Conceptual Thermal Control System Design for a Lunar Surface Habitat

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Thermal & Fluids Analysis Workshop
TFAWS 2021
August 24-26, 2021
Virtual Conference

Overview

- The NextSTEP, Appendix A-Habitation BAA was released in April 2016, with a focus on developing deep space habitation concepts, engineering design and development, and risk reduction efforts leading to a habitation capability in cislunar space.

- The objective of the NextSTEP solicitation is to identify habitation concepts that can support extensive human spaceflight missions in the Proving Ground (around and beyond cislunar space) while encouraging application to commercial habitation capabilities in low-Earth orbit.

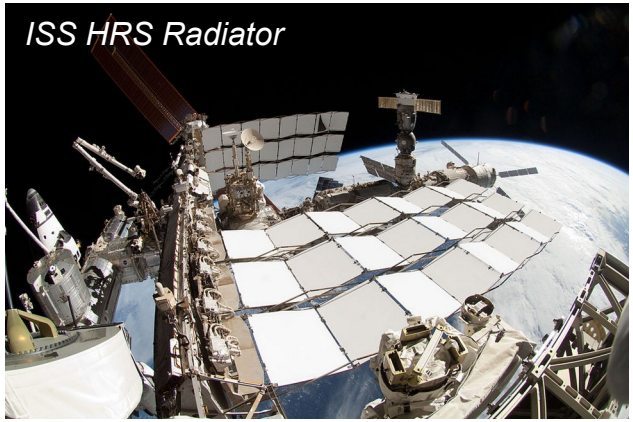
- Government sponsored Moon-to-Mars Surface Habitat (SH) conceptual design studies and trades have been undertaken to develop a Reference Architecture for the SH Thermal Control System (and other systems) to inform and exchange lessons learned, ground rules & assumptions and requirements with NextSTEP partner efforts.

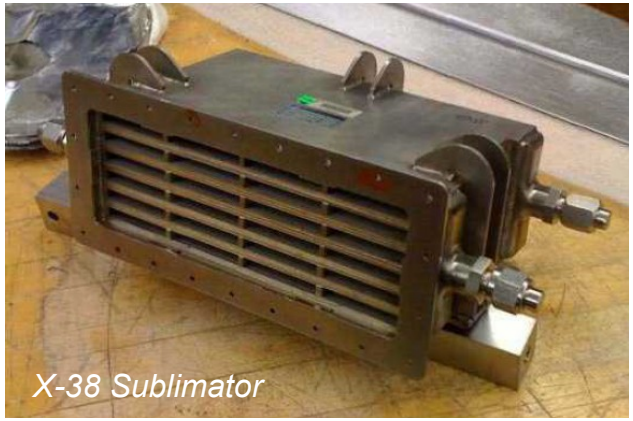
Lunar Surface Habitat Architecture Reference

Crew:	2-4
Power:	15 kW
Night Power:	2 kW
Eclipse:	100 hours
Pressure:	10.2 psia
Lifetime:	15 years
Mission Duration:	30-60 days
Mass:	12 mT
Habitable Volume:	175 m^3
Location:	Lunar South Pole

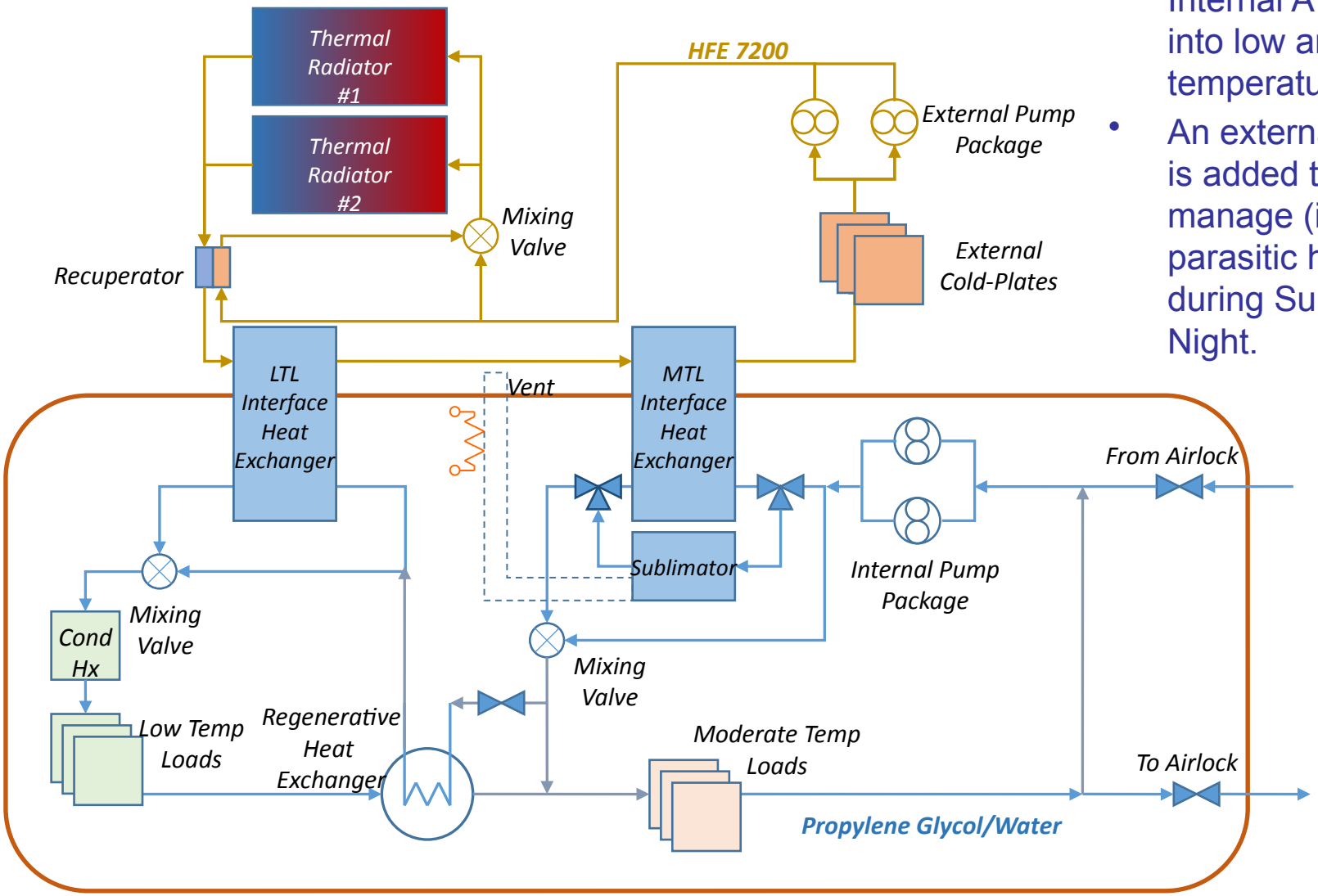
Surface Habitat ATCS Description

- The Surface Habitat (SH) Thermal Control System (TCS) is designed to reject 15 kWt of heat under nominal 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.
- The TCS has two loops with HFE 7200 as the working fluid externally and a 60/40 water/propylene glycol mixture as the internal fluid.
- The internal TCS loop is subdivided to provide both low and moderate temperature service analogous to the ISS ATCS. The low temperature service is intended primarily for ECLSS (e.g. condensing heat exchanger) as well as any payloads that may require it.
- Heritage hardware is utilized where possible.



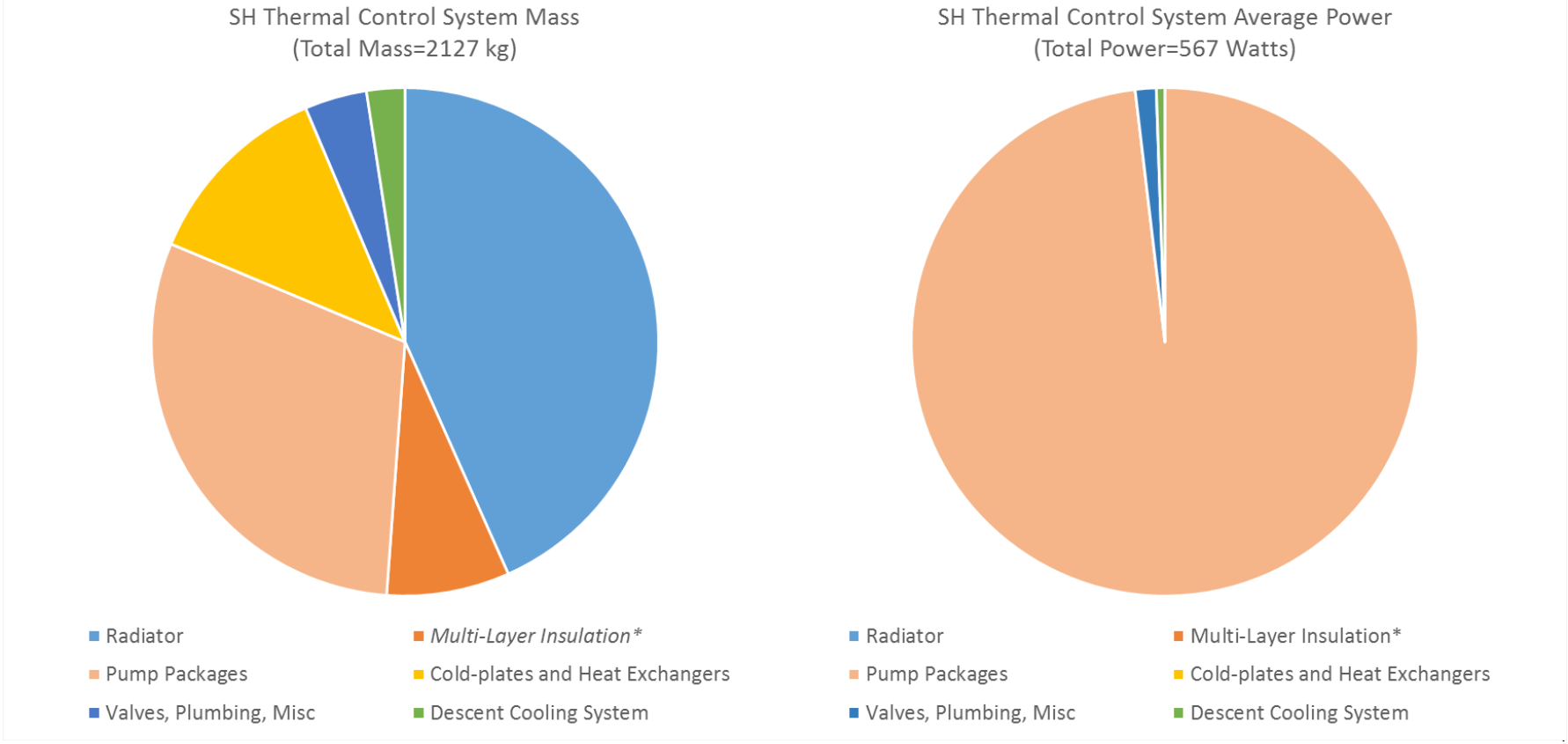


Conceptual Surface Habitat Thermal Control System



- Internal ATCS parsed into low and moderate temperature loops.
- An external recuperator is added to thermally manage (i.e. minimize) parasitic heat loss during Survive-the-Night.

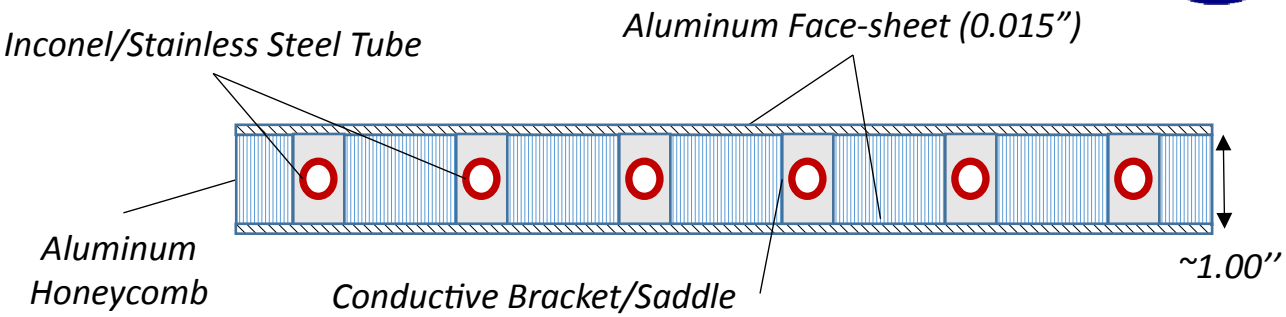
Surface Habitat TCS Resource Estimates

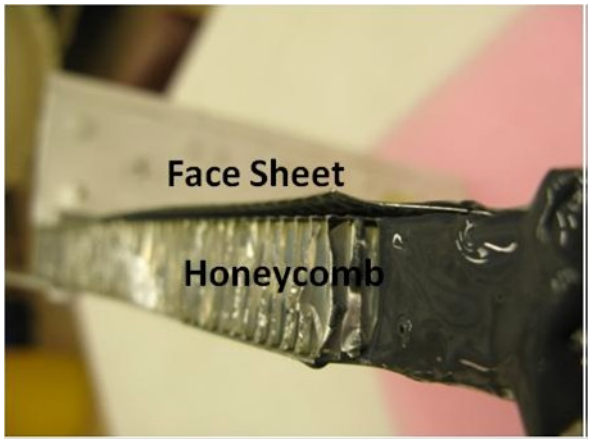


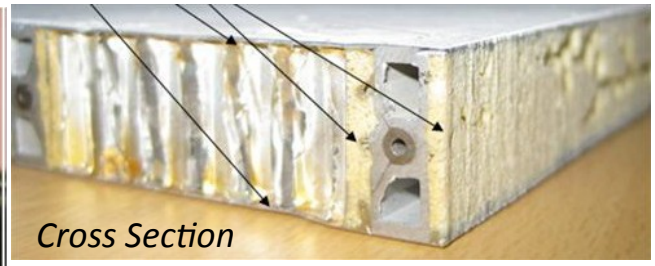
- Primary drivers for mass and power are the thermal radiators and circulating fluid pump packages. Internal volume for TCS < 1 m^3.
- MLI included for reference but is generally considered part of the SH inflatable structure. Outer beta cloth covering not included but surface optical properties are a factor in thermal heat leak in to and out of the habitat.

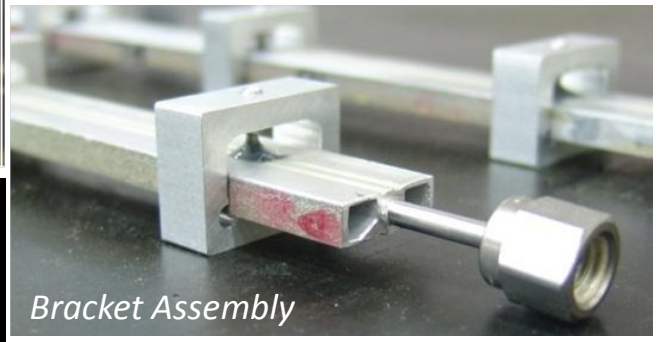
Surface Habitat Thermal Radiator Design

- Based on ISS deployable radiator design with modifications.
- ISS design may not be retractable in lunar gravitational field without modification.
- Coolant tube diameter layout and geometry modified to support single phase HFE 7200 instead of freezable Ammonia.
- Aluminum face-sheet thickness increased from 0.010” to 0.015” for performance improvement.
- Four panels per side (~3 x 2m) needed for total area of 48 m^2 in SH application.

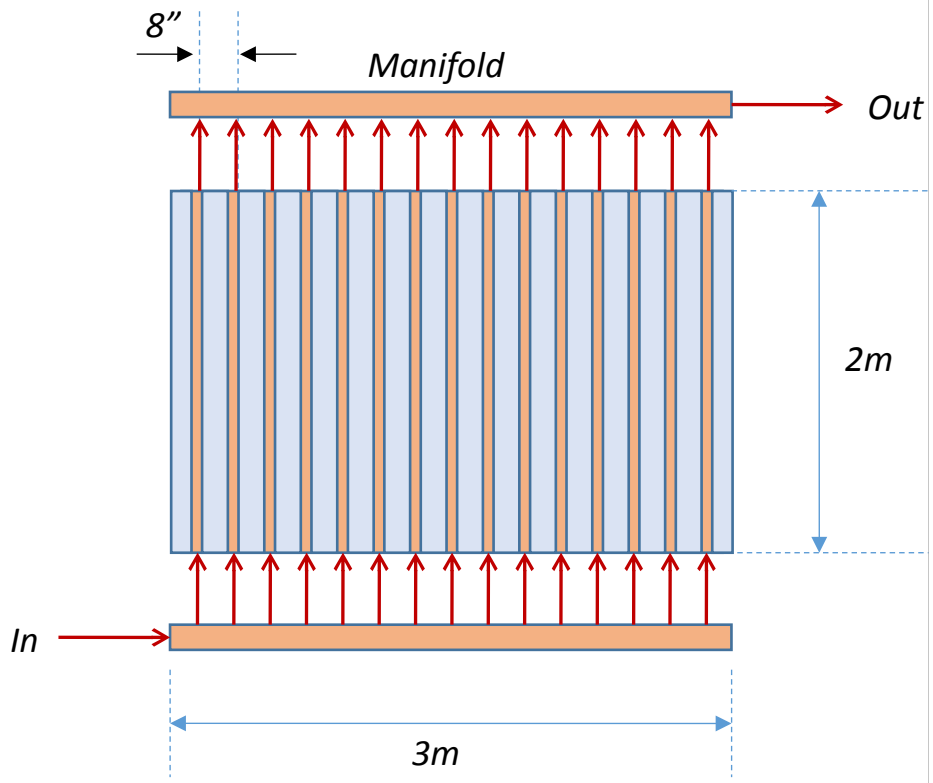


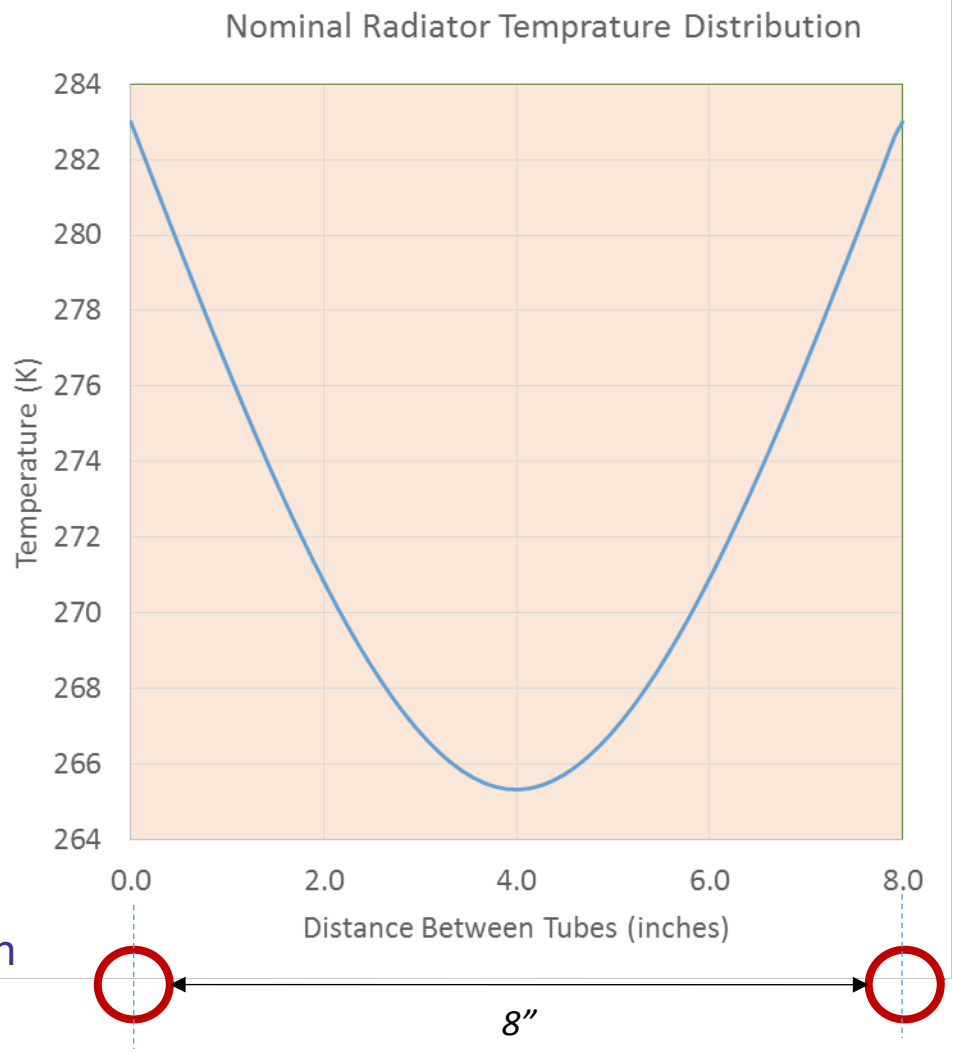






Thermal Radiator Panel Design



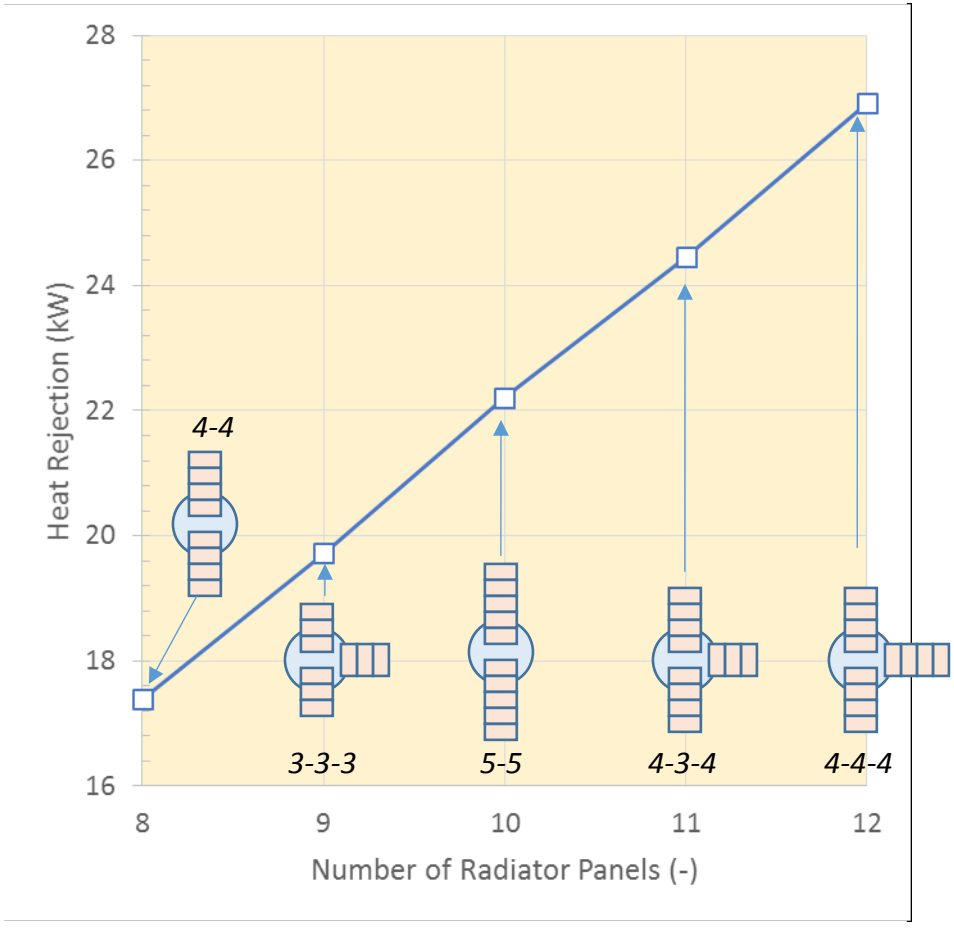


- Fluid enters the radiator via a manifold that splits the flow into 15 tubes. A balance between the spacing of the tubes and radiator fin efficiency is desired.
- At 8” spacing with a nominal fluid temperature of 283K and 0.015” aluminum face-sheets, the predicted temperature profile is shown with an estimated fin efficiency of 85.5%.

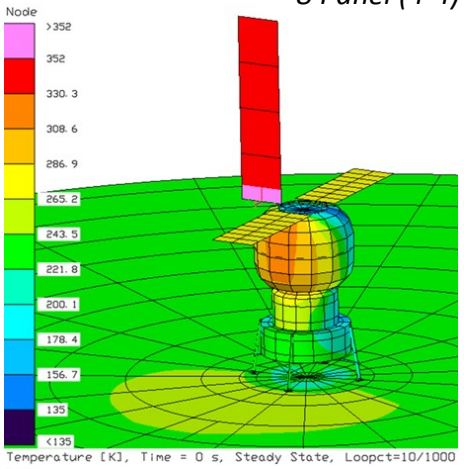
Surface Habitat Heat Rejection and Growth Scenarios

Number of Radiator Panels Required vs Heat Rejection

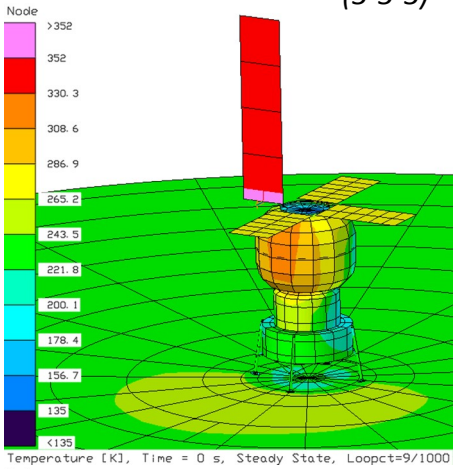
Radiator Temperature 283K, 85% Efficiency



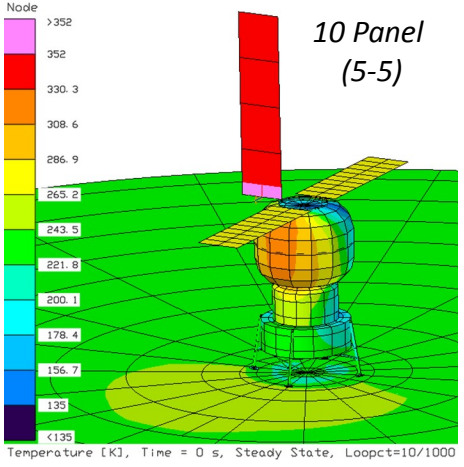
Baseline
8 Panel (4-4)



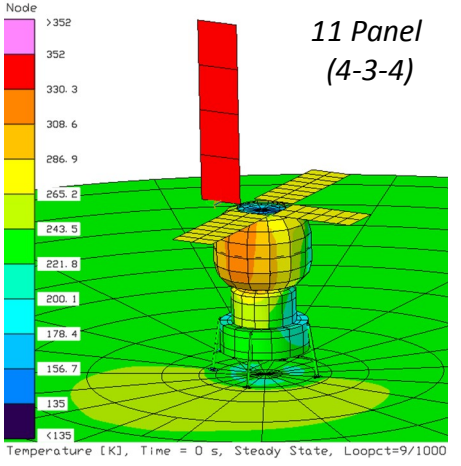
9 Panel
(3-3-3)



10 Panel
(5-5)

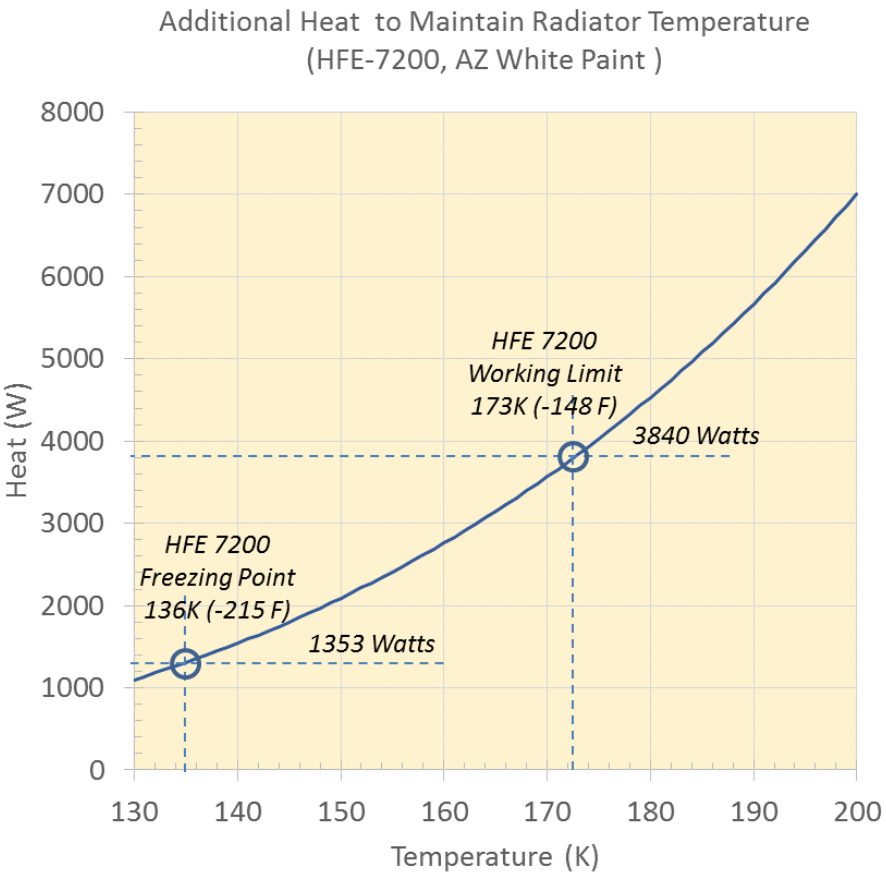


11 Panel
(4-3-4)



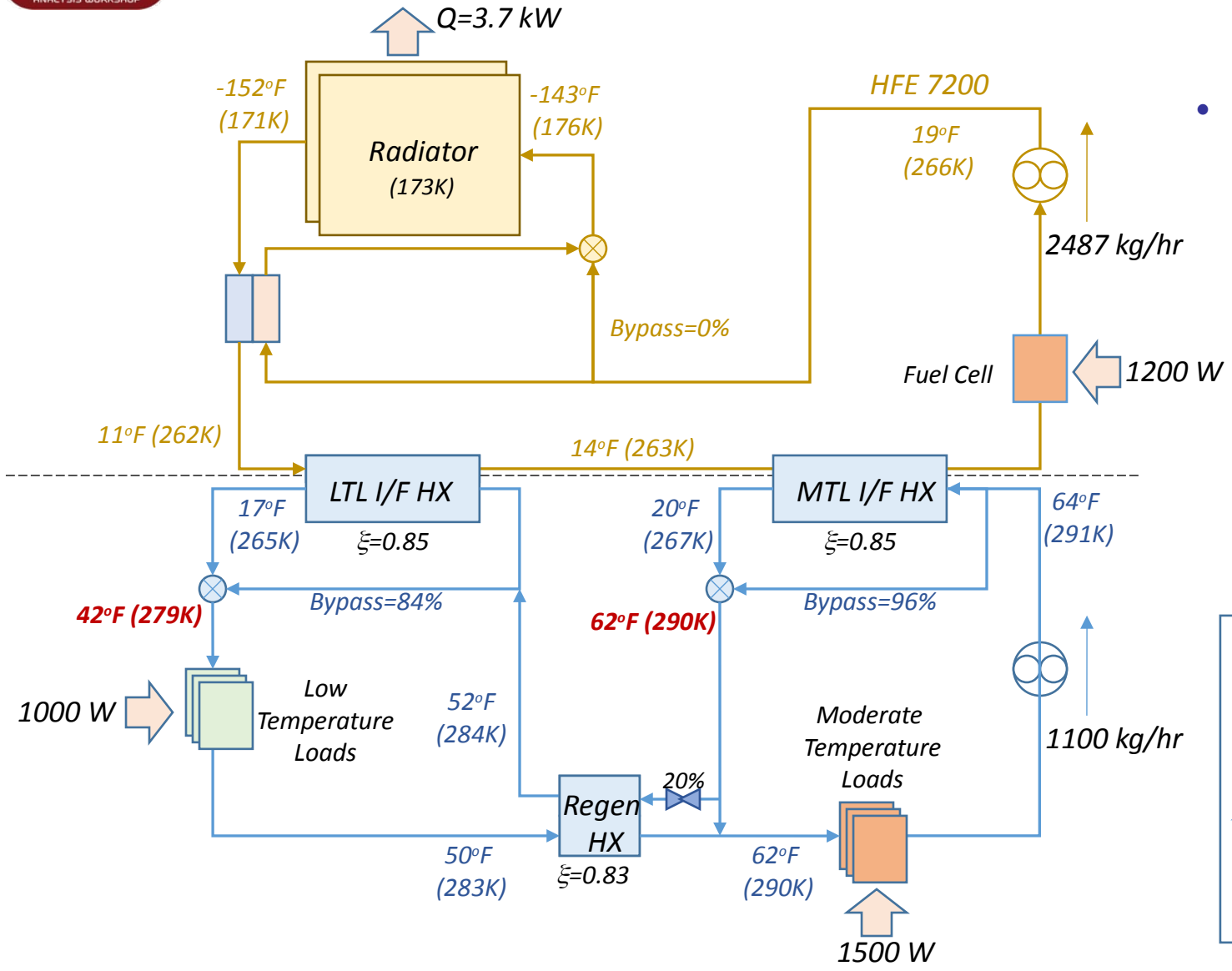
- Results are for Primary Landing Site, a Lunar Ground Temperature 217K (-70°F) and Worst Case Orientation.

Surface Habitat Survive-the-Night

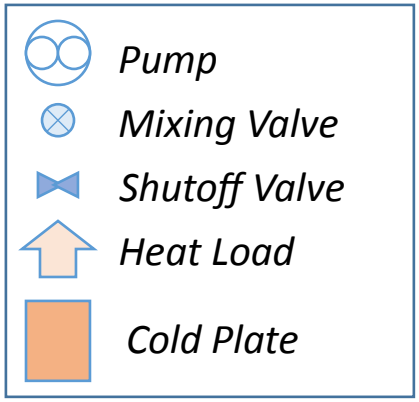


- A 100-hour eclipse is possible at the Lunar South Pole. Additional heat will be needed to maintain the SH inflatable volume and thermal radiators above minimum temperature limits during the dormant Survive-the-Night scenario.
- Survive-the-Night may vary in duration and with partial illumination.
- To maintain the SH at minimum temperature would require 1550 watts to offset the heat leak through the inflatable volume.
- The radiator fluid (HFE 7200) has a lower working temperature limit of -100°C (-148°F) and a freezing point of -137°C (-215°F).
- To maintain the radiators just above the working or freezing temperature limits would require nearly continuous heat of at least 3840 or 1353 watts, respectively.
- For the fluid working limit, the un-mitigated (i.e. no counter-measures) 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

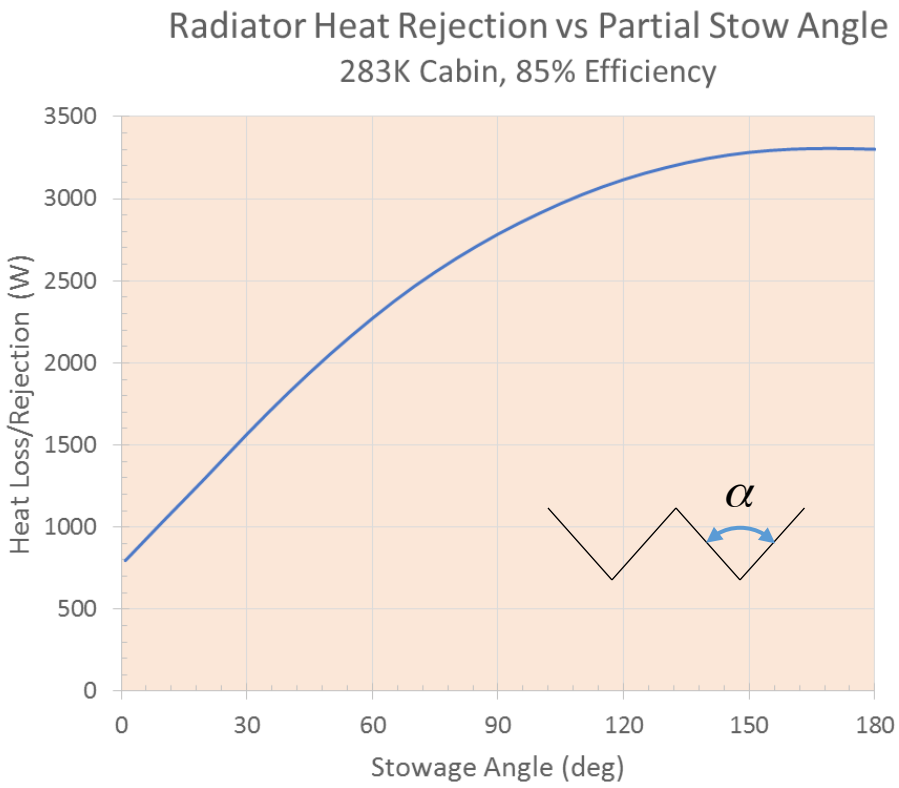
Simulation for Survive-the-Night Heat Load (3.7 kWt)

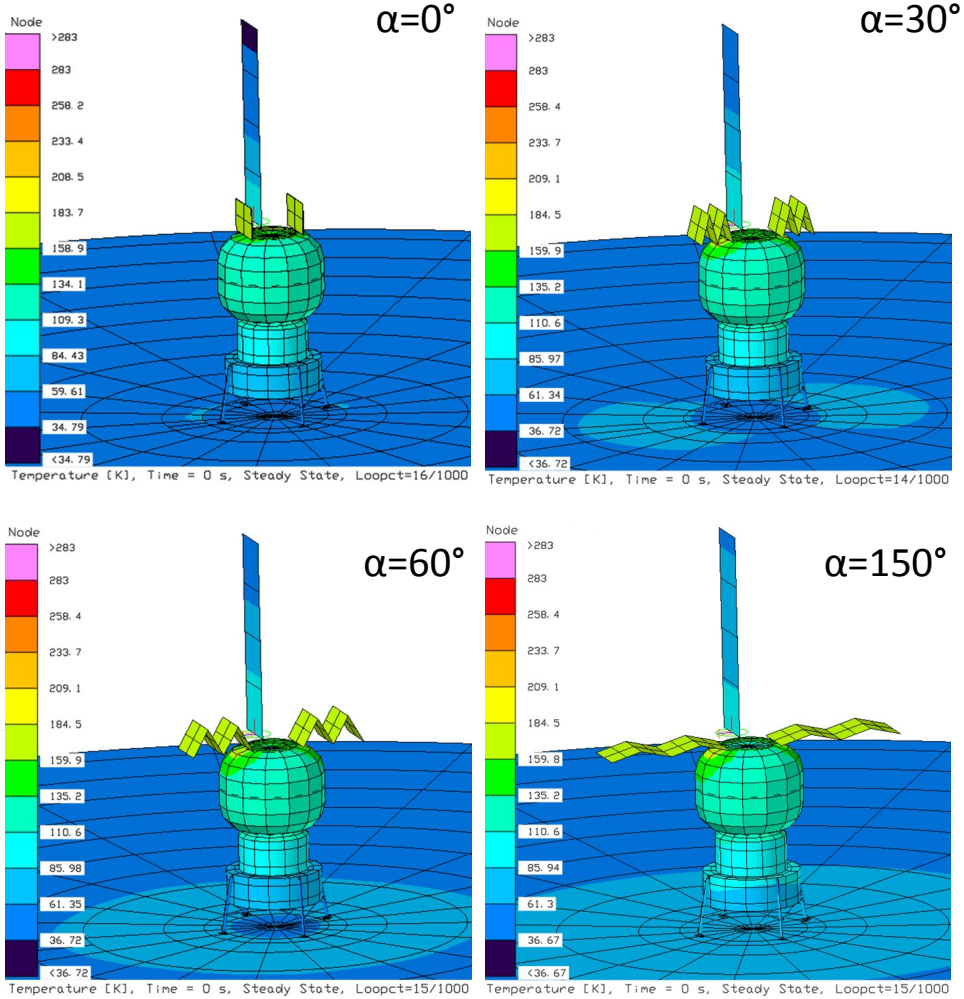


- Re-generative fuel cell sized to provide 2.5 kWe which results in 1.2 kWt waste heat introduced into the external loop via cold plate mounting.



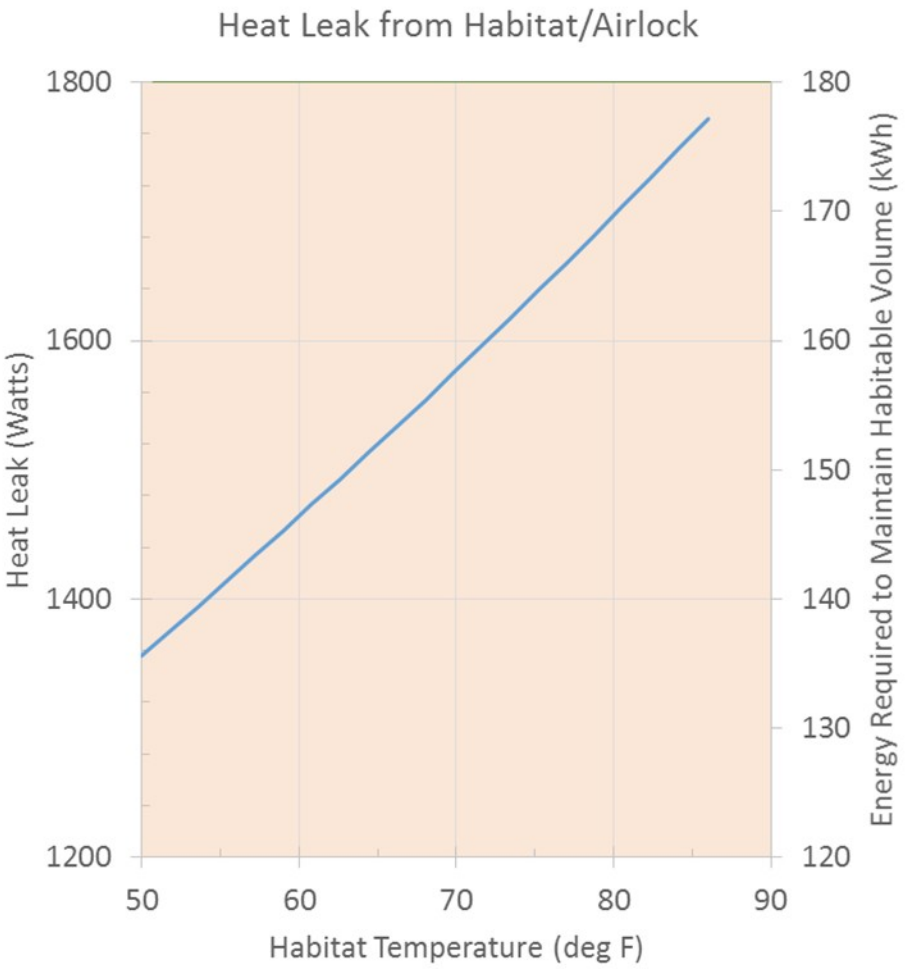
Mitigation Strategy: Retractable Radiators





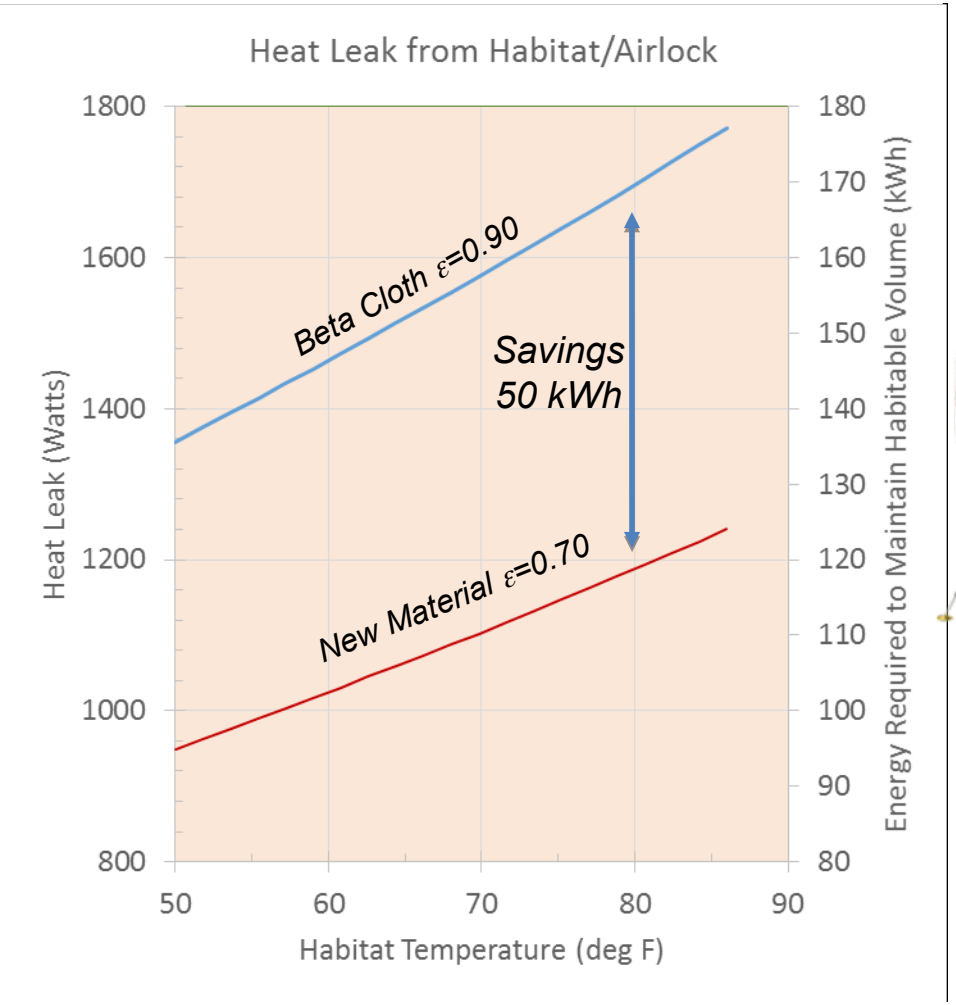
- Stowing the thermal radiators for Survive-the-Night could greatly reduce energy storage requirements. Heat leak from the Surface Habitat is fixed.

Mitigation Strategy: Habitat Temperature



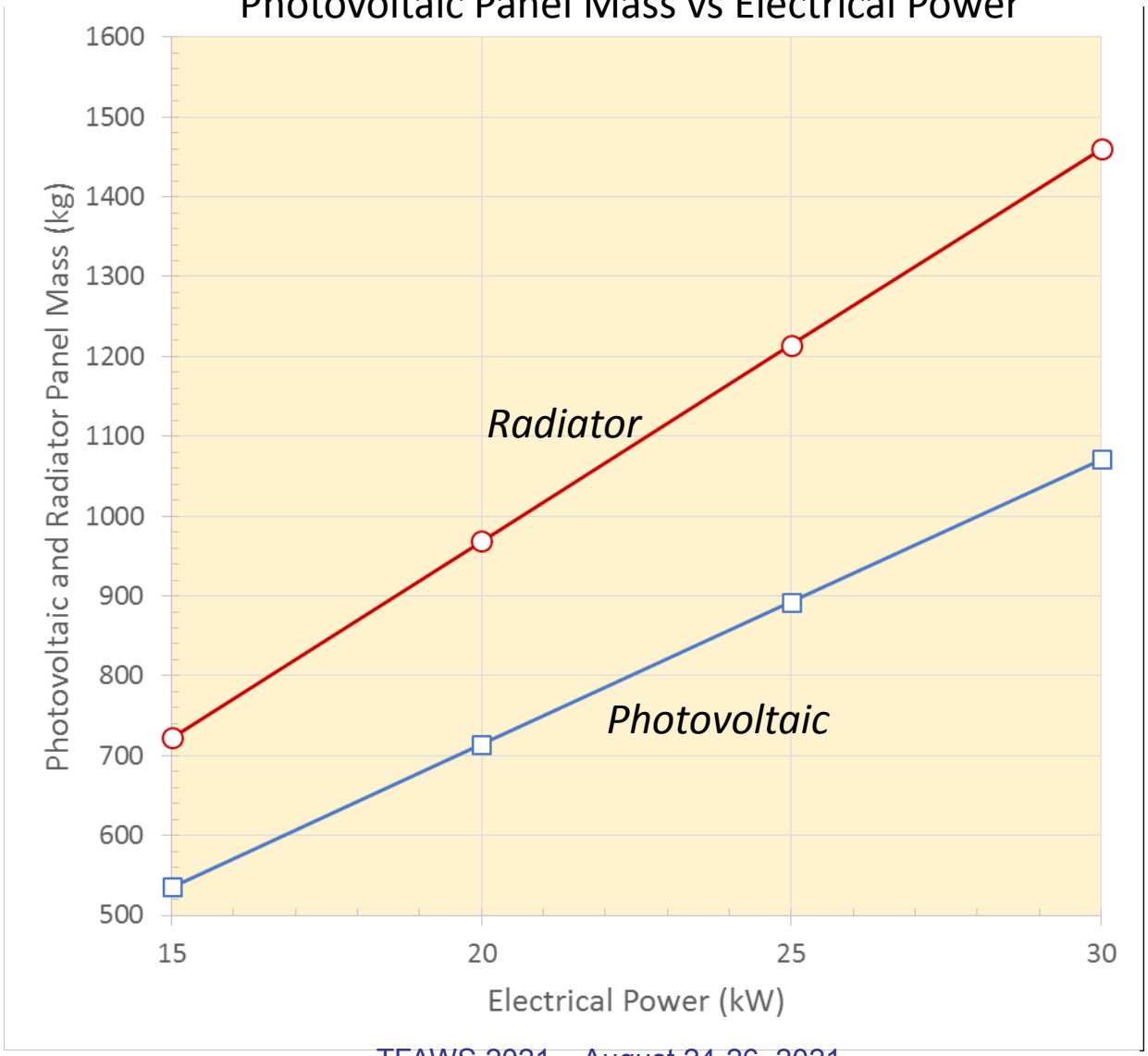
- In addition to the heat loss from the radiators, approximately 1550 watts of make-up heat would be needed to maintain the SH habitable volume above 68°F.
- The heat required is proportional to the habitat internal temperature as shown.
- Allowing the un-crewed habitat temperature to sink below respirable atmosphere limits could save on the total energy required (and 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**.
- For both the thermal radiators and habitat, the total required stored energy would be **~550 kWh** if no measures to reduce the heat loss are taken.

Mitigation Strategy: Lower Emittance Covering



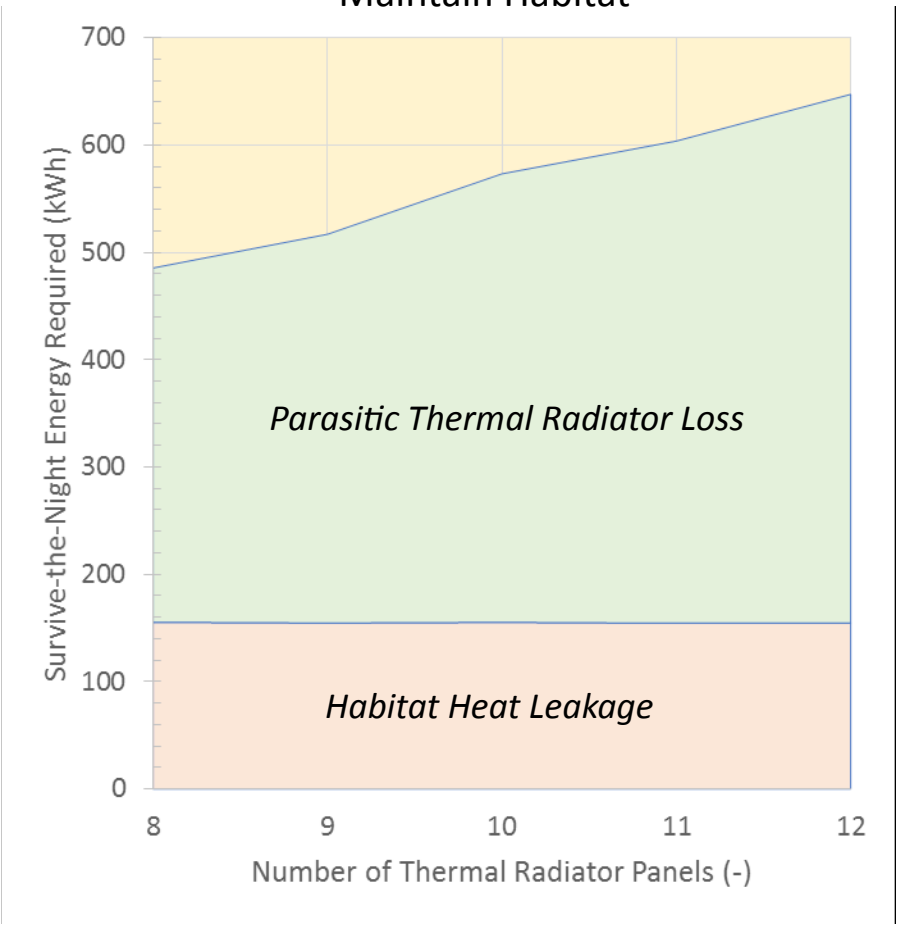
- Baseline design utilizes beta cloth for the outer covering of the inflatable structure. Beta cloth has an infrared emittance of 0.9 (along with a solar absorptance 0.4).
- Reducing the emittance could significantly reduce heat leak during survive-the-night periods.
- Some margin to reduce the emittance exists as the surface habitat has a net heat loss during daylight operations. Prefer 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**.

Thermal/Power Growth Sensitivity

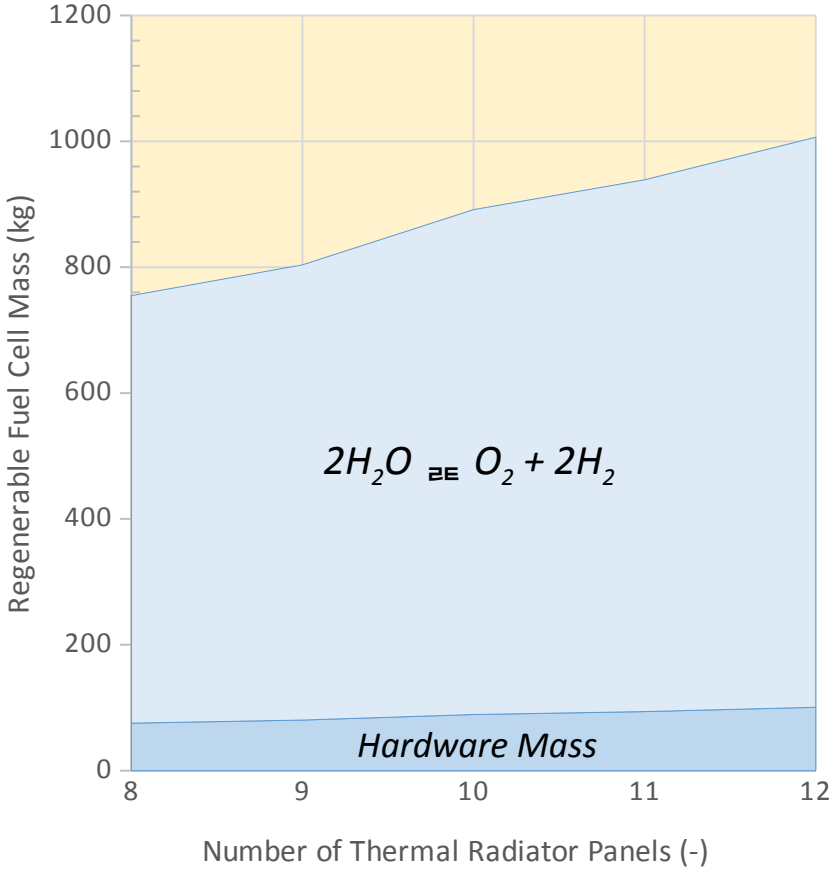


Survive the Night Considerations for Growth

Thermal Energy needed to Maintain Habitat



Total Re-generable Fuel Cell Mass Needed to Thermally maintain Habitat*

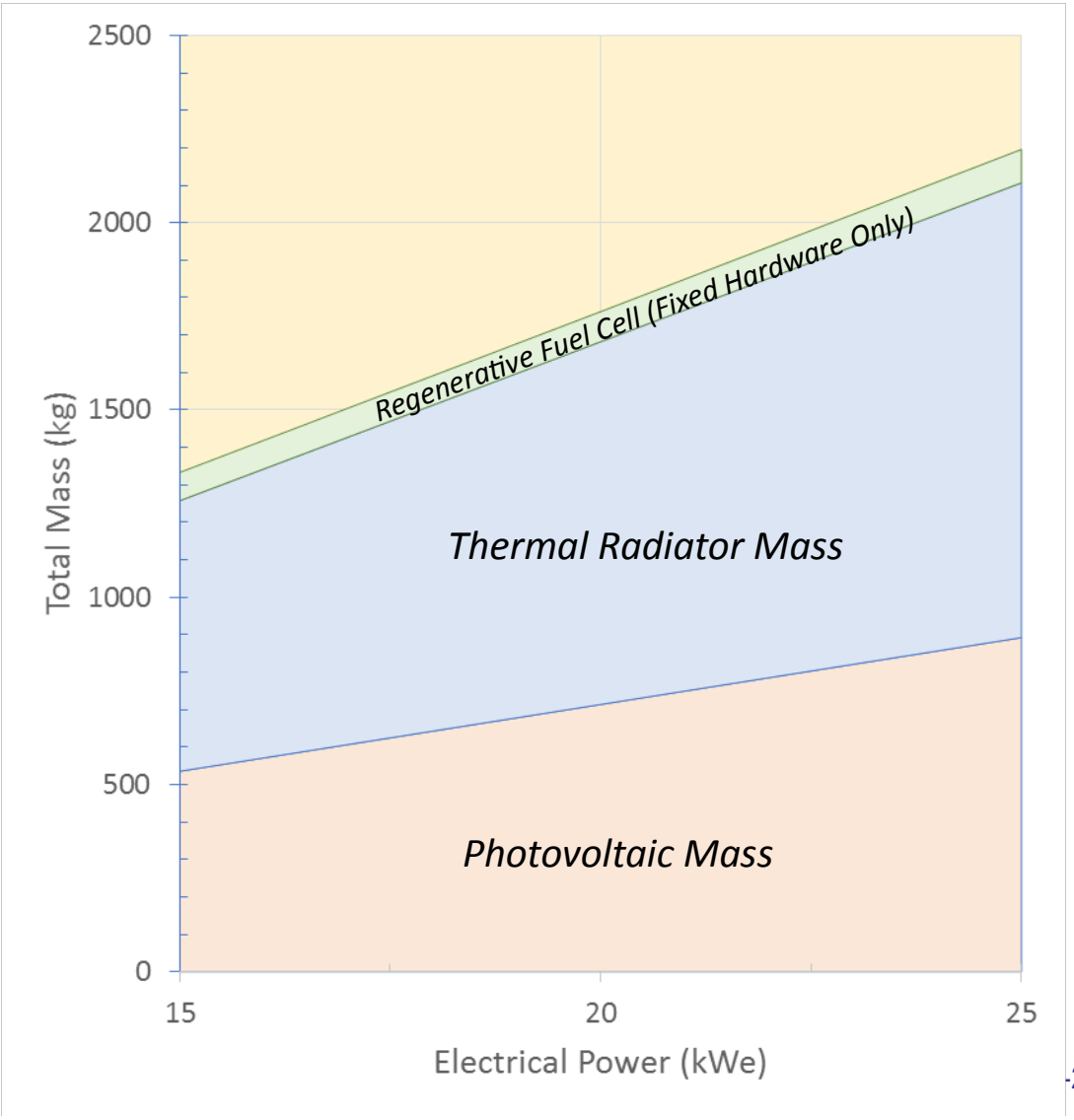


- Thermal can utilize both electrical energy and waste heat from fuel cells. Fuel cells nominally produce 400 kWe/kg with 243 kWt/kg of waste heat at 62.2% efficiency.

*Ian Jakupca, NASA Glenn Research Center, *Overview of Regenerative Fuel Cell Technologies for Space Applications*, 29 July 2020

Overall Thermal/Power Growth Sensitivity

Total Radiator/Photovoltaic/Fuel Cell Mass vs Electrical Power



- Regenerative fuel cell represents 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 a constant 1550 watts during the eclipse.
- Electrical power and thermal heat rejection correlate 1:1 in the Survive-the-Night scenario.
- Additional EPS mass may be required to scale up peripheral components for increased power requirements.
- Thermal Control System needs additional pump power to support increased power levels (included).

Summary

- A TCS Reference Architecture for a 30 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 500 kg per 10 kWe is needed for the radiator panels.
  - Some additional TCS pump power will also be required to accommodate larger heat dissipation.
- 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 240 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.