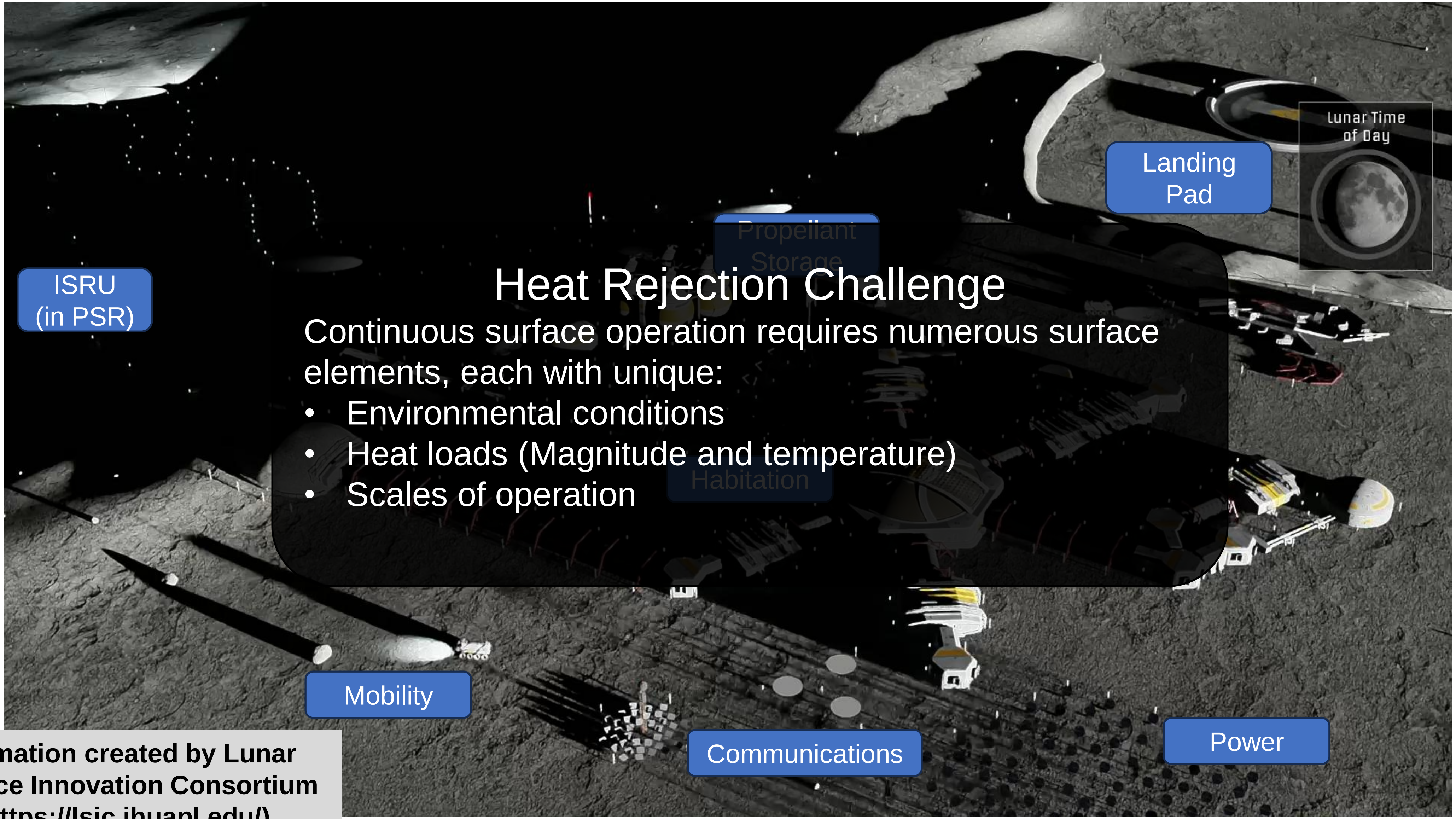
Parametric-Based Heat Rejection Trade Study for Lunar and Martian Surface Operations

Noah Andersen *HX5, LLC (NASA JSC)*
Thomas Chen *NASA JSC*

Presented By
Noah Andersen

Thermal & Fluids Analysis Workshop
TFAWS 2026
August 31 – September 4, 2026
NASA Marshall Space Flight Center
Huntsville, AL

Motivation



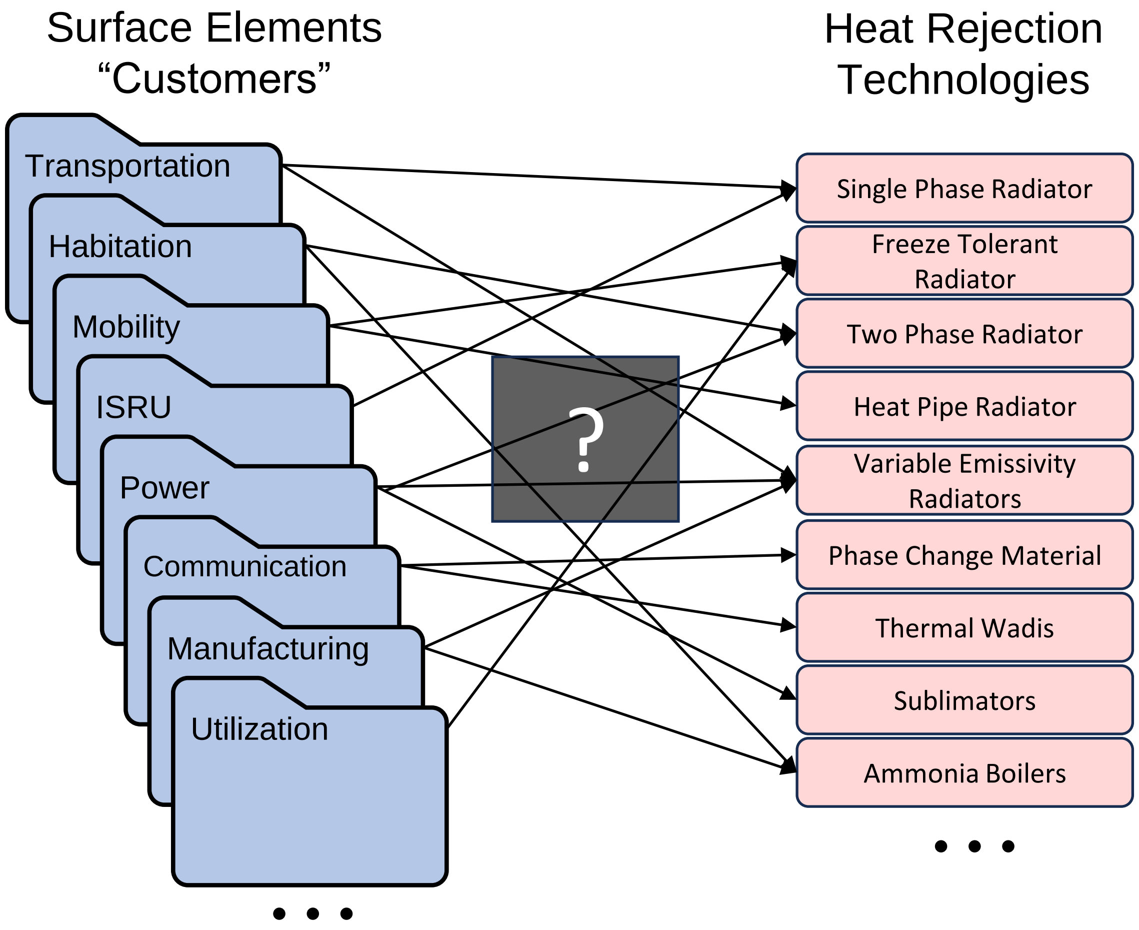
Heat Rejection Challenge

Continuous surface operation requires numerous surface elements, each with unique:

- Environmental conditions
- Heat loads (Magnitude and temperature)
- Scales of operation

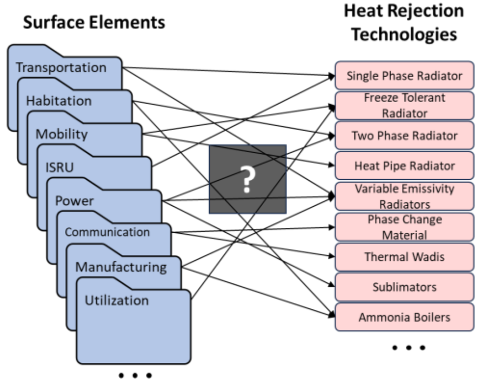
Animation created by Lunar Surface Innovation Consortium (https://lsic.jhuapl.edu/)

Motivation

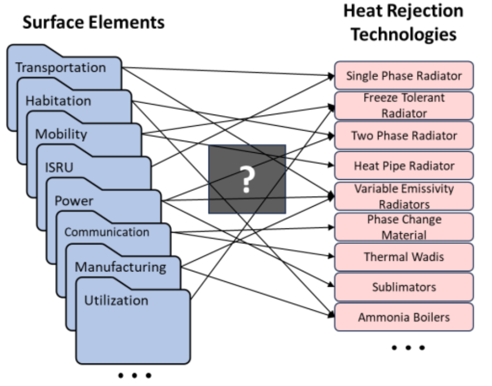

Surface Elements
"Customers"
Heat Rejection
Technologies
Transportation
Habitation
Mobility
ISRU
Power
Communication
Manufacturing
Utilization
• • •
?
Single Phase Radiator
Freeze Tolerant
Radiator
Two Phase Radiator
Heat Pipe Radiator
Variable Emissivity
Radiators
Phase Change Material
Thermal Wadis
Sublimators
Ammonia Boilers
• • •

Motivation

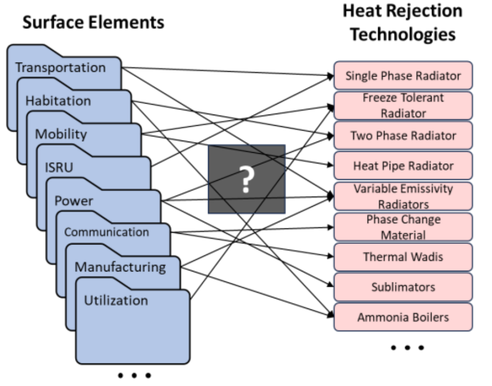
Lunar Highlands



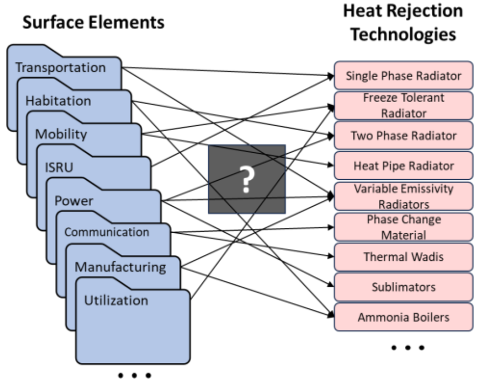
Lunar Mare



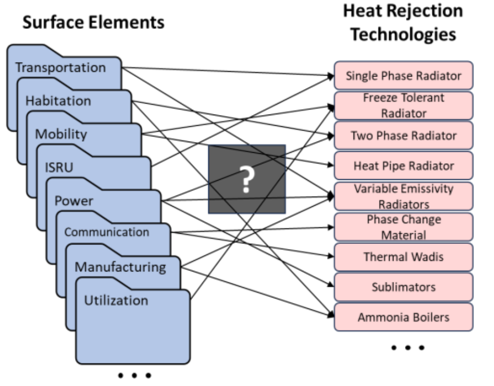
Lunar South Pole



Mars Mid-Latitude



Mars Equatorial



Goals of Analysis

1. Identify a list of:
   - Surface elements that require heat rejection
   - Heat rejection technologies
   - Environmental conditions

2. Develop a modeling framework for characterizing the performance of a vast number of heat rejection technologies across numerous environments and applications

3. Use modeling framework to determine the most promising heat rejection technologies for operation on the Moon and Mars.

Overview of Modeling Framework

ATC_Explore_Database.xlsx

Sheet 1 (Heat Rejection Technologies)

For each technology:
- Basic description of the technology
- Dependency on other technologies
- How is technology affected by parametric inputs? (heat load, environment, etc.)
- Assessment criteria notes (i.e. TRL, reliability, robustness, etc.)
- References

Sheet 2 (Surface Elements)

For each surface element:
- Description of system
- Point of contacts with experience in technology.
- Assumptions
- What environment is expected to operate in?
- What heat load/temperature/etc. is expected?
- References

Sheet 3 (Environments)

For different thermal environments (varying latitude on Moon and Mars):
- Surface Temperature
- Atmospheric Temperature
- Solar Fluxes
- Atmospheric Pressures
- Gravity Field
- Wind Velocity
- Potential Dust

Microsoft Teams Reference Folder

- Reference PDF/word/ppt for every heat rejection technology source that is referenced in Excel Sheet
- Reference PDF/word/ppt for every surface element source that is referenced in Excel sheet
- Reference PDF/word/ppt for every environmental condition source referenced in Excel sheet

Surface Elements

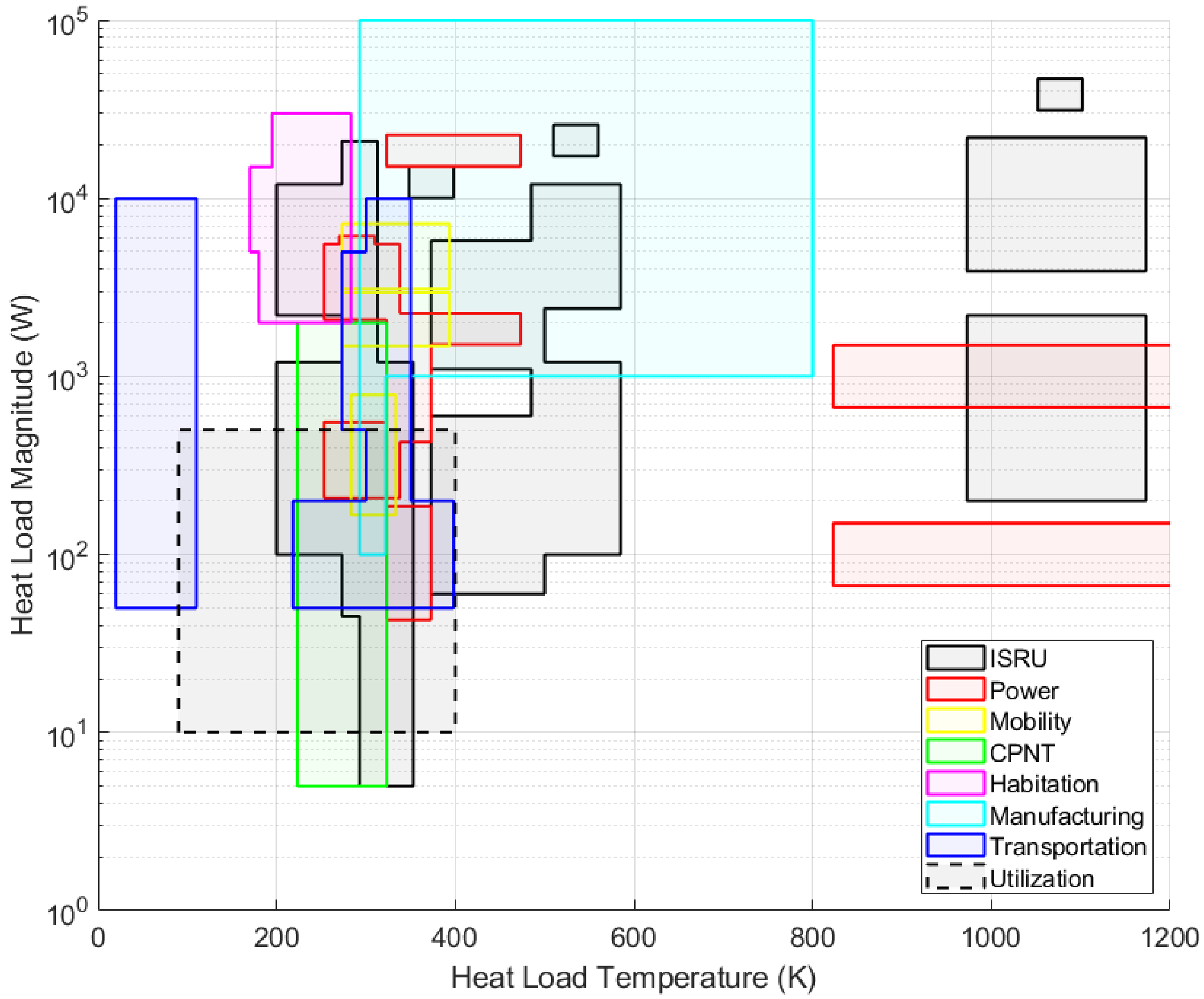
- Following surface elements were evaluated to identify the required heat rejection characteristics (magnitude, temperature, turndown ratio, etc.)

CPNT	Habitation	ISRU	Manufacturing	Mobility	Power	Transportation Systems	Utilization Systems
Orbiters for relaying data	Lunar Foundational Surface Habitat	Mars ISRU Propellant Plant	Using Regolith to Build Structures	Pressurized Rover	Solar Concentrator	Cryogenic Fluid Management (CFM)	Scientific Demos
Ground communication	Lunar Multi-purpose Habitat	Lunar ISRU Water Plant	Sintering of Regolith	Unpressurized Rover	Fission Surface Power	Commercial Lunar Payload (CLPS)	
	Mars Monolithic Habitat	Lunar ISRU Molten Regolith Electrolysis Plant		EVA	Fuel Cells	Landers	
	Mars Transit Vehicle	Lunar ISRU Carbothermal Reactor			Batteries	Mars Ascent Vehicle (MAV)	
		ISRU Mining and Excavation			Generic PMAD		
					Solar Arrays		
					Power Beaming		
					RTGs		
					Superconducting Cable Transmission		

Surface Elements

- Many of the surface elements have heat rejection needs between 200 and 350 K
- Higher temperature surface elements are generally either power generation, ISRU, or manufacturing
- Lower temperature surface elements are generally scientific experiments or propellant

Range of Heat Load Magnitude and Temperature

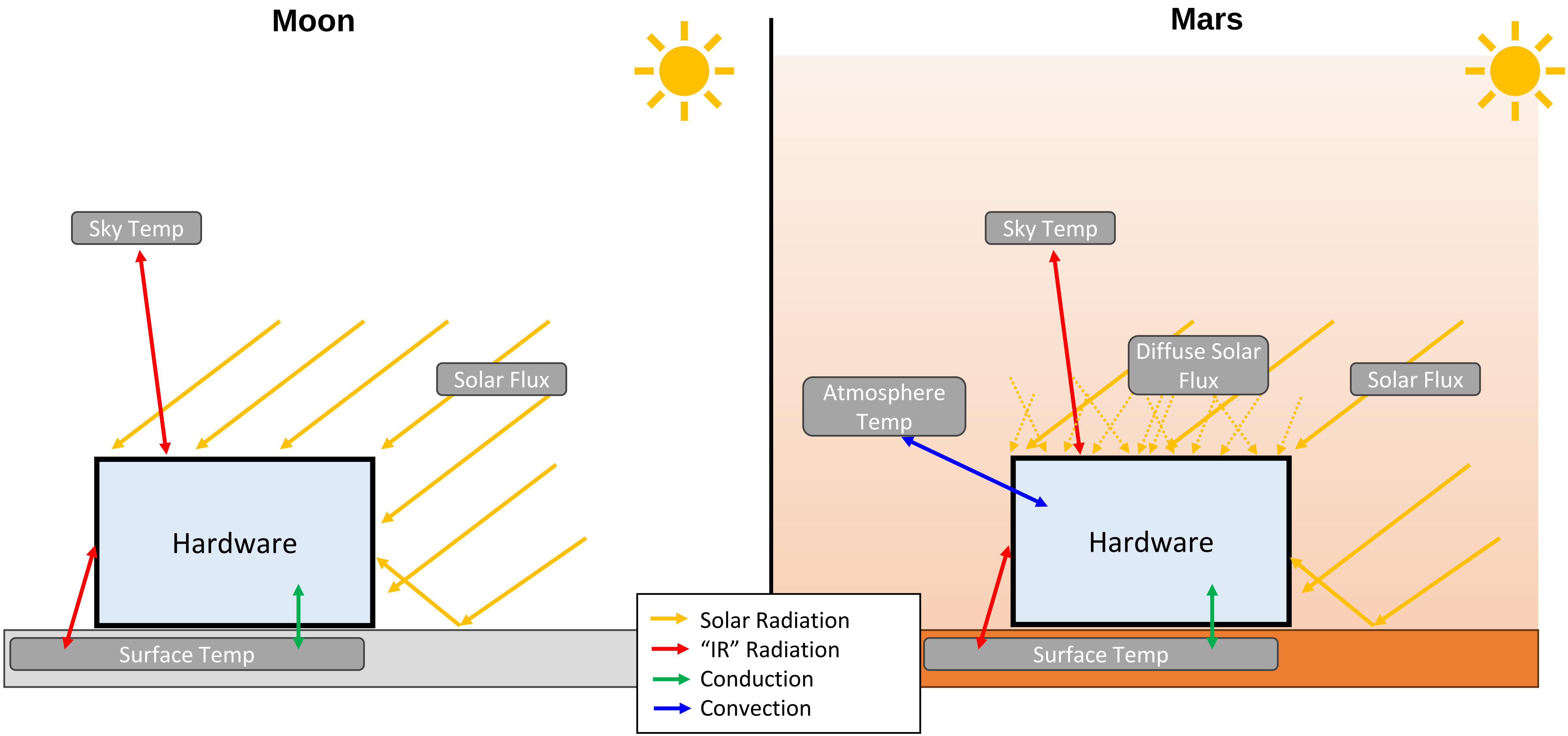


Heat Rejection Technologies

- Over 60 heat rejection technologies were originally identified and qualitatively assessed to determine the strengths and weaknesses of each technology.
- List of 60 technologies was reduced to 35 technologies that warrant further modeling and integration into study.

Two-Phase Flow Devices	Heat Pipes	Heat Pumps	Dual Function Radiators	Internal Radiator Adjustments	External Radiator Adjustments	Thermal Storage	Venting	Other
Thermo-syphon Radiator or System	Composite Heat Pipe Radiator	Vapor Compression Heat Pump	Combined Radiator and Solar Panel Function	Composite Flow through Radiators with Gas Gap	Sun Shades (Deployable and/or Freestanding)	Ground-Coupled Radiator	Sublimator	Cooling Tower
Two-phase Thermal Control Systems with Mechanical Pump/Separator	Axial-Groove Heat Pipe Radiator	Solar Vapor Compression Heat Pump	Combined Radiation Protection and Heat Rejection Function	Composite Reflux Boiler Tube Radiator	Unfurlable Radiator	Phase Change Thermal Storage	Evaporative Cooler	Electro-Luminescent Cooling
Low-Power Two-phase Thermal Control System	Arterial Heat Pipe Radiator	Stirling/Thermoacoustic Heat Pump, Duplexes		Serpentine Single Phase Radiator Design	Rotary Fluid Coupler	High-Capacity Phase Change Thermal Storage	Joule Thomson (JT) Coolers - Compress CO_2 to Allow for Venting	Pumped Fluid Loops with Regenerative Heat Exchanger
Two-phase Thermal Control Systems with Electrohydrodynamic Pumping	Arterial Heat Pipe Radiators with Electrohydrodynamic Pumping	Thermoelectric Heat Pump		Freeze/Thaw Tolerant Radiator with Variable-Conductance Radiator	Variable Emittance Radiator Coatings	Thermal Wadi	Ammonia Boiler	Novel Thermal Control System Coolants (Single Phase)
Capillary Pumped Loop		Thermoacoustic Heat Pump		Direct Condensation Radiator (DCR)	Shape Memory Alloy Radiator	Geothermal Energy Storage		Microchannel Heat Exchanger
		Complex Compound Heat Pump		Freeze/Thaw Tolerant Radiator	Inflatable Radiator	Dual Sink		Supercritical Fluids
		Geothermal Heat Pump		Drainable Radiator for "On/Off" Capability	Two Sided Radiator			Martian Atmosphere Liquid Heat Exchanger
		Zeolite Heat Pump		Passive Thermal Control Heat Switch	Parabolic Reflector Radiator			Environment Pressure and/or Temperature Manipulation to Use Phase Change
				Improved Radiator Flow Geometries to Reduce Pressure Drop and Pump Power	Manipulating the Radiator Surface to Promote Convection			
				Liquid Droplet Radiator	Dust Tolerant Radiator			
				Moving Belt Radiator	Trihedral Radiator			
				Lithium Chloride Radiator	Gimbled Radiator			

Simple Characterization of Environments



Environments

Lunar Environments

Latitude	Surface Temperature (K)	Sky Temperature (K)	Direct Solar Flux (W/m^2)
South Pole	28.5 – 304.0	2.73	1315 - 1420
-67.5°	61.0 – 347.4	2.73	1315 – 1420
-45°	81.0 – 374.4	2.73	1315 – 1420
-22.5°	87.7 – 390.8	2.73	1315 – 1420
Equator	90.7 – 404.6	2.73	1315 – 1420
+22.5°	88.4 – 389.7	2.73	1315 – 1420
+45°	81.7 – 376.2	2.73	1315 – 1420
+67.5°	48.4 – 340.5	2.73	1315 – 1420
North Pole	27.3 – 284.6	2.73	1315 – 1420

Martian Environments

Latitude	Atmosphere Temperature (K)	Surface Temperature (K)	Sky Temperature (K)	Direct Solar Flux (W/m^2)	Diffuse Solar Flux (W/m^2)
-50°	136.8 – 281.4	136.8 – 306.6	77.2 – 233.0	0 – 626	0 – 186
-25°	155.1 – 284.9	151.2 – 314.7	105.1 – 236.5	0 – 636	0 – 212
0°	152.9 – 278.1	147.6 – 316.1	116.4 – 225.3	0 – 614	0 – 196
+25°	153.0 – 265.4	148.5 – 301.7	115.1 – 214.0	0 – 538	0 – 167
+50°	145.4 – 257.4	145.3 – 284.0	86.0 – 205.8	0 – 453	0 – 129

Goals of Analysis

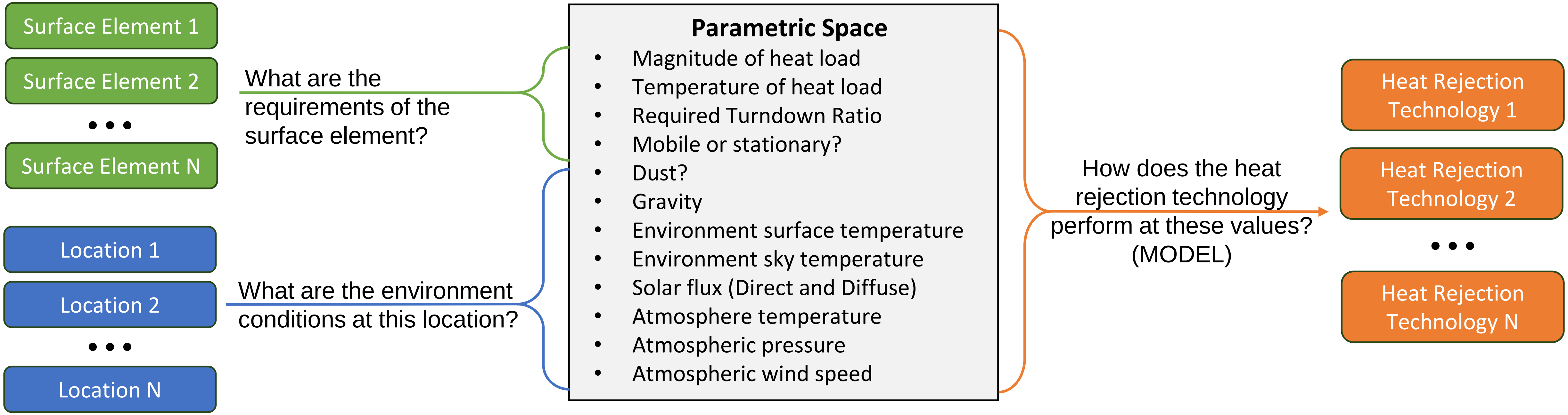
1. **Identify a list of:**
   - **Surface elements that require heat rejection**
   - **Heat rejection technologies**
   - **Environmental conditions**

2. **Develop a modeling framework for characterizing the performance of a vast number of heat rejection technologies across numerous environments and applications**

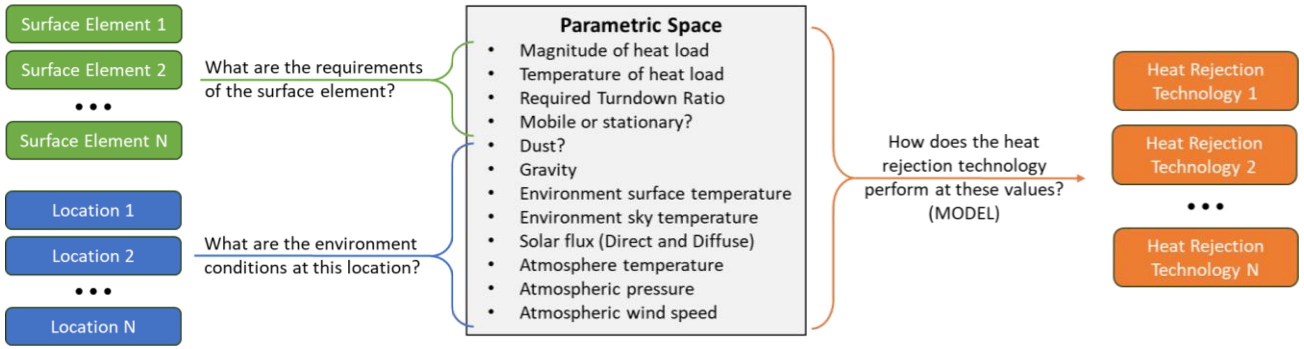
3. **Use modeling framework to determine the most promising heat rejection technologies for operation on the Moon and Mars.**

Modeling Framework – Parametric Space

- Surface elements and heat rejection technologies will be compared by relating both to a "parametric space".



Modeling Framework – 2D Example

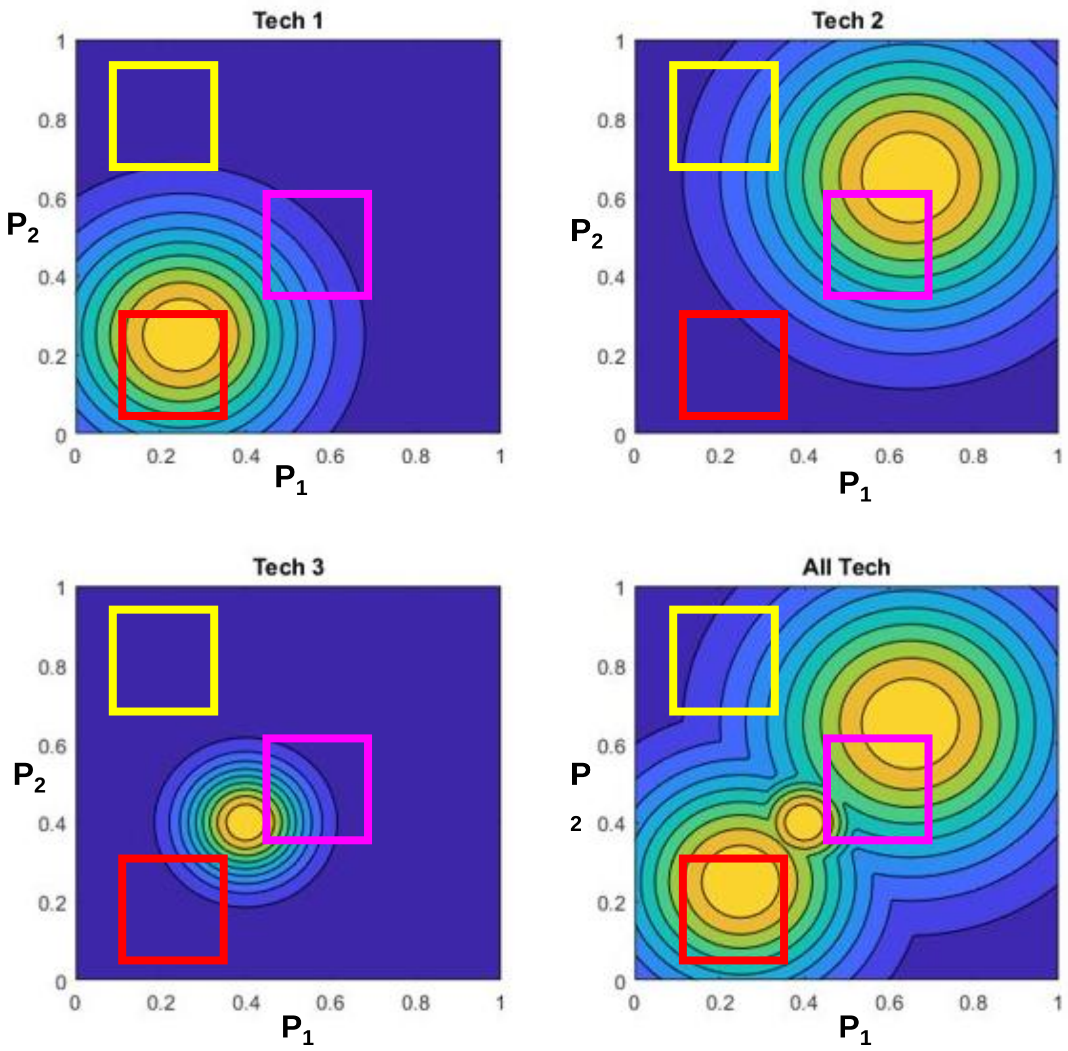


- **Contour plots could represent many variables of interest (mass, power, volume, reliability, Figure of Merit…)**

Customer 1 is satisfied by Tech 1

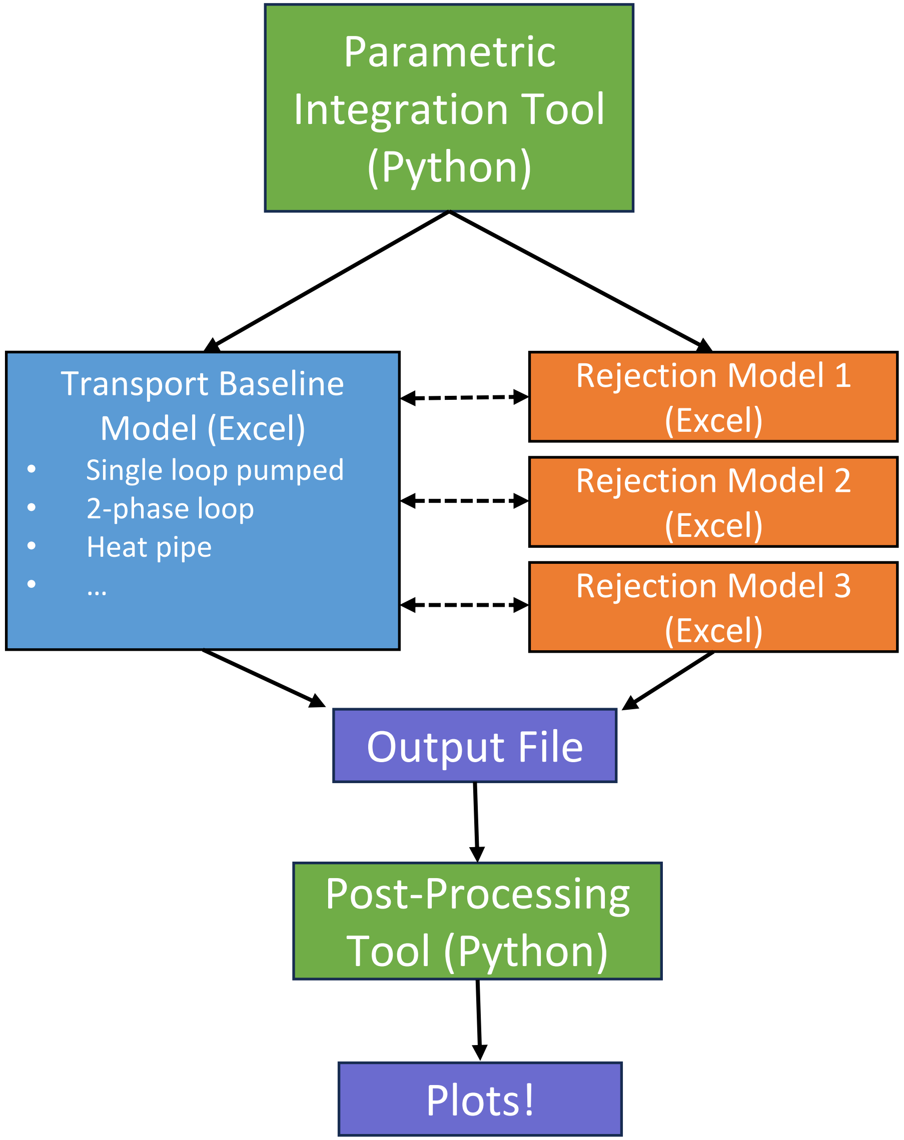
Customer 2 is satisfied by Tech 2 and Tech 3 combined

Customer 3 is not satisfied by any technologies



Modeling Framework

1. Thermal control system is broken into two categories of models:
   - **Transport model**: Basic model to capture the transfer of heat to the rejection technology through various approaches.
   - **Rejection models:** Higher fidelity models that capture size the rejection technologies.
2. Integration tool is used to determine the parametric sweeps that will be conducted.
3. Results are written to output files that can be post-processed using processing model that is used to analyze results



Model Framework Considerations

Why Excel Based Modeling?

- Modeling in Excel allows for an accessible model that does not rely on any complicated software, making the model and framework available to anyone
- Modeling in Excel forces models to be simple and generic, avoiding issues with slow models being used to evaluate across a wide range of parameters.

Why separate transport and rejection models?

- Goal of project was to evaluate heat rejection technologies, so emphasis was placed on rejection models.
- Still important to capture the impacts of transport loop if it limits the feasibility of rejection.
- Framework still allows connection between models to account for impact of rejection on transport (and vice-versa).

Why is the framework integrated with Python?

- Python integration tool enables rapid setup of parametric sweeps.
- All models are GUI-based allowing for engineers with limited comfort or experience in coding or Python to still set up and run models.
- Original plan of using VBA to control parametric sweeps resulted in too many challenges.
- Python script was converted into executable so GUI can be run even without Python.

Evaluation Criteria

- Figure of Merit (FOM) will be used to assess the performance of each technology.

$$\mathbf{FOM} = \sum w_i \cdot x_i$$

  - x_i is an assessment criteria.
  - w_i is a scaling factor for each assessment criteria.
- Weighting factors were determined by anonymously ranking the importance of each assessment criteria.
- In addition to this FOM, the team will also look at equivalent system mass as a secondary figure of merit.

Assessment Criteria	Description	Weighting
Mass	Total mass of the heat rejection system and required support infrastructure	0.171
Power	Total power usage of heat rejection system and required support infrastructure	0.165
Reliability	Likelihood of a technology to perform its intended function without failure	0.163
Volume	Total volume of heat rejection system and required support infrastructure	0.110
Deployability	Ability and simplicity of stowing, launching, and deploying a technology.	0.106
Maintainability	Ability and simplicity of system to be inspected and repaired.	0.092
TRL	Technology Readiness Level	0.081

Goals of Analysis

1. Identify a list of:
   - Surface elements that require heat rejection
   - Heat rejection technologies
   - Environmental conditions

2. Develop a modeling framework for characterizing the performance of a vast number of heat rejection technologies across numerous environments and applications

3. Use modeling framework to determine the most promising heat rejection technologies for operation on the Moon and Mars.

Still In Progress…

Evaluating Heat Rejection Technologies

- Development of 35 heat rejection models is in work
- Final conclusions have not been completed yet – results expected by end of FY26.
- Subsequent slides will address a few technologies and some of the trades that can be conducted upon completion of this study.

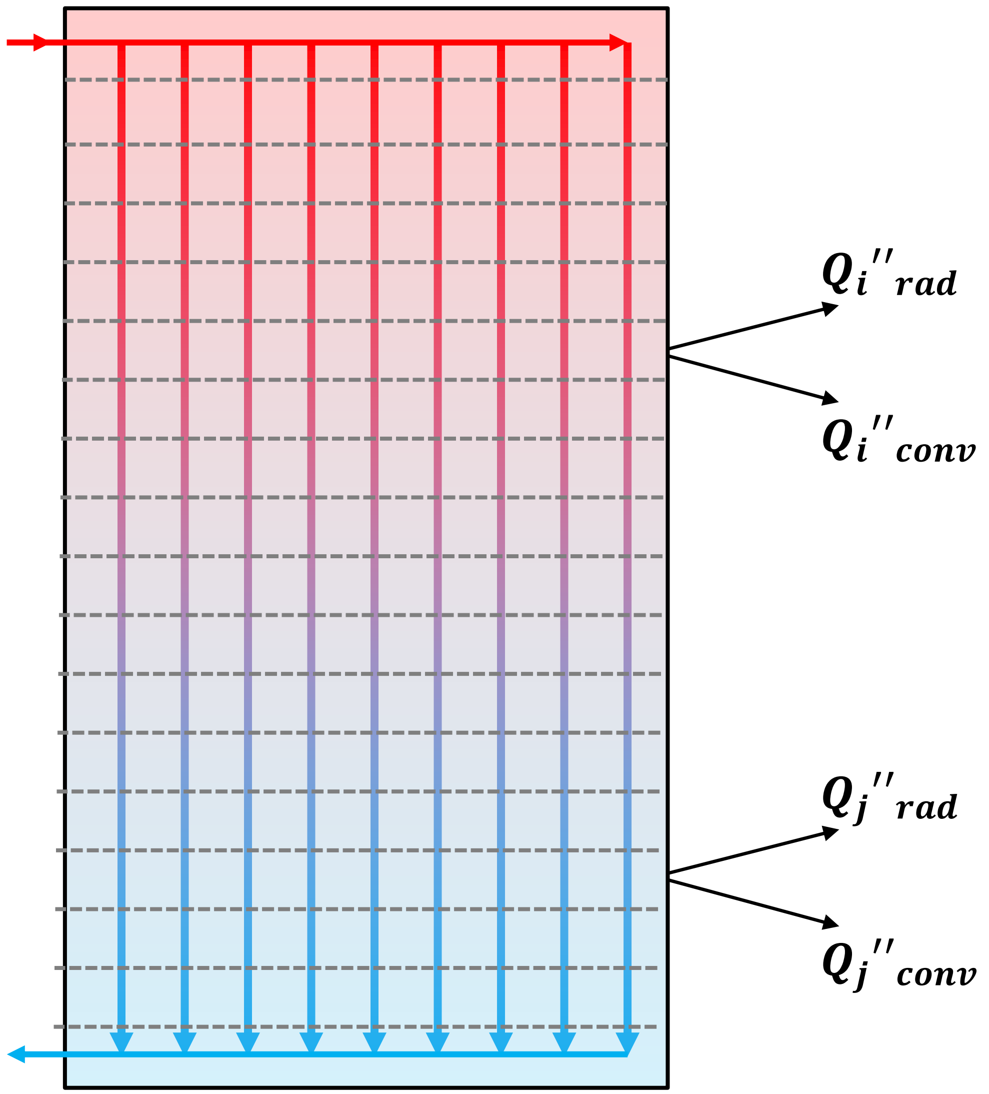
Basic Parallel Flow Radiator

Modeling Approach:

- Radiator is broken into N segments in the direction of flow, each segment assumed isothermal
- Energy balance on each segment is conducted to determine radiator temp and drop in temperature of fluid

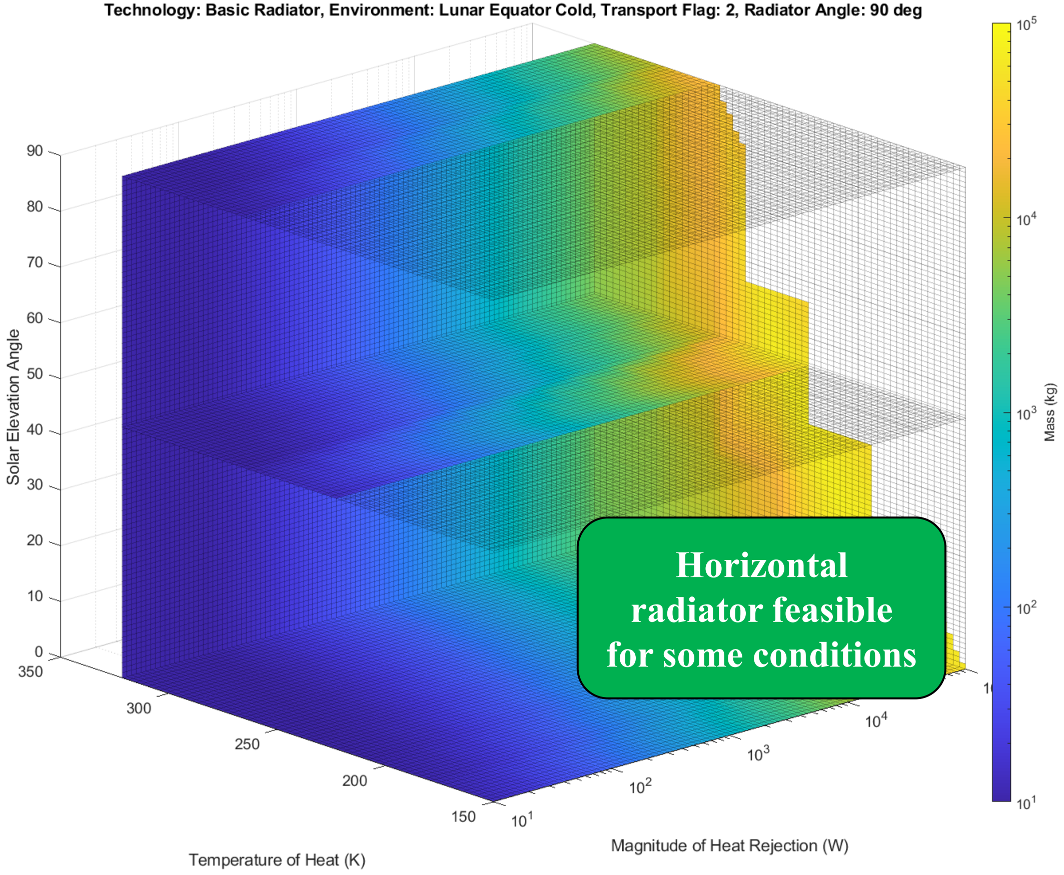
$$\dot{m} c_p \Delta T_{i,fluid} = A_i \left(Q''_{rad,i} + Q''_{conv,i} \right)$$

- Area of each segment is iterated until the desired heat rejection off the total radiator is met
  - Given area: Mass, volume, and pressure drop are determined
- Mass/power/volume of radiator is combined with mass/power/volume of transport loop (computed in separate model) to provide an assessment of total system

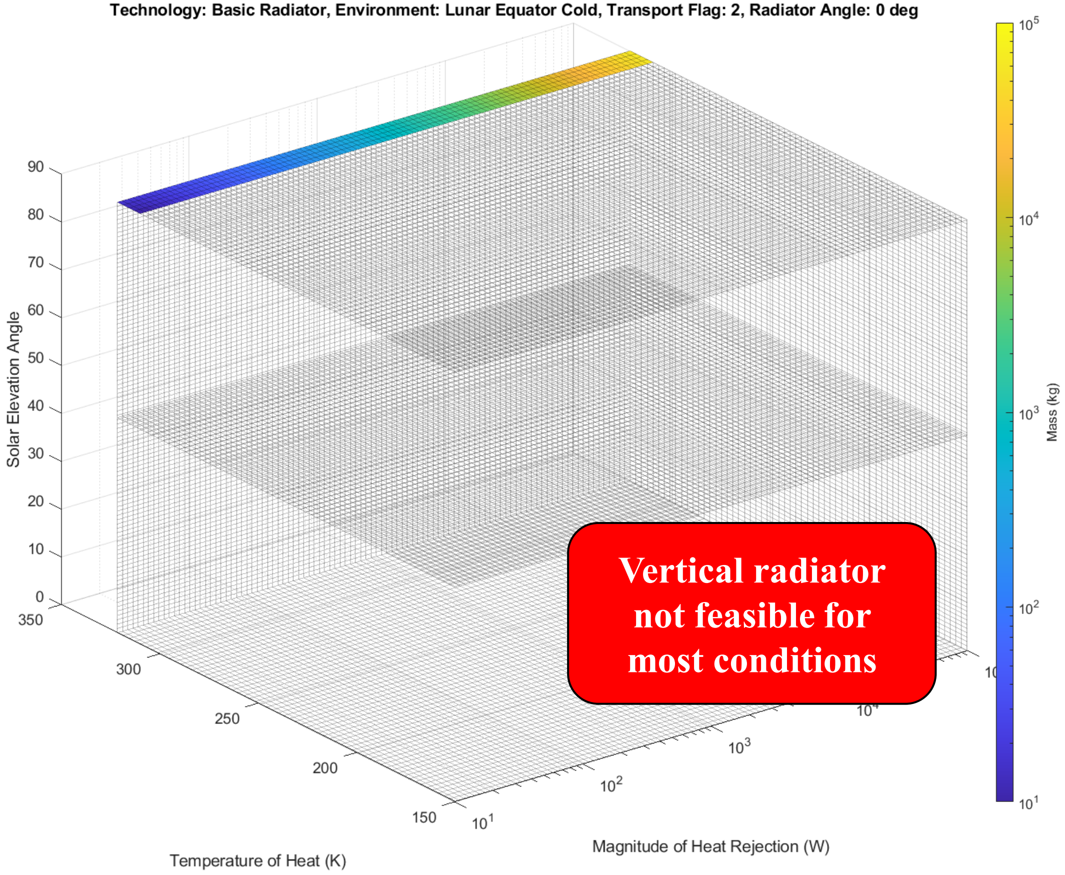


Basic Parallel Flow Radiator – Example Results

Mass of Horizontal Radiator on Lunar Equator



Mass of Vertical Radiator on Lunar Equator

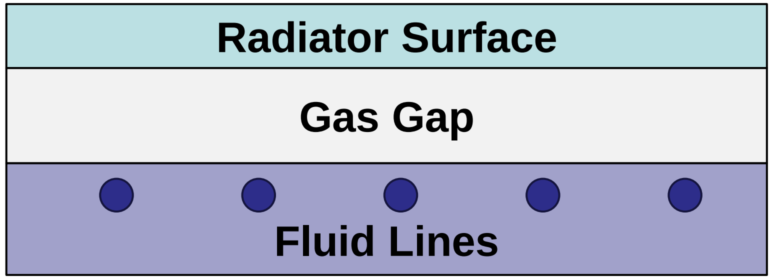


Examples of Additional Models Built

Gas Gap Radiator:

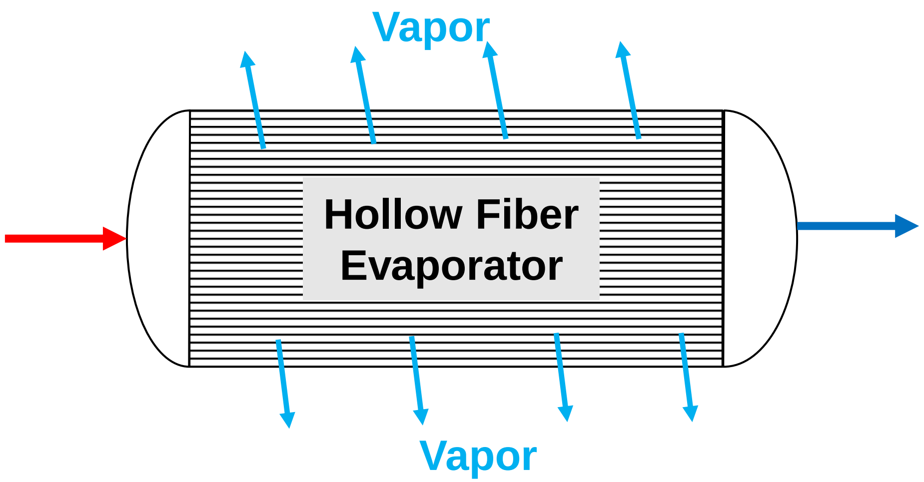
- Features a gap between the working fluid and radiator surface that can be evacuated to enable higher turndown ratios
- Benefits: high turn down ratio
- Disadvantages: less effective at max heat load

Gas Gap Radiator



Evaporator:

- Vents water to reject heat in warmer environments
- Benefits: works in hot environments where radiators struggle
- Disadvantages: Uses a consumable



Geothermal Energy Storage:

- Heat generated during the day is rejected into the regolith, and used as a source of heat during night
- Benefits: helps with large swings in environment temperature
- Disadvantages: More complicated deployment

Conclusions

- Parametric based analysis of heat rejection technologies will enable trades across various:
  - Heat rejection technologies
  - Surface environments
  - Customer needs
  - Design decisions
- Modeling framework will be used to evaluate performance of technologies by assessing the mass, volume, power, turndown ratio, reliability, robustness, TRL, and deployability of all technologies
- Conclusions pulled from study will enable strategic decisions on capability gaps, promising low TRL technologies, and development of heat rejection roadmaps.