periods and is mostly bypassed during normal operations.

A 100-hour eclipse is possible at the Lunar South Pole and the radiators may be retracted during this time to mitigate parasitic heat losses. Additional heat may be required to keep the NOVEC 7200 [2] above working (if circulating) or freezing temperature limits. Other mitigation strategies are also under consideration.

The thermal radiators may be retracted during the Survive-the-Night scenario and are based on an areal density of the ISS Heat Rejection System thermal radiators (14 kg/m^2) as shown in Figure 3, although the ISS design isn’t qualified to deploy/retract in the lunar gravitational field. Mass margins are applied to account for additional mass to enable the deployment or retraction mechanism to function in the lunar environment. Once deployed, the thermal radiators are assumed to be oriented horizontally for one side to face deep

Figure 3. ISS Heat Rejection System Radiators

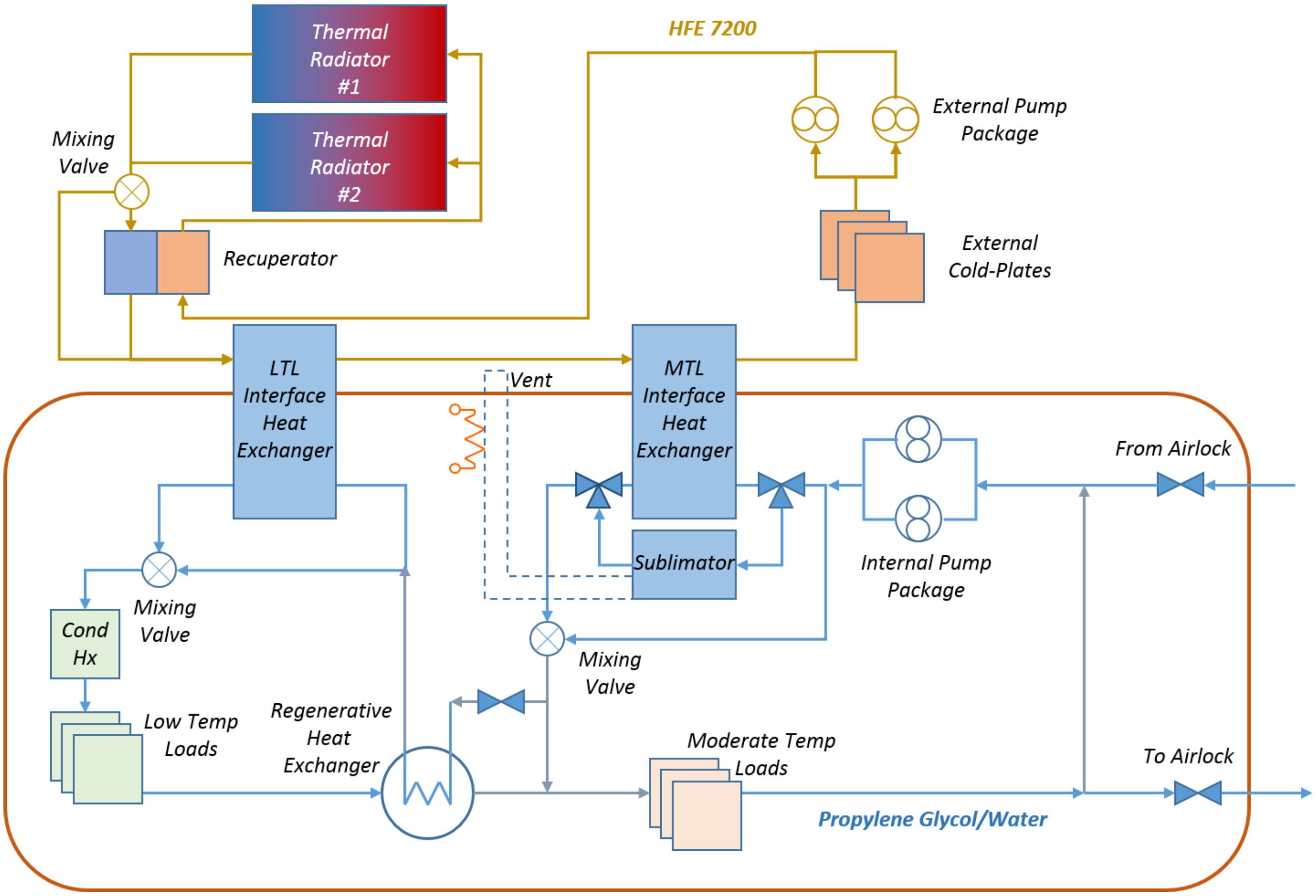

Figure 2. Lunar Surface Habitat Thermal Control System Design

space with the backside radiating mostly to lunar terrain. Each 3m x 2m radiator panel will contain 10 embedded flow tubes, spaced approximately 8” apart, to provide a fin efficiency of 85% based on a face-sheet thickness (front and back) of 0.015” as shown in Figure 4.

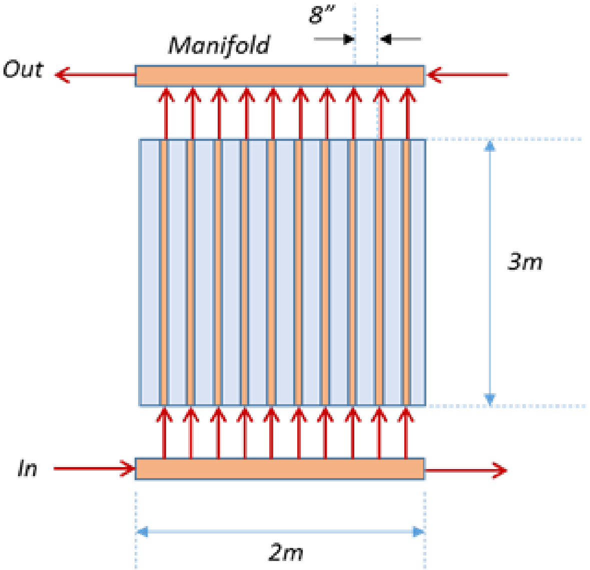

Figure 4. Individual Radiator Panel

The total mass of the SH TCS is shown in Figure 5, broken down by major component. The deployable thermal radiators

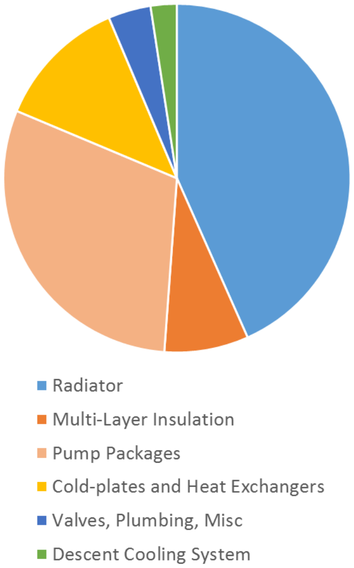

Figure 5. SH Thermal Control System Mass

and internal and external loop pump packages are the major contributors with nearly 75% of the total mass. A 10 layer Multi-Layer Insulation (MLI) is chosen for the habitat and airlock. Performance of the MLI is considered to be degraded for the inflatable habitat to account for possible creases resulting from folding and packing.

A sublimator is added for heat rejection during descent or on-orbit loiter before the thermal radiators are deployed. The sublimator water tank is sized to reject 4300 watts for three hours but could presumably be scarred to increase that time with LSS water.

External cold-plates are included to accommodate external loads such as batteries or fuel cells.

Thermal math models, developed in Thermal Desktop [3], are utilized to assess overall thermal radiator heat rejection capacity for the primary SH landing site and to consider system growth due to increased electrical power system demand. The thermal math model of the habitat, with thermal radiators and photovoltaic arrays deployed, is shown on an adiabatic ground plane representing the primary landing site in Figure 6. The sun vector is elevated approximately 1.5° above the ground plane and aligned with the radiator on the leading edge. Solar reflection and re-radiation from the habitat are evident on the ground plane.

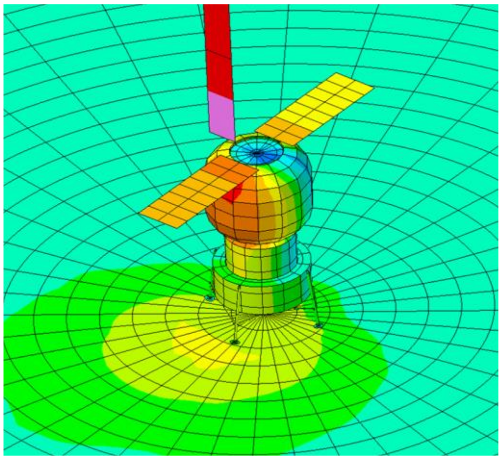

Figure 6. SH Thermal Math Model including Lunar Surface

Results are shown in Figure 7 for heat rejection capability versus number of thermal radiator panels. The baseline case (with 8 double-sided panels) is shown on the far left. Heat rejection capacity for the baseline is just above required at 17 kW. Adding panels to the TCS can increase heat rejection capacity up to 27 kW with 12 panels. An increase in both internal and external TCS loop flow may be needed to accommodate the additional heat rejection. As shown in the figure, a third radiator array is utilized to provide the extra capacity. The 10-panel configuration may not be desirable if extra mass is needed to support 5 panel arrays.

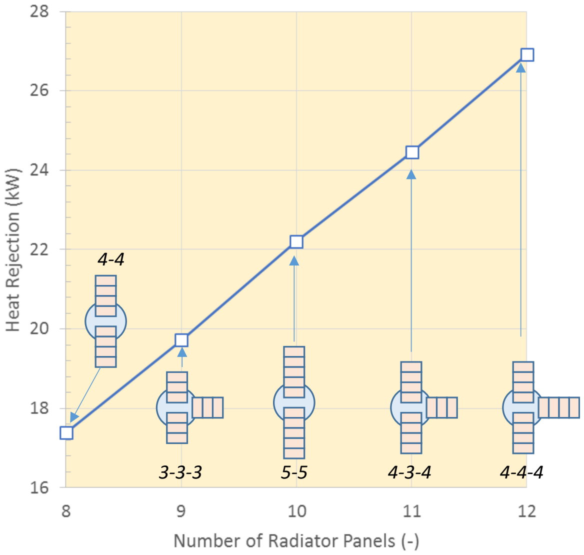

Figure 7. SH Thermal Radiator Growth Scenarios

Detailed thermal/fluid models of the individual thermal radiator panels are developed as shown in Figure 8. The model includes flow through both the individual fluid passages and the supply/return manifolds for an accurate assessment of pressure drop. The individual flow paths are embedded in “saddles” or brackets which are subsequently sandwiched between two aluminum face-sheets. A honeycomb core (to provide stiffness) is also sandwiched in the interstitial spaces formed by the brackets and face-sheets.

4. SURVIVE-THE-NIGHT SCENARIO

Eclipse periods lasting up to 100 hours are possible at the Lunar South Pole. Additional heat will be needed to maintain the SH inflatable volume and thermal radiators above minimum temperature limits during the dormant Survive-the-Night scenario.

Survive-the-Night scenarios may vary in duration and with partial illumination, although system sizing is based on the worst case (total eclipse). Maintaining the SH at a minimum temperature of 283K would require 1550 watts to offset the heat leak through the inflatable volume.

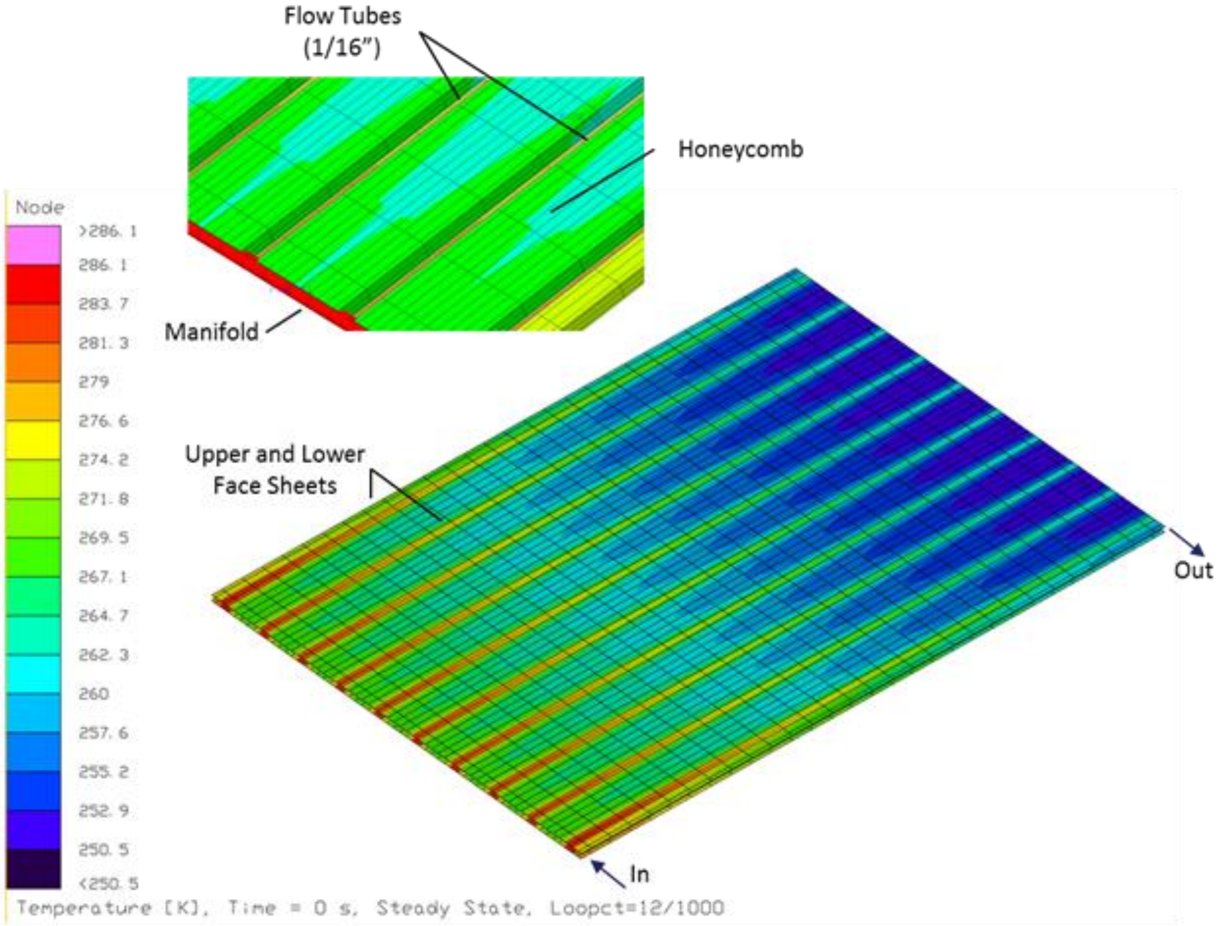

Figure 8. SH Radiator Panel Thermal/Fluid Model

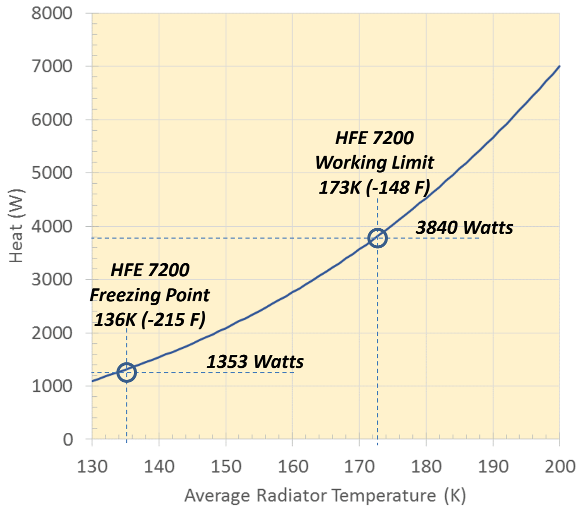

Figure 9. Additional Heat to Maintain Radiator Temperature (NOVEC-7200, AZ White Paint)

The radiator fluid (NOVEC 7200) has a lower working temperature limit of -100°C (-148°F) and a freezing point of -137°C (-215°F). To maintain the thermal radiators just above the working or freezing temperature limits would require nearly continuous heat of at least 3840 or 1353 watts, respectively, as shown in Figure 9.

For the fluid working limit, the un-mitigated (i.e. no countermeasures) total energy required would be 540 kWh for the 100 hour Survive-the-Night scenario.

Mitigation strategies to reduce the power requirement, including energy storage, preconditioning the SH (warm) and stowing or reconfiguring the radiators, are under consideration.

5. MITIGATION STRATEGIES

Stowing the thermal radiators for Survive-the-Night could greatly reduce energy storage requirements. Parasitic heat losses from the radiators versus stowage angle are shown in Figure 10. Completely closing the radiators reduces the overall heat needed to maintain the radiators from nearly 3400 W to about 700 W. Since the radiator panels reject heat on both sides, the bottom surface of the outermost panels still view the environment.

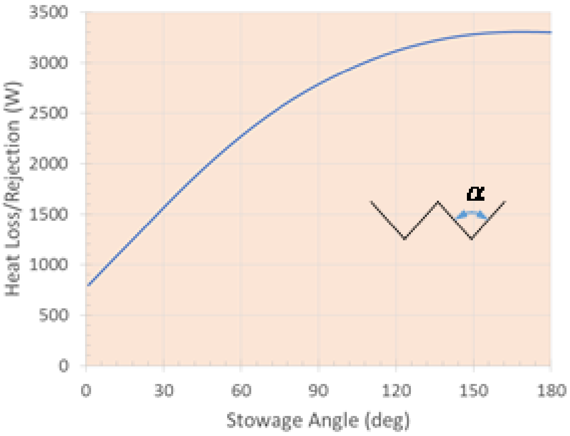

Figure 10. Radiator Heat Loss vs Partial Stow Angle

In addition to the heat loss from the radiators, approximately 1550 watts of make-up heat would be needed to maintain the SH habitable volume above (293 K) 68°F during Survive-the-Night.

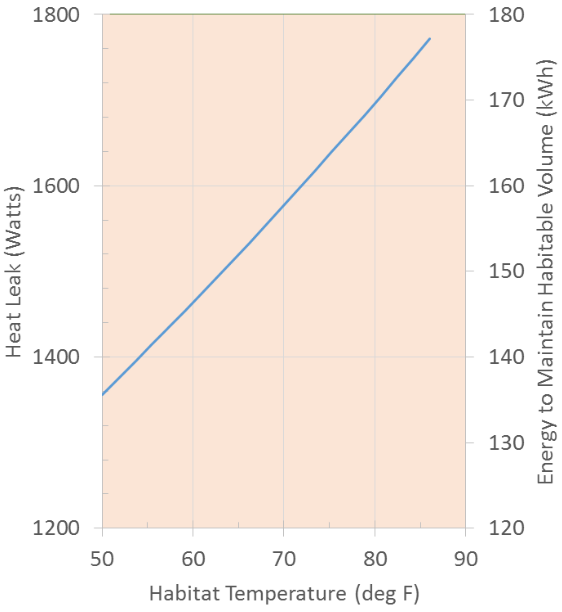

Figure 11. Heat Leak from SH Habitat/Airlock versus Internal temperature

The heat required is proportional to the habitat internal temperature as shown in Figure 11.

Allowing the un-crewed habitat temperature to sink below respirable atmosphere limits could save on the total energy required (with the atmosphere ostensibly returned before crew arrives).

Pre-heating the habitat to store energy may also mitigate the energy required. For the nominal case, the energy required would be 155 kWh.

The SH baseline design utilizes beta cloth for the outer covering of the inflatable structure. Beta cloth has an infrared emittance of 0.9 with a solar absorptance 0.4.

Reducing the surface emittance could significantly reduce heat leak during survive-the-night periods as shown in Figure 12.

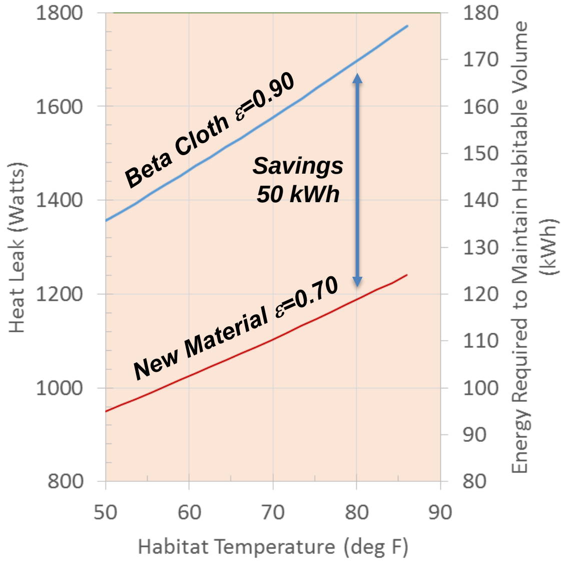

Figure 12. Heat Leak from SH Habitat/Airlock

Some margin to reduce the emittance exists as the surface habitat has a net heat loss (~850 watts) during daylight operations. The preference would be to not to have a net heat gain during operational periods because of extra load for the TCS. The potential energy savings is on the order of 50 kWh.

6. FUEL CELL TRADES

Hydrogen/Oxygen Regenerative Fuel Cells (RFC) provide the energy needed to support a 100 hour Survive-the-Night Scenario for a given thermal radiator size.

Habitat heat leak does not vary with electrical power sizing and is approximately constant at 1550 watts during the eclipse. The TCS can utilize both electrical energy and waste heat from fuel cells to maintain the habitat and prevent the radiators from freezing. Fuel cells nominally produce 400 kWe/kg with 243 kWt/kg of waste heat at 62.2% efficiency [4].

The total RFC logistics (H_2 and O_2) and hardware masses versus electrical power are shown in Figure 14 along with the thermal radiator and photovoltaic masses.

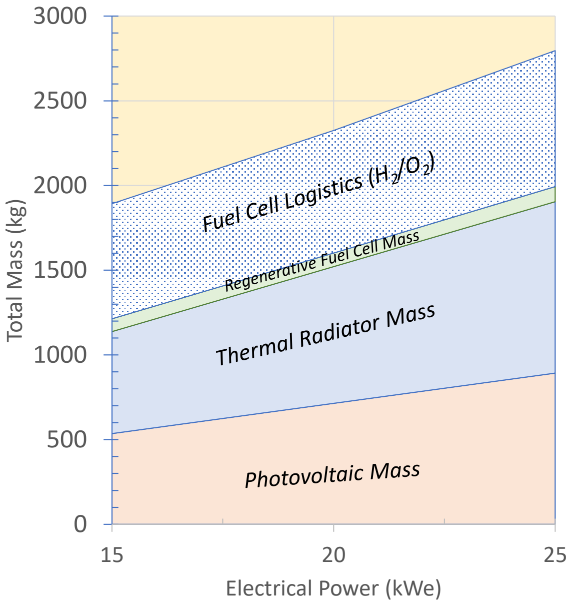

Figure 14. Total Radiator/Photovoltaic/Fuel Cell Mass versus Electrical Power

Additional Electrical Power System (EPS) mass may be required to scale up peripheral distribution components for increased power requirements.

7. SUMMARY

A TCS Reference Architecture for a 30 to 60-day Surface Habitat mission to the Lunar South Pole is presented. TCS and energy storage needs may be minimized through Survive-the-Night mitigation strategies.

Additional thermal radiator capacity is needed to accommodate EPS growth. With the current TCS deployable radiator design, approximately 400 kg per 10 kWe is needed for the radiator panels. Some additional TCS pump power will also be required to accommodate larger heat dissipations.

Fixed re-generable fuel cell mass impacts for Survive-the-Night appear to be slight with increasing radiator size. The amount of water or oxygen/hydrogen required for Survive-the-Night energy storage will grow with increased radiator size (approximately 130 kg per 10 kWe).

Future plans are to continue refinement of the SH ATCS concept with detailed thermal modeling to provide performance predictions and support trade studies.

APPENDIX

NOMENCLATURE

ATCS	Active Thermal Control System
BAA	Broad Area Announcement
ε	Infrared emittance
ECLSS	Environmental Control and Life Support System
EPS	Electrical Power System
HFE	Hydro-Fluoro-Ether
HRS	Heat Rejection System
ISS	International Space Station
K	Degree Kelvin
kg	kilogram
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
kWt	kilowatt-thermal
MLI	Multi-Layer Insulation
mT	Metric Ton (1000 kg)
NextSTEP	Next Space Technologies for Exploration Partnerships
psia	pounds per square inch absolute
SH	Surface Habitat
TCS	Thermal Control System

ACKNOWLEDGEMENTS

Special thanks to Dawn Naville who developed detailed thermal radiator panel models to support this work. And thanks to the Deep Space Habitat Project Office and Team for their support.

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BIOGRAPHY

Greg Schunk *received a B.M.E in Mechanical Engineering from the Georgia Institute of Technology in 1983 and M.S.E in Engineering from the University of Alabama in Huntsville in 1999. He has been with the NASA Marshall Space Flight Center (MSFC) for over 38 years. His experience includes thermal analysis/heat transfer/fluid modeling for many projects including the Next Generation Space Telescope, International Space Station, Shooting Star Experiment, Chandra X-Ray Observatory, Project Constellation and the Space Launch System (SLS). He provided both on-orbit and lunar surface thermal assessments for the Altair Lunar Lander (Project Constellation) and is currently involved with conceptualization of Life Support and Thermal Control Systems for Lunar Surface Habitation as part of the Artemis Program.*

Stephanie Babiak *received a B.S. in Mechanical Engineering from The University of Alabama in Huntsville. She has worked as a thermal engineer for 10 years with experience in the design, analysis, testing, and hardware integration of numerous thermal control components and systems. She is currently supporting the NASA Artemis Program with thermal modeling of a conceptual Lunar Surface Habitat to provide thermal radiator sizing estimates as well as predictions for Lunar Survive-the-Night scenarios.*

Brian Evans *received his B.S. in Mechanical Engineering from Auburn University in 1975. Prior to MSFC, Brian worked on U.S. and international petrochemical gas & oil plant constructions with cryo-fluids to high temp flare gas stack structures and thermo/fluid dynamics. Subsequently at MSFC since 1979, he has been designing, analyzing, testing thermal-fluid flight system hardware, and providing mission flight support to manned spacecraft thermal/fluid systems (active and passive architectures, pressurized & unpressurized compartments) all combined for over 45 yrs. He has worked on programs including Shuttle/Orbiter payloads and onboard vehicle systems, Spacelab/Spacehab/Middeck, ISS Structures/Payload Rack thermal/vent subsystems, O-g experiment designs, In-situ spaceflight Fab & Repair, ARES, SLS, and currently assists in the Moon to Mars Human Exploration thermal design efforts for lunar Surface Hab and Mars Transit Hab designs. He is a pilot and is a registered P.E. in two states.*