

National Aeronautics and  
Space Administration



# Johnson Space Center Thermal Technology Roadmap 2026

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*Amentum*

# Johnson Space Center (JSC) Overview

- The Hub of Human Spaceflight
- Established in 1961 as the Manned Spacecraft Center
- Science, technology, engineering, and medicine
- Home of mission control and astronaut training

# Human Spaceflight Programs Currently Supported at JSC

International Space Station

Commercial Crew

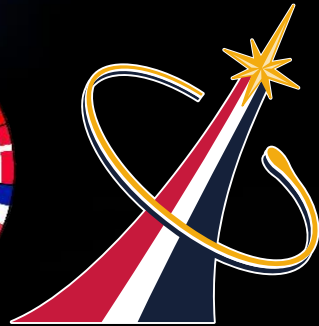
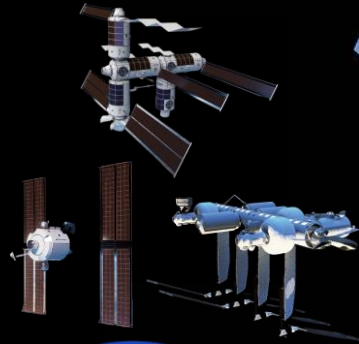
Commercial LEO

Orion

Gateway

Human Landing System

Extravehicular Activity &  
Human Surface Mobility



# Human Spacecraft Thermal Systems Development at JSC

## International Space Station

## Commercial Crew

## Commercial LEO

## Orion

## Gateway

## Human Landing System

## Extravehicular Activity & Human Surface Mobility



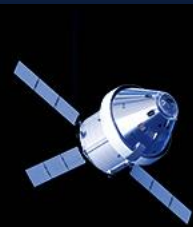
- 75 kW
- Dual pumped loops
  - Internal: Water
  - External: Ammonia
- Deployable Radiators
  - 73 ft x 11 ft x 6
- Heat pipes
- Shell heaters
- MLI
- Localized dynamic radiative environment
- Optical property degradation leading to structural loads issues
- Large heat pipe & 2-phase ATCS dev prior to ISS



- ATCS
- PTCS
- TPS
- Supplemental cooling during pre-launch, ascent, entry, post-landing



- ATCS
- PTCS



- 5 kW
- Dual pumped loops
  - Internal: PGW
  - External: HFE-7200
- Body-Mounted Radiators
  - 24m<sup>2</sup>
- PCM
- Ammonia Boiler
- Software controlled heaters
- MLI / SiOx tape on CM
- TPS



- 6.3 kW
- Dual pumped loops
  - Internal: PGW
  - External: HFE-7200
- Body-Mounted (HALO = 36m<sup>2</sup>) & Deployable Radiators
- Unique challenge due to cislunar environment and 7-day lunar orbit
- Potential lunar dust deposition
- Optical property degradation



- ATCS
- PTCS
- TPS



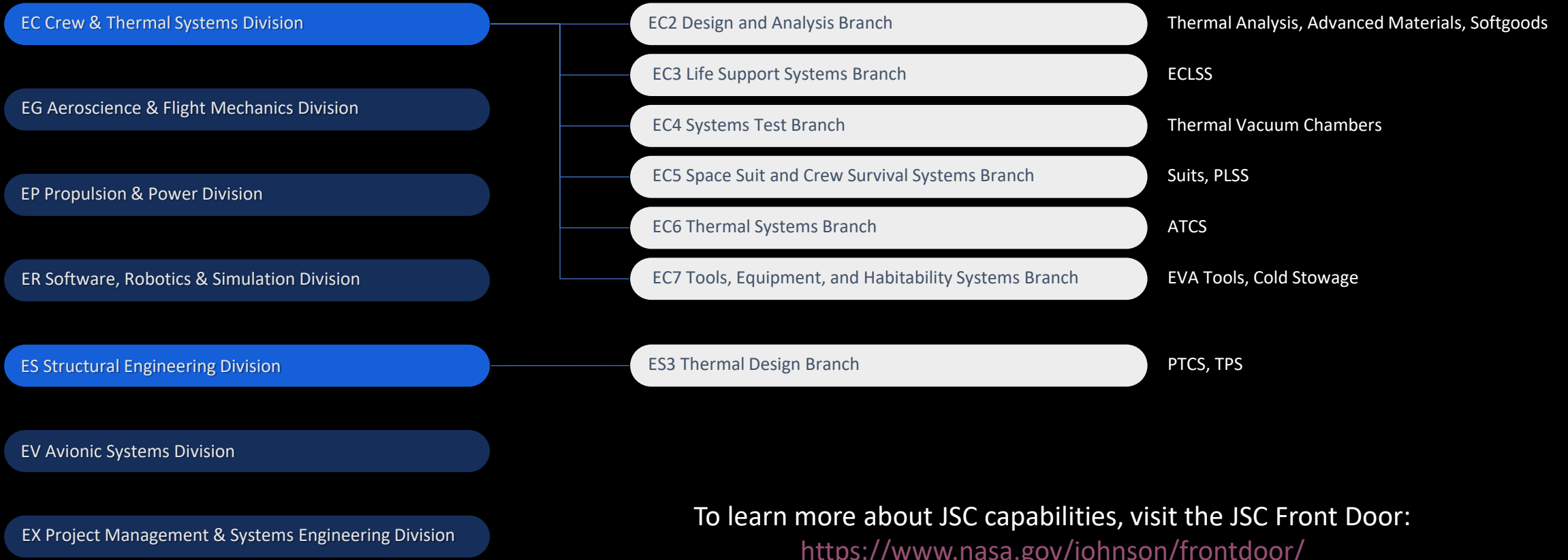
- Spacesuits
- Rovers
  - Lunar Terrain Vehicle (LTV)
  - Pressurized Rover (PR)
- Multi-Purpose Habitat (MPH)

# JSC Engineering Directorate



EA12 Chief Engineers Office

EA13 Directorate Integration Office



To learn more about JSC capabilities, visit the JSC Front Door:

<https://www.nasa.gov/johnson/frontdoor/>

# Needs & Current Tech/Flight Development

- NASA identifies and prioritizes technology gaps and shortfalls to inform technology investment strategies and investments both internally and externally
  - NASA's Exploration Systems Development Mission Directorate (ESDMD) has published Rev. C of the Moon to Mars Architecture Definition Document (ADD)
    - <https://www.nasa.gov/MoonToMarsArchitecture/>
    - **Architecture-Driven Technology Gaps** are included in Appendix D
  - NASA's Space Technology Mission Directorate (STMD) has consolidated its previous list of 187 technology shortfalls into the **2026 Civil Space Shortfalls** containing 32 broader, integrated categories.
    - <https://www.nasa.gov/spacetechpriorities/>
  - Programs also have their own technology and flight hardware development needs
- JSC informs and is guided by these technology needs, gaps, and shortfalls

# Needs & Current Tech/Flight Development

Thermal systems are categorized as follows:

## Temperature Regime

- Cryogenic ( $< -150^{\circ}\text{C}$ ) (TX 14.1)
- Moderate Temperature ( $-150^{\circ}\text{C}$  to  $500^{\circ}\text{C}$ ) (TX 14.2)
- High Temperature ( $> 500^{\circ}\text{C}$ ) (TPS) (TX 14.3)

## Human/Robotic

- Human Spacecraft
- Satellite/Robotic Spacecraft

## Active/Passive

- Active (ATCS)
- Passive (PTCS)

# Needs & Current Tech/Flight Development

- Organization
  - TX14 Thermal Management Systems
    - TX14.1 Cryogenic Systems
    - **TX14.2 Thermal Control Components and Systems**
      - **Heat Acquisition (TX 14.2.1)**
        - Cold plates, heat exchangers, condensing heat exchangers
      - **Heat Transport (TX 14.2.2)**
        - Fluid loops, pumps, heat pumps/two phase systems [here or under system?]
      - **Heat Rejection and Storage (TX 14.2.3)**
        - Heat Rejection: Radiators, radiator turn-down devices, coatings
        - Heat Storage: Phase change materials
      - **Insulation and Interfaces (TX 14.2.4)**
        - MLI
      - **Thermal Control Analysis (TX 14.2.5)**
      - **Heating Systems (TX 14.2.6)**
      - **Thermal Control System**
        - Verification and Validation (TX 14.2.7)
        - Measurement and Control (TX 14.2.8)
        - System architecture, integrated performance, hybrid systems
    - **TX14.3 Thermal Protection Components and Systems**
      - Thermal Protection Materials (TX 14.3.1)
      - Thermal Protection Systems (TX 14.3.2)
      - Thermal Protection Analysis (TX 14.3.3)
      - Thermal Protection System Testing (TX 14.3.4)
      - Thermal Protection System Instrumentation (TX 14.3.5)
  - TX09 Entry, Descent, and Landing
    - TX09.1 Aeroassist and Atmospheric Entry
      - Thermal Protection Systems (TX09.1.1)
  - TX06 Human Health, Life Support, and Habitation Systems
    - TX06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems
      - Atmosphere Revitalization (TX06.1.1)
        - Condensing Heat Exchangers
    - TX06.2 Extravehicular Activity Systems
      - Portable Life Support System (PLSS) (TX06.2.2)
        - Thermal Control
    - TX06.3 Human Health and Performance
      - Food Production, Processing, and Preservation (TX06.3.5)
        - Refrigeration, Cold Stowage

# Heat Acquisition Gaps

- **Advanced Heat Exchangers**
  - Improved efficiency
  - Reduced mass
  - Advanced materials
  - Advanced manufacturing

# Condensing Heat Exchangers & Water Separators

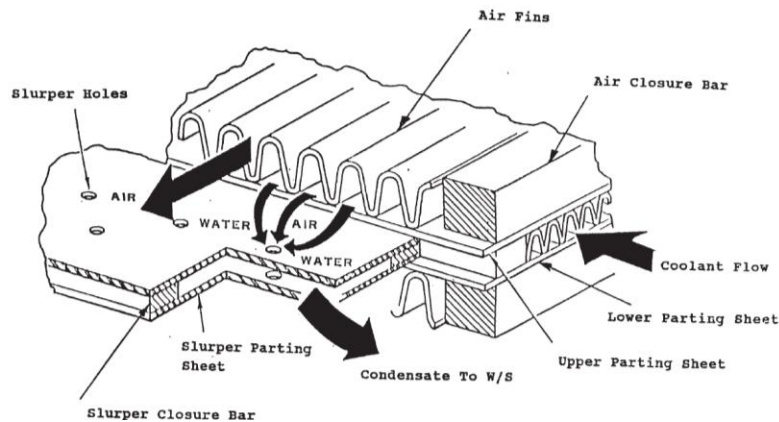
- CHX are a critical function of closed-loop life support
  - Provide sensible and latent cooling to the vehicle
  - ~50% of reclaimed water on ISS is from CHX condensate
- Current technology utilizes a hydrophilic coating to gather condensate and control microbial growth in conjunction with a monthly dry-out. Slurper bars and water separator is used to draw condensate off the CHX, delivering it to the WPA
- Three problems with current technology
  - Coating longevity
    - *Hydrophobic contamination* turns hydrophilic surfaces hydrophobic leading to *water carry-over*
    - *CHX's must be uninstalled and refurbished* on a regular basis (significant crew time & resources)
  - Microbial and fungal growth concerns
    - Current coating utilizes silver oxide to mitigate microbe growth and *must be dried out on a monthly basis* to prevent bio-film formation
    - Potential for flaking, potential for hydrophobic contamination, and additional logistics tracking with MCC
  - Current coatings may react with airborne contaminants which may cause downstream impacts to WPA
    - *Chemical reaction between contaminants and coatings* which produce DMSD's that degrade filters in the WPA
    - Currently on ISS, WPA filters can remove compounds, but are degraded at an accelerated rate (replaced every year)

***To enable long duration spaceflight and reduce upmass/downmass  
a more robust CHX is needed***

# CHX & Water Separator Technologies Being Pursued

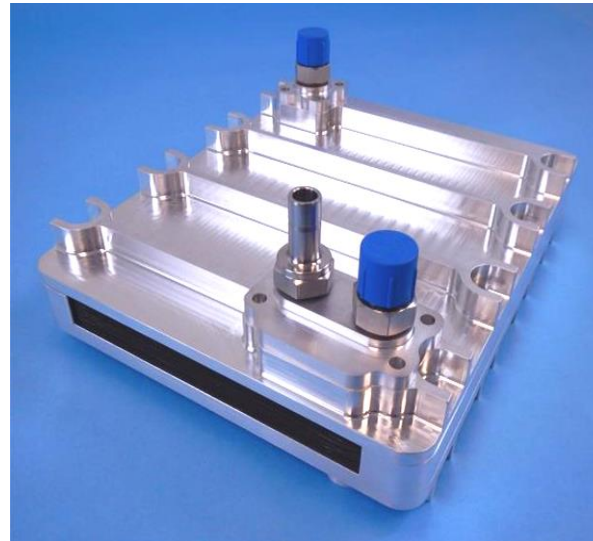
## Collins Advanced Coating

- Reformulation of current coating to address issues with wettability, dissolution, microbial growth, and DMSD production
- Reformulation primarily replaces problematic portions of their coating with more favorable coatings to decrease potential for coating contaminations and increase antimicrobial capabilities
- Concept utilizes same water separator as currently on ISS
- Titanium 3D printed CHX also being pursued with use of the new coating to decrease mass and move away from brazed CHX's



## Laser Processed Condensing HX (LP-CHX)

- Dimpled plate heat exchanger replaces typical plate/fin heat exchanger
- Condensing surfaces are 99.95% pure laser processed silver which exhibit antimicrobial properties
- Designed to eject condensate from the outlet of the LP-CHX (i.e. hydrophilic/hydrophobic insensitive)



## Condensate Separator for Microgravity Conditions (COSMIC)

- Water separator (COSMIC) is placed directly downstream of the LP-CHX and sized for full airflow, condensing rates, and various water droplet dimensions
- Once water enters, it functions similar to the current water separator in terms of water removal
- Concept allows for hydrophilic/hydrophobic insensitive condensing surfaces to be utilized, like the LP-CHX



# Heat Transport Gaps

- Novel Heat Transfer Fluids
- HFE 7200 Replacement
- TCS Fluids for Long Duration, Deep Space Missions
- Gas Trap for Non-Water Fluids
- In Situ Coolant Health Assessment
- In Situ Coolant Tube Repair
- Coolant Flexlines that Are Impermeable
- Automated Coolant Leak Locating
- Coolant Tubing with Reduced Mass
- Pumps with Increased Efficiency and Reduced Mass
- High Efficiency Heat Pumps


# Novel Heat Transfer Fluids

Early Career Faculty (ECF) 2023 Award


## Sadaf Sobhani

- *Cornell University*
- PLASMa: Precision Ionic Liquids for Advanced Spacecraft Thermal Management

### PLASMa: Precision Ionic Liquids for Advanced Spacecraft thermal Management



**Sadaf Sobhani (PI)**  
Cornell University



### Research Objectives

**Goal of this research program**

- Use machine learning and novel ionic liquids to develop **thermally stable, low viscosity, high-performance heat transfer fluids.**

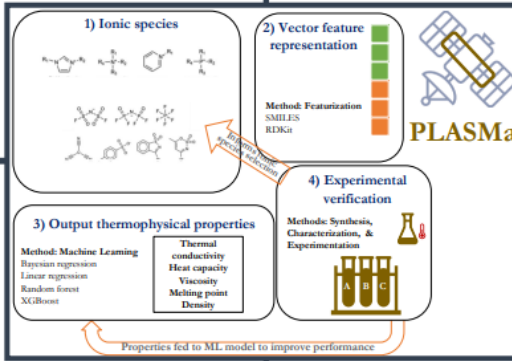
**Innovation and Advancement of the State-of-the-Art**

- Machine learning model enables **targeted fabrication of ionic liquids** for heat transfer applications
- Ionic liquids enable **low-volatility, near zero vapor pressure and tunable thermal properties**

**TRL Levels**

**Initial:** Ionic liquids for heat transfer applications TRL 2.

**Upon Completion:** Prototypes will be developed and validated (TRL 3).



**Approach**

We will use **machine learning** to design novel ionic liquids for spacecraft thermal management. We will **experimentally characterize** fluid stability, thermophysical properties, and material compatibility.

Research Step	Outcome
Build and train machine learning model	Identify ionic liquids with requisite thermophysical properties
Fabricate ionic liquids and measure properties	Validate composition-property relationship for ionic liquids
Create and test properties of ionic liquids	Demonstrate novel high-performance heat transfer fluids

### Potential Impact

Benefits to...

**Space Science and Exploration**

- Safe non-toxic ionic liquids are suitable for future crewed missions
- Enabling technology for lunar surface and deep space thermal systems
- Machine learning for ionic liquid discovery proposed as a fundamentally new technology as part of active thermal control design

**“Spin-off” Technologies**

- Extensible to more complex ionic liquid formulations to increase domain space, as well as other subsystems (e.g., advanced ionic liquids for electric propulsion)

# HFE 7200 Replacement

- HFE 7200 is the heat transfer fluid in the external coolant loops for Orion and Gateway
- 3M has ceased production of HFE 7200 to exit manufacturing of perfluoroalkyl substances (PFAS)
- Orion and Gateway have stockpiled HFE 7200
- JSC is working with the NASA Engineering and Safety Center (NESC) to identify and evaluate alternate coolants for use in future missions

# Coolant Servicer System (CSS)




- Coolant Servicing System (CSS)
  - The Coolant Servicing System (CSS) is a Government Furnished Equipment (GFE) project for Gateway to remove entrapped air from and refill the Gateway HALO, IHAB, and ALM module Internal Active Thermal Control System (IATCS) coolant lines
  - The CSS will utilize a Commercial Over the Shelf (COTS) Intravehicular Activity (IVA) drill to power the refill pump and utilize the Fluid Storage Hub (FSH) GFE Project's Gateway Water Transfer Reservoir (GWaTR) bag as a PGW reservoir
  - CSS utilizes the module IATCS pump for overall coolant loop degassing



- Changes from Heritage Design / Gateway Use-case
  - Testing showed ISS heritage gas trap membrane is incompatible with PGW, resulting in leakage from the liquid side to the gas side of the membrane
  - CSS design minimizes complexity to improve ease of use over ISS heritage Fluid Servicer System (FSS)
    - Current CSS design includes no manual valves or electronics


# A Compact, Gravity-Insensitive Gas Trap for Extreme Temperature Environments (SBIR)



**SBIR · STTR**  
America's Seed Fund™  
POWERED BY NASA

**Z2.01-1555 - A Compact, Gravity-Insensitive Gas Trap for Extreme Temperature Environments**

PI: Thomas Conboy , Creare, LLC - Hanover, NH



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NON-PROPRIETARY DATA

**IDENTIFICATION AND SIGNIFICANCE OF INNOVATION**

The overall project goal is to develop a lightweight, low maintenance, gravity-insensitive gas trap for accumulation of trapped non-condensable gas in spaceborne coolant loops circulating low surface tension fluids. Our technical approach is to develop a dual membrane gas trap featuring both hydrophilic and superhydrophobic microporous titanium alloy tube structures. The specific innovations include (1) the use of novel microporous hydrophilic material treated with FLSP techniques to enhance bubble point with negligible impact to liquid permeability; (2) the use of novel microporous superhydrophobic material treated with FLSP techniques to enhance liquid entry pressure with negligible impact to gas permeability; (3) the unique design layout including an inlet separation stage and gas accumulation core, and (4) the development of a concept of operations for the gas trap venting that eliminates large pressure gradients on porous materials.

**TECHNICAL OBJECTIVES AND PROPOSED DELIVERABLES**

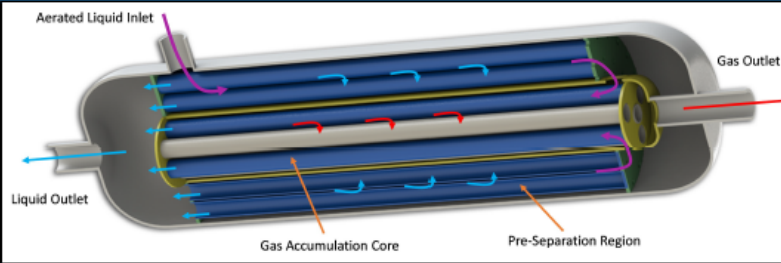
In Phase II, we will work with NASA and our partner, Sierra Space, to further develop, demonstrate, and lay the groundwork for commercialization of the gas trap technology. Our proposed effort includes the following specific technical objectives: (1) We will conduct further work to further optimize hydrophobic and hydrophilic structures in small scale trials with larger sample size, then extend the process to processing of external hydrophilic and hydrophobic tube structures; (2) With this process developed, we will fabricate a full-scale gas trap capable of serving a multi-kW spaceborne thermal coolant loop; (3) We will demonstrate its steady state and transient performance over a wide range of conditions in a laboratory coolant loop with bellows-type accumulator. The loop will be suitable for installation onto a parabolic flight for microgravity testing; (4) We will then conduct microgravity flight tests of the gas trap within the aerated coolant loop, using our anticipated concept of operations, aboard a series of parabolic flights to advance the technology to TRL-6 (ie, demonstration in a representative environment). Finally, we will deliver the prototype to NASA for further performance evaluation.

**TRL**

*Estimated*

1	2	3	4	5	6	7	8	9

**IMAGE TITLE: Creare's Gas Trap Design**



**NASA APPLICATIONS**

Gas traps are needed for enhanced reliability in thermal control for NASA missions including on-board the ISS. The current proposed effort would enable high reliability coolant loops for use in future lunar habitats or extreme environments circulating low-surface-tension fluids. Other governmental applications (e.g., DoD) are similar to NASA uses, specifically high reliability coolant loops operating in extreme environments for aircraft, ships, and ground vehicles.

**NON-NASA APPLICATIONS**

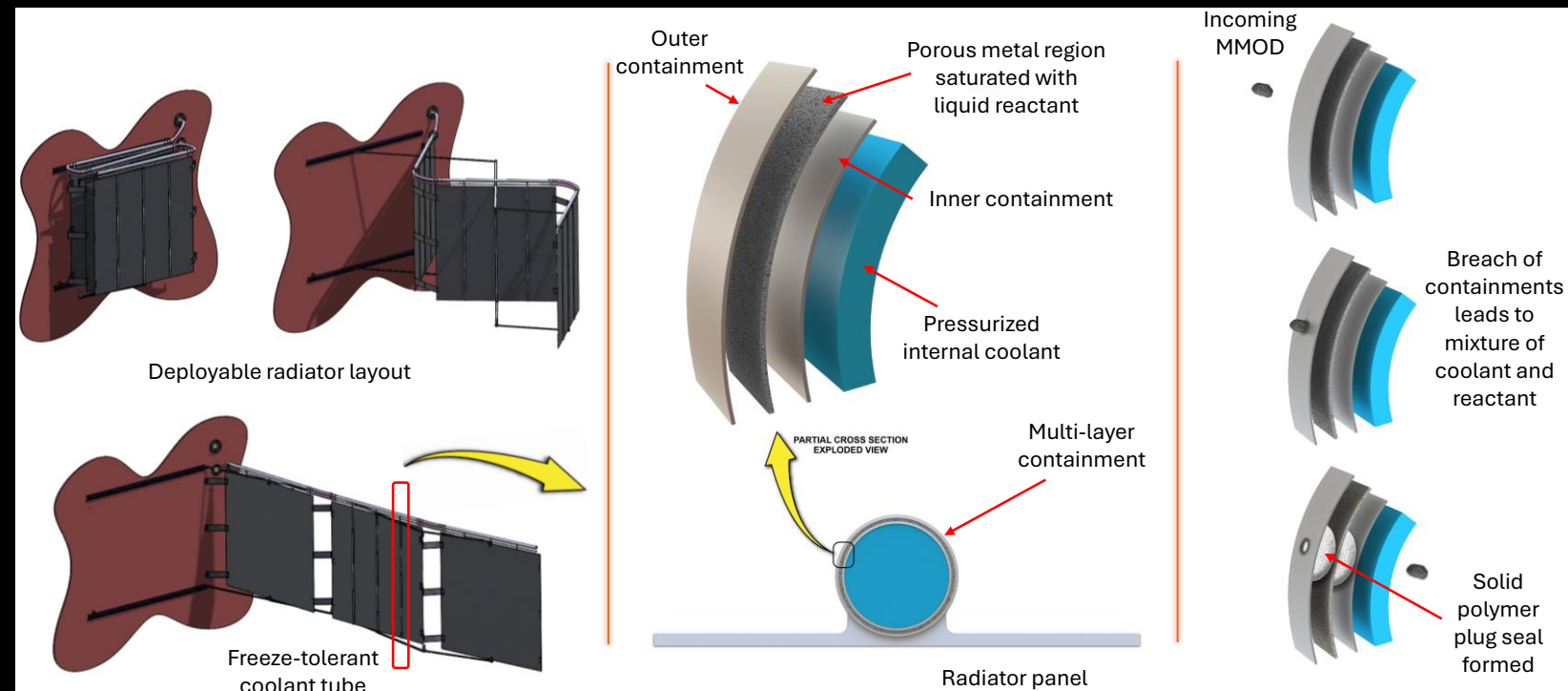
The superhydrophobic membrane development has commercial applications for various chemical industries including steam separation and chemical processing with two-phase caustic chemical flows. The gas trap itself has application in high reliability coolant with minimal available maintenance such as in nuclear power plants or in other remote power stations.

**FIRM CONTACTS**

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Creare, LLC  
EMAIL: [tmc@creare.com](mailto:tmc@creare.com)  
PHONE: (603) 643-3800

# Self-Healing Radiator Coolant Tubes for Spacecraft Thermal Control (SBIR)

- NASA Phase II SBIR
  - Create
- Passively seal-healing radiator tubes to reduce risk of loss of coolant due to an MMOD strike
  - Multi-layered coolant tube with a microporous metallic matrix containing a reactive liquid
  - Upon MMOD breach, reactant polymerizes with escaping coolant, sealing damage and preserving system integrity

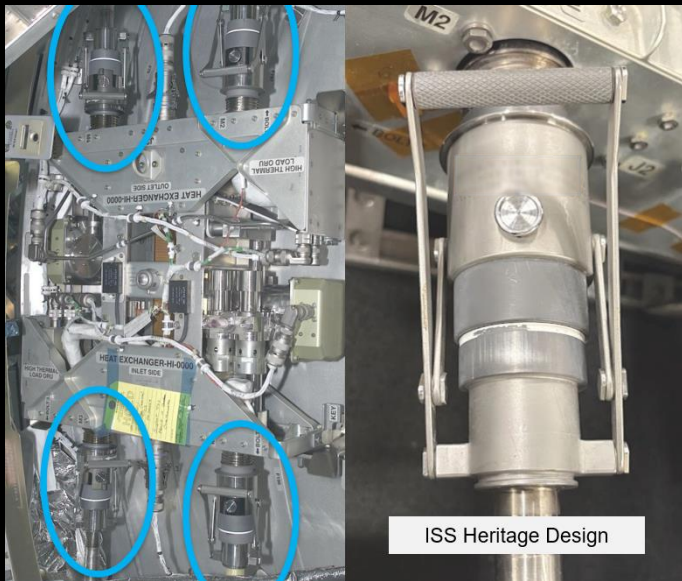


# Redesign of EVA Quick Disconnects for Exploration Surface Application

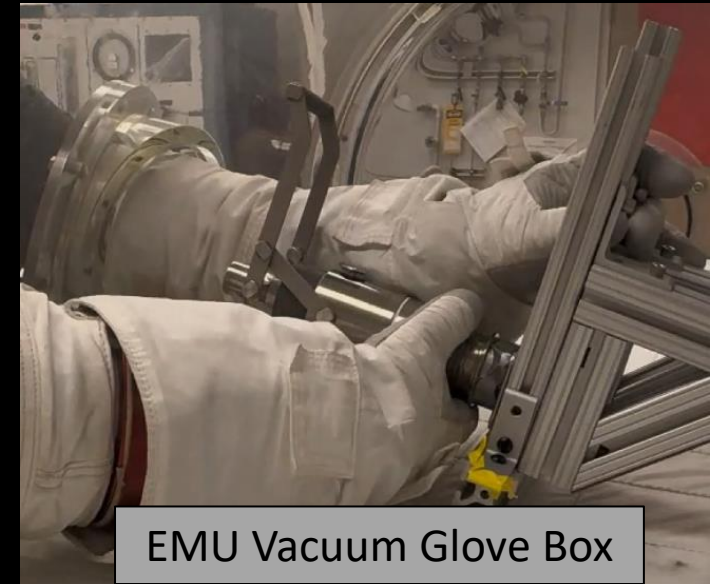
**Purpose:** Start fundamental redesign work of EVA (Crew Glove) compatible Quick Disconnects for lunar / martian surface application.

**Technical Challenge:** Improve ISS Heritage design for EVA-Glove compatibility and provide dust tolerance solutions for a lunar / martian surface.

**Proposed Solution:** (1) Create a few redesigns of the QD actuation mechanism that is simpler / higher leverage & integrate positive pressure cold gas purge to prevent dust contamination. (2) Complete dust chamber / glove box testing of prototypes to gather lessons learned and iterate further.



← Iterative prototyping →



Integrated Testing

# Heat Rejection Gaps

- Variable Heat Rejection
- Advanced Radiators – Deployable
- Advanced Radiators – Body Mounted
- Thermal Control Coatings
- Dust Tolerant Thermal Systems

# Insulation and Interfaces – Variable Emittance Coatings Tech Dev

## Current Project Objectives:

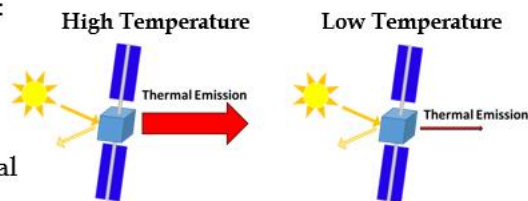
- (1) Work with collaborators to fabricate variable emittance samples with reduced transition temperature, high emittance contrast, and low solar absorptance
- (2) Develop temperature-dependent FTIR and calorimetry measurements at JSC
- (3) Trade study modeling of variable emittance coatings

## Project Motivation:

**Thermochromic variable emitters** change their emittance (heat rejection properties) based on temperature, so they can adapt to changes in internal or external heat loads

**Variable emittance coatings (VECs)** could:

1. Eliminate the need for dual loop ATCS architecture typically used on human spacecraft mission by preventing freezing of transport fluids
2. Reduce or eliminate the need for survival heaters on robotic spacecraft

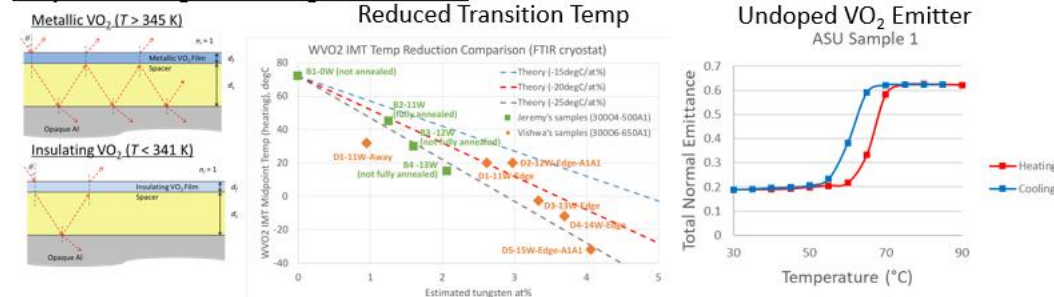


## JSC Capabilities:

1. Temperature-dependent spectral reflectance and transmittance measurements
2. Calorimetry experiment to measure temperature-dependent heat rejection
3. Thermal modeling of VECs integrated with spacecraft systems
4. Ultimate project goal is to demonstrate  $\sim 1 \text{ m}^2$  prototype radiator in TVAC



## Project Concept and Progress to Date:



$\text{VO}_2$  changes from an insulator to a metal at  $68 \text{ }^\circ\text{C}$  (undoped), which is used to create temperature-tuned variable emittance devices. PSI, Plasmonics, and ASU have developed samples with reduced transition temperature and significant emittance contrast. Voltage tuned devices can also be developed using electrochromic materials such as  $\text{Nb}_2\text{O}_5$  (UNT) and  $\text{WO}_3$ . Novel materials such as GST are also explored (UMN).

## Collaborators and Funding:

Org	Team Member	Role	Funding
JSC/ES3	Sydney Taylor, PhD	PI	ES Seed funding, ICA, CIF
PSI	David Woolf, PhD	Collaborator	CCRPP
Plasmonics	James Ginn, PhD	Collaborator	SBIR Ph I & II
ASU	Liping Wang, PhD	Collaborator	ES Seed finding, ICA, CIF
UNT	Richard Zhang, PhD	Collaborator	MUREP MSTAR
UMN	Sam Keller	Collaborator	NSTGRO

# Actively Controlled Louvers (SBIR)

## Summary of Technology

- Performance of spacecraft radiators may degrade significantly when subjected to ionizing radiation during space travel, dust during lunar landing and surface operations, and excessive heat loss during lunar nights near the poles. Currently, passive louvers provide limited protection against these hazards. They are inadequate and are not scalable to the large spacecraft planned for future manned missions to the moon and beyond.
- This SBIR project proposes to develop, demonstrate, and deliver an actively controlled, lightweight, low-power, fast-actuating, compact and highly scalable device to protect spacecraft radiators from degradation due to ionizing radiation, dust, and excessive heat loss.
- Phase I accomplishments: (i) Designed and constructed a sub-scale 0.14 m<sup>2</sup> device, (ii) Evaluated the device's effectiveness under lab conditions: obtained 100% attenuation of UV, 70% attenuation of X-rays, 85% mitigation of dust, and 92% reduction in heat loss.

## Proposed Goals

- Build on the Phase I research to design and construct a modular device to protect the spacecraft radiators
- Evaluate one module over a broad range of laboratory and simulated lunar surface conditions (including tests in cryogenic vacuum dust chamber)
- Fine-tune the design based on the above tests and construct a 7 m<sup>2</sup> prototype
- Use customer discovery to develop a technology transition roadmap
- Deliver prototype device to NASA along with documentation

## Development Plan for Phase II Year 1

- Selection of KPPs and test conditions: to be completed by the end of Q1
- Analysis, design, and construction of a single module: end of Q2
- UV transmission, X-ray transmission, dust mitigation and heat loss tests: End of Q3
- Collaboration with JSC cryogenic vacuum chamber team to develop test methods to evaluate the device under lunar conditions: end of Q4



(a) View from the front of louver module with vanes in closed position.

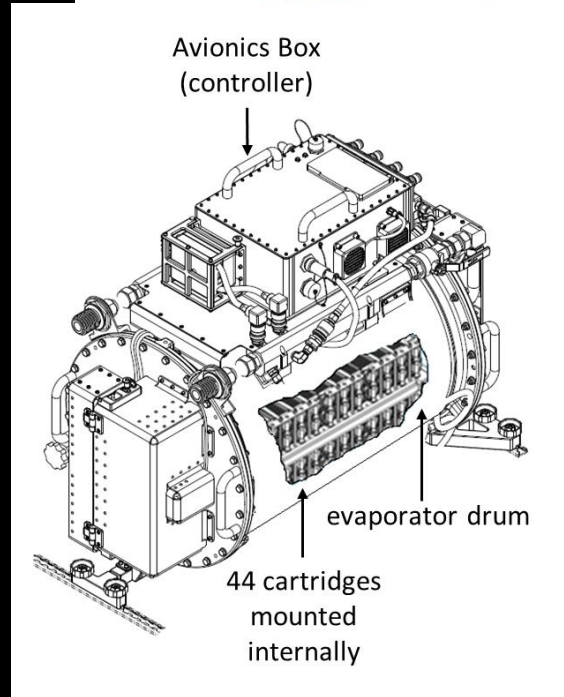
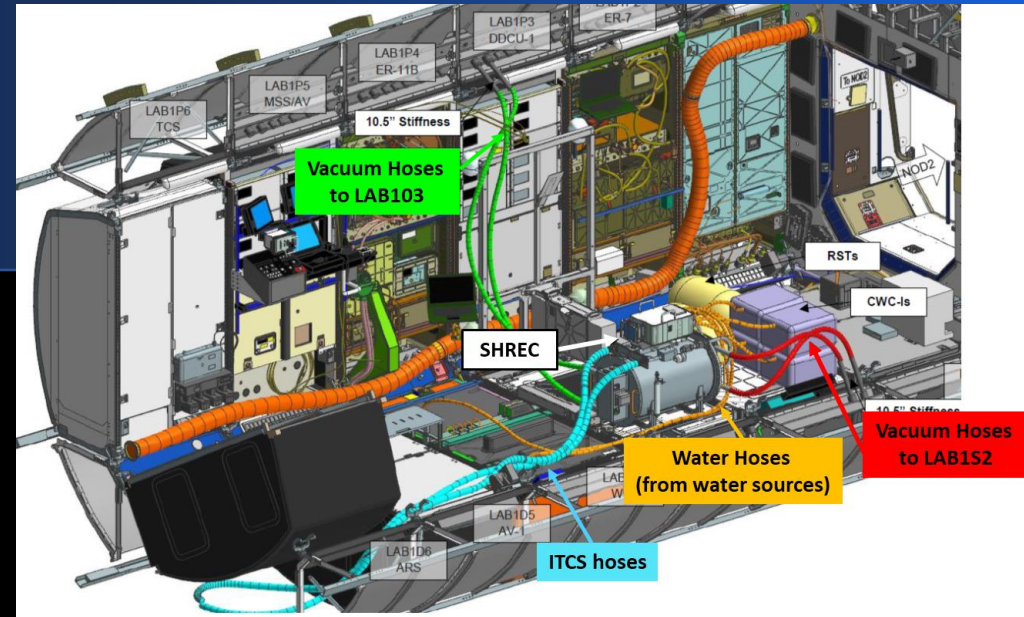
NASA Phase II SBIR:  
Analytical Scientific Products LLC



(b) View from the back of louver module with vanes in closed position.

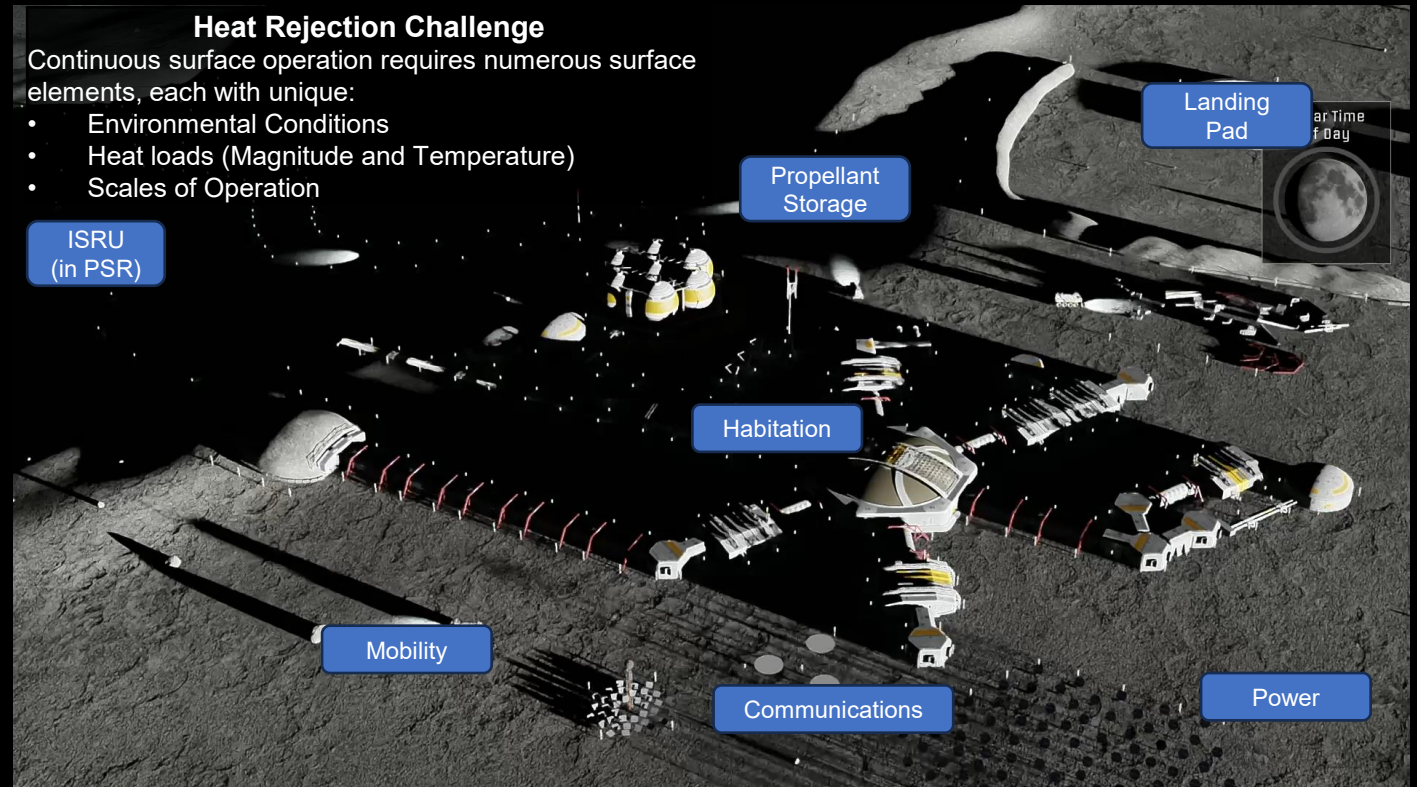
# Supplemental Heat Rejection Evaporative Cooler (SHREC)

- Supplemental Heat Rejection Evaporative Cooler (SHREC) was developed as a back-up heat rejection system for ISS in the event of a dual external thermal control system (ETCS) loop failure
- When needed, ISS will transition to minimal power and SHREC will be deployed IVA, inline with the internal thermal control system (ITCS) to provide evaporative cooling while the crew repairs one of the failed ETCS loops
- Heat rejection is provided by 44 hollow fiber cartridges that are configured to flow ITCS coolant in parallel and are mounted in an evaporator drum exposed to vacuum
- The SHREC cartridge design is based on the spacesuit water membrane evaporator (SWME)
- SHREC has a dedicated controller to maintain a range of ITCS coolant outlet temperature



# STMD ATC-Explore: Assessment of Advanced Heat Rejection Systems to Enable and Optimize Exploration Surface Operations

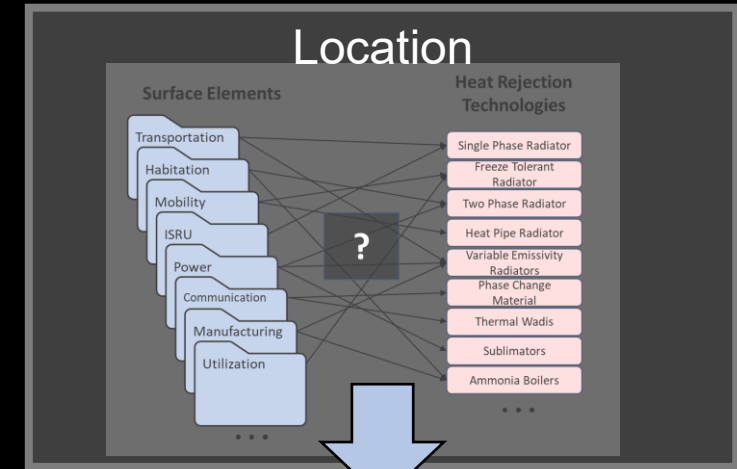
- **Challenge:** For surface operations there are many surface elements with unique operating parameters (environment, heat loads, and scale)
- **Objective:** The multi-Center (JSC, MSFC, and GRC) study aims to assess the state-of-the-art and in development heat rejection approaches to compare against one another and for different customers (e.g., habitats, ISRU, power, etc.)
- **Output Impact:** Informs technology roadmaps/portfolios for prioritization of certain technologies; highlights gaps technologies or surface parameters; and provides surface element designers with heat rejection approaches appropriate for their needs



# STMD ATC-Explore: Progress and Forward Plan

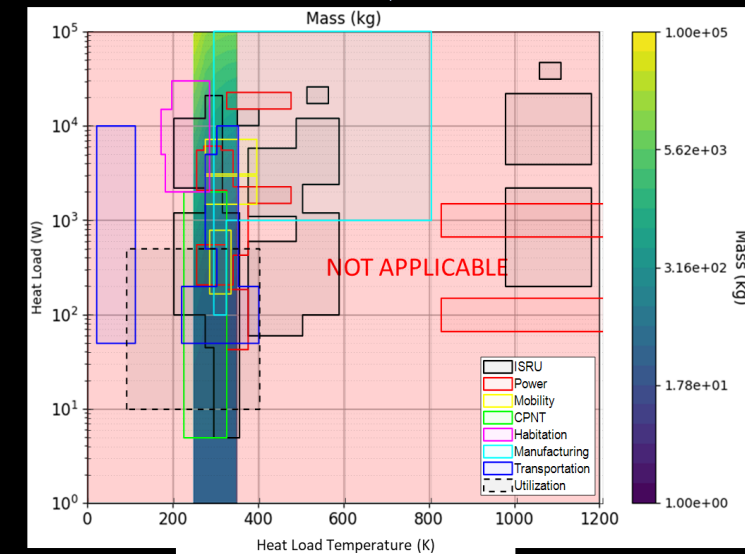
PROGRESS

- Database of surface elements and heat rejection technologies
- Develop a modeling framework
- Determine the location parameters for Lunar and Mars surface
- Determine the heat rejection needs of each surface element
- Qualitative performance assessment of heat rejection technologies



NEXT STEPS

- Build “simple” scaling models to allow for quantitative assessment
- Conduct an expansive investigation across all surface elements and heat rejection technologies to determine
  - Best technologies for each surface element
  - Technologies gaps that require investment
  - Technology portfolio roadmaps to support surface operation



# Heat Storage Gaps

- Phase Change Materials with Increased Energy Storage

# Alternate Phase Change Material (PCM) Heat Exchanger Development for Orion

- Mezzo Technologies designed and delivered a Phase Change Material Heat Exchanger Engineering development unit
- The Thermal Systems Branch is partnering with Lockheed Martin to subject the EDU to a full test series
  - Thermal Systems Branch performed leak and functional testing
  - Lockheed Martin's Denver environmental test labs performed vibration and shock testing to Orion qualification levels
- With successful completion of the test campaign, the expectation is that Lockheed Martin will work with Mezzo Technologies to continue design and development of the heat exchangers to be incorporated into future flight units
- Implementation of this alternate heat exchanger would result in a **mass savings of 58 pounds per flight vehicle.**



# Thermal Control Analysis Gaps

- Advanced modeling techniques
- Lunar and Martian thermal data and modeling tools
- Window thermal modeling and analysis
- Cross-domain sharing of thermal results
- Thermal sizing due to lunar dust adhesion

# Human Thermal Modeling (Overview)

1927	Bazett and McGlone	Measured temperature gradients in the arm
1934	Alan Burton	1st mathematical model of temperature distribution
1936	Burton and Bazett	1st transient conduction model for the body
1948	Pennes	Blood flow on tissue temperature

1961	Wissler	1st multi-element human thermal model
1964	Wissler	Human thermoregulation model using finite difference method and solved on a digital computer
1985	Wissler	15 segment, 225 node model
2001	Wissler	Modified by Nyberg, added LCVG for Constellation program

1966	Stolwijk and Hardy	Skin blood flow, sweating, and shivering
1970	Stolwijk	25 node model used for Apollo PLSS
1972	Montgomery	41 node "immersed man"
1977	Kuznetz	41 node "metabolic man", LCG, EMU (Shuttle, ISS)

Wissler

METMAN

2009	Wissler	3780 node model
2013	Wissler/Diller	6300 node C code translation with Python GUI

1997	Kraning and Gonzalez	SCENARIO
1999, 2001		Fiala
1996		ThermoAnalytics, Human Thermal Module

# Human Thermal Modeling Development

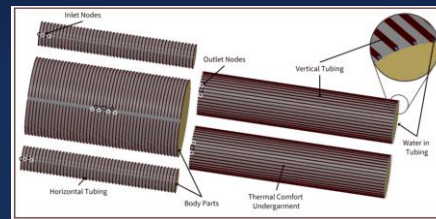
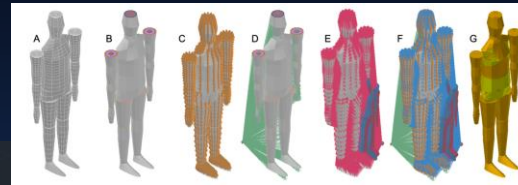
## Polaris Dawn, 2023-24

Custom version of METMAN to support testing and mission simulations



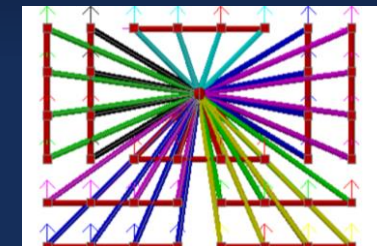
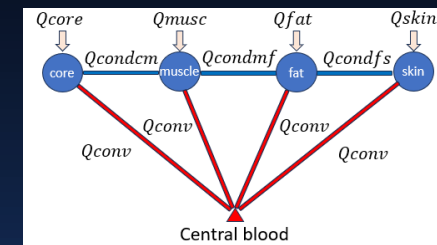
## NSTGRO, 2022-26

”Modeling of Human Thermoregulation Response to Spaceflight Changes Applied to the Technological Design of EVA Liquid Cooling and Ventilation Garments”



## NESC, 2024-2025

Thermal Desktop® version of METMAN for accessibility & compatibility



# Refrigeration Gaps

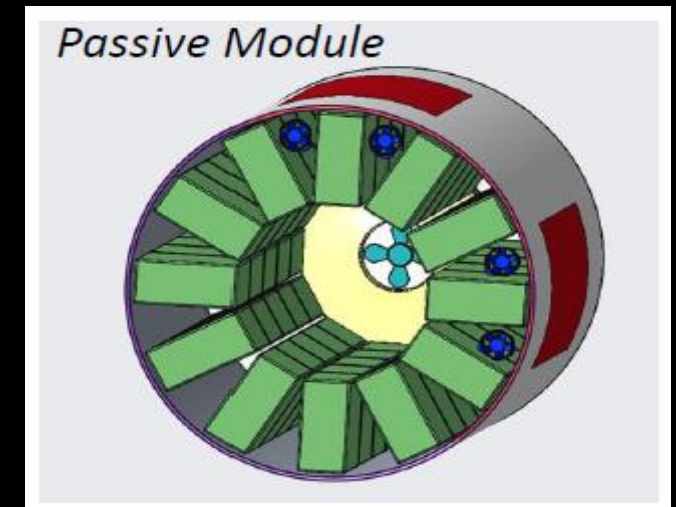
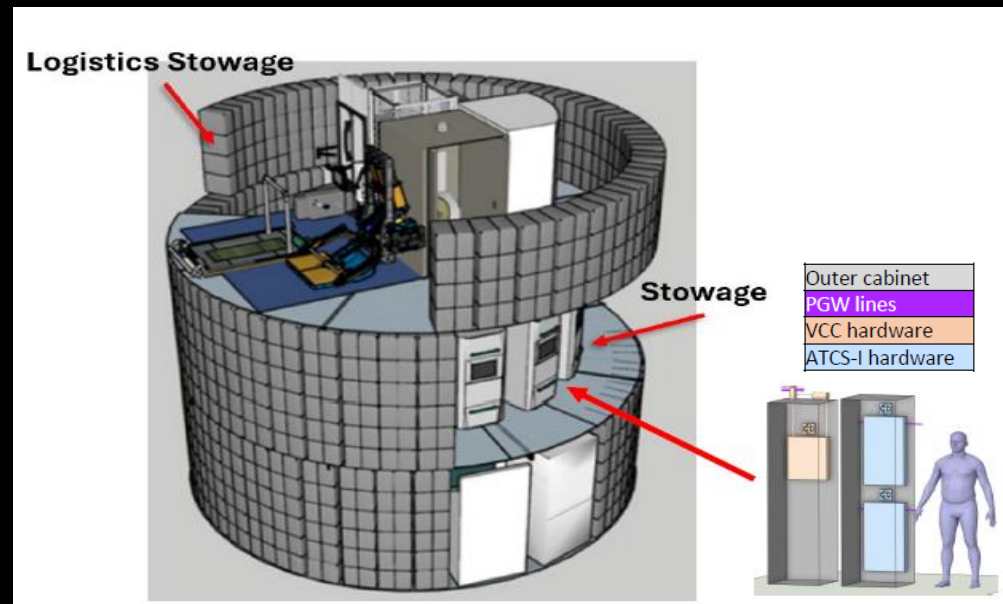
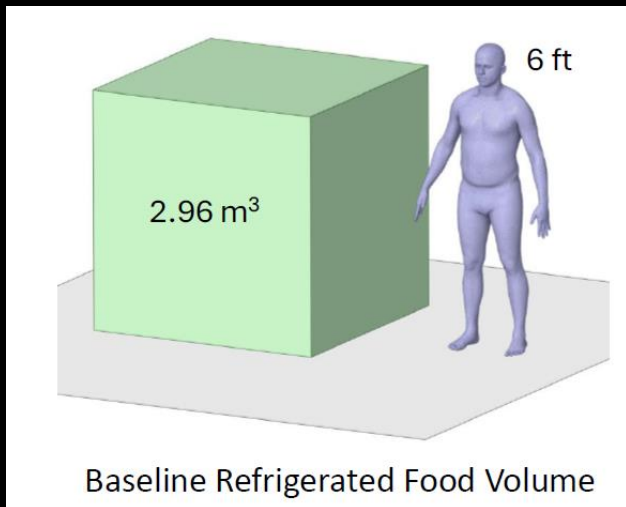
- Refrigerated long term stowage chamber for food preservation in deep space (passive and active approaches)

# Refrigeration

- Refrigeration via heat pumps or other means may be required for storage of food or science samples, or even for cooling of whole habitats in hot environments
  - Temperature requirements range from room temperature down to cryogenic
  - Many different technologies are possible
- JSC manages the cold stowage freezer fleet for ISS
  - Many active freezers as well as phase change materials and dewars for passive cold stowage
- JSC has conducted a few refrigeration research projects and SBIR contracts
  - Mostly focused on vapor compression cycle
  - Oil management in micro-gravity
  - Scroll & screw compressors
  - Vacuum insulation

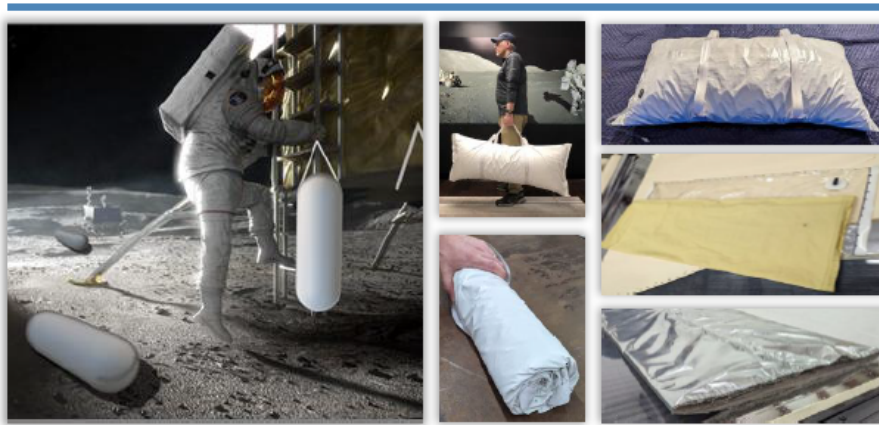
# Mars Refrigeration Project

- Human Mars missions will last from 1 to 3 years round trip, and if supplies are prepositioned for some mission phases, those supplies may need to have a shelf life of up to 5 years.
- NASA food scientists have been studying methods to extend the shelf life of the shelf-stable space food. Data has demonstrated refrigeration can extend the shelf-life of some nutrients and quality factors.
- Mars Refrigeration team has traded 3 vapor-compression-cycle, active-thermal-control-system-integration, and a passive-module approach to meet mission needs based on current requirements using the ESM parameter as well as reliability, development time, operational cost, and ease of integration
- Project team will also be investigating options for the surface of the Mars and Moon



# Lunar Extreme Water Container (LEWC)

NASA Phase II SBIR:  
Moonprint Solutions



## Identification & Significance of the Innovation

- Optimized collapsible multi-layer container design with maximum packing efficiency (70%) and packing factor (100:1 objective) to reduce delivery and storage volume (logistics cost) in comparison with rigid containers
- Materials and container design that are freeze tolerant (9% volume expansion)
- Development of softgoods materials that can be flexed at cryogenic temperatures in PSRs (-215C) and not become damaged (crack / leak / lose strength)
- Development of softgoods materials and container design that can survive long-term handling in contact with lunar dust and rocks without loss of integrity
- A container that can operate in a lunar dust environment by EVA crew in space suits
- Development of dust shedding materials and dust transport mitigation techniques that limit the transfer of lunar dust into habitable spaces to protect crew and LSS health

## Technical Objectives

1. Design a reusable lightweight & highly packable water storage/transfer container for long-term lunar EVA/IVA function
2. Identify and validate softgoods materials that can flex without damage at cryogenic temperatures during PSR operation
3. Identify and validate container materials & designs that facilitate operation in lunar dust and minimization of dust transport into habitats
4. Fabricate and test full-scale units for structural and operational

## Key Deliverables

- Materials test data to verify robustness in lunar environments
- Prototype unit and structural / performance data
- Commercialization plan
- Reports: ITSMP, KO, Quarterly, Final, NTSR

## NASA Applications

- Artemis mission support (water delivery to the lunar surface)
- Artemis ISRU mission support (transportation/storage of water)
- Cargo transfer bags with controlled environments
- Space suit materials for use in PSRs and for dust mitigation
- Dust protective covers for robots
- Collapsible transportable cryogen storage
- Storage of other fluids or gasses

## Non-NASA Applications

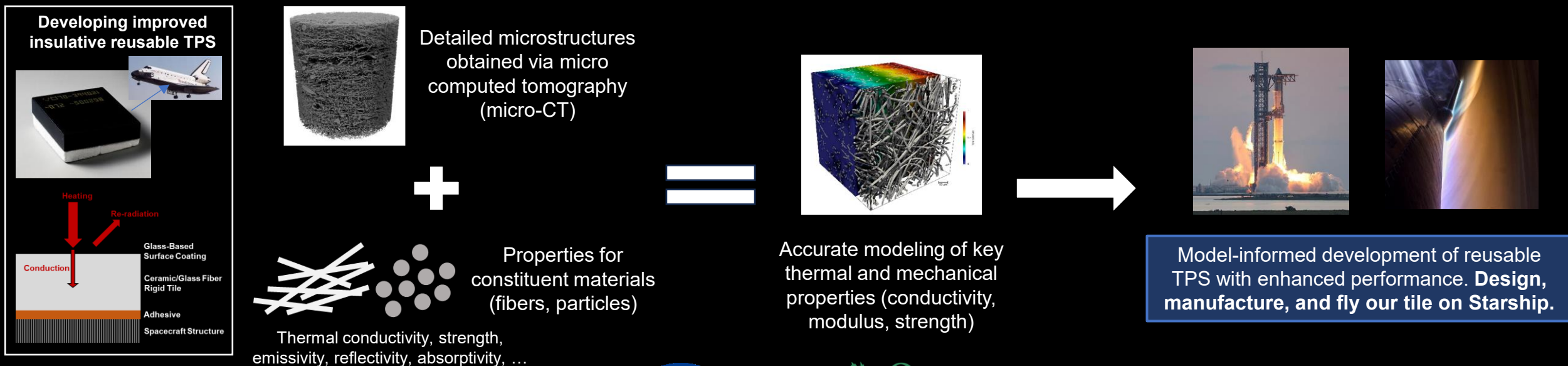
- Commercial space station water & fluids containment
- Commercial lunar surface mission support for water mobility
- Cargo transfer bags
- Dust covers for robotics use in industrial applications

# TPS Gaps

- TPS Development, Testing, and Analysis for Human Mars Exploration
- Robust High-Velocity Earth Entry TPS
- TPS Flight Performance Data for Human Mars Entry and Earth Return
- Accessible and Low Cost High Enthalpy TPS Test Facilities, including CO<sub>2</sub> Working Gas for Crewed Mars Entry
- Rapidly Reusable TPS for High Cadence Flight
- TPS Integration Approaches for Rapid Installation, Removal, and Refurbishment
- Robust Waterproofing Approaches for Reusable TPS
- Modern Supply Chain for Insulative Reusable TPS
- Micro- and Meso-Scale Modeling Tools for Reusable TPS
- Cost Efficient TPS Certification
- Cost Efficient TPS Manufacturing
- Validated Thermostructural Modeling for Thermal Protection Systems Integrated onto Aeroshell Structure

# PROTECT: Production & Reuse of Thermally Efficient Ceramic TPS (ECI-26)

PROTECT will utilize newly emerging materials characterization methods and advanced computational and predictive tools to aid in the design of new reusable TPS for future NASA and commercial industry space vehicles.



PROTECT was awarded as an Early Career Initiative (ECI) Project for FY26 & 27. Team members are located at NASA JSC, ARC, KSC, and GRC, and external partners are University of Illinois Urbana-Champaign, Oak Ridge National Laboratory, and SpaceX.



### STMD Shortfalls:

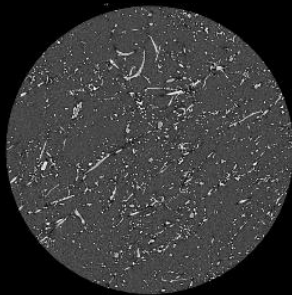
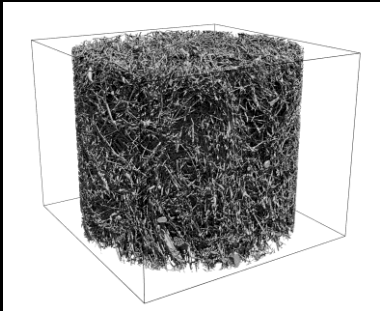
- 1569: High Mass Mars Entry & Descent Systems
- 1568: Entry Modeling and Simulation for EDL Missions
- 1623: Advanced Thermal Modeling Capabilities
- 1624: Advanced Thermal Management Technologies
- 1567: Entry Capabilities for Small-Scale and Commercial Spacecraft
- 1572: Performance-Optimized Low-Cost Aeroshells for EDL Missions

### ESDMD Architecture-Driven Technology Gap:

- 1104: Mars Entry, Descent, and Landing for Human Exploration

# Micro- and Meso-Scale Modeling of Reusable TPS

Entry Systems Modeling (ESM) Project supports NASA JSC and University of Illinois Urbana-Champaign in the development of analysis & modeling techniques for reusable fibrous TPS.



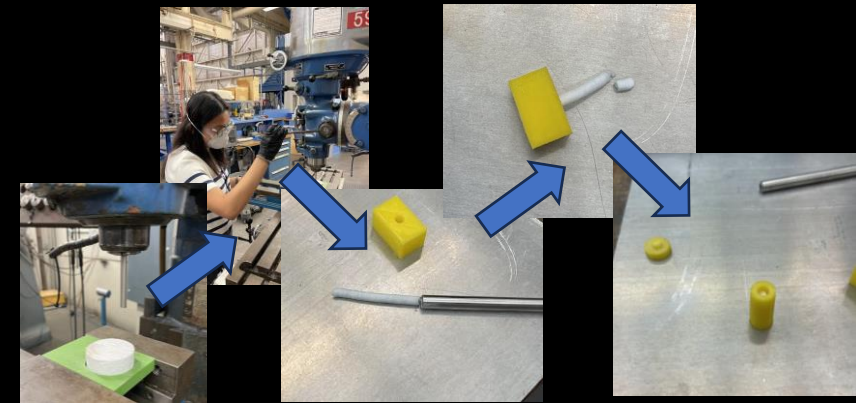
In collaboration with UIUC, capability to resolve fibrous microstructure using micro-CT has been demonstrated in collaboration (*first time for fibrous ceramic TPS – to our knowledge*)

**Goal:** Capture the microstructure of reusable TPS and process data into useful form for modeling of thermal transport & mechanical properties.

For FY26, we are pursuing two tasks to advance the state of the art for modeling of reusable TPS:

**Task 1: Advanced micro-CT of reusable fibrous ceramic TPS:** (a) Assess effects of sintering & material formulation on microstructure, (b) Segmentation approaches for identifying unique fiber types

**Task 2: Molecular modeling of ceramic fibers:** (a) Effect of tuning microstructure and composition on thermal properties, (b) molecular methods to estimate bulk fiber properties



Sample preparation at NASA JSC



Zeiss Xradia 630 Versa (UIUC) for **Micro Computed Tomography (Micro-CT)**

# Low Cost and Robust Coatings for Reusable TPS

**CIF-25 Project:** Advanced coatings for robust, reusable, and low-cost thermal protection systems (TPS)

This project had two aims:

## Glass Frit Development

Goal: Develop in-house glass frit to replace obsolete heritage frit.

Glass Frit



+

Emittance Agent



+

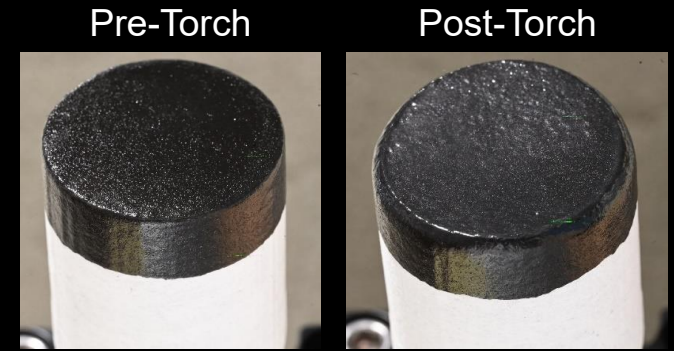
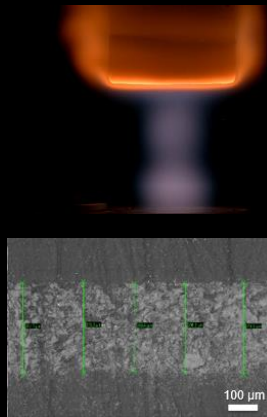
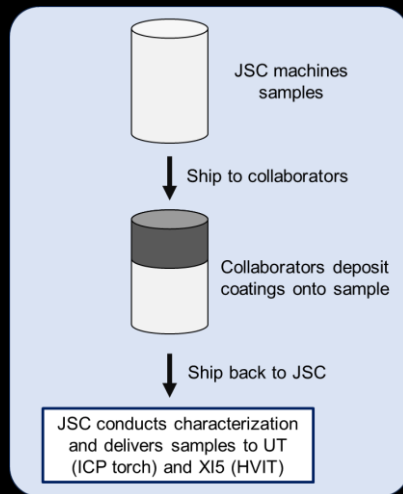
Carrier Fluid



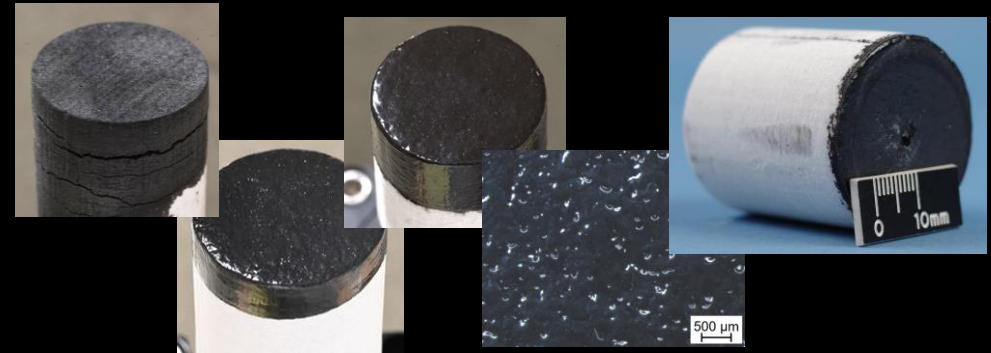
RCG Slurry

## Collaborator Testing

Goal: Test and characterize a suite of novel coating concepts from collaborators spanning industry and government labs.



Successful development and testing of JSC-made glass frit-based coatings.



Extensive testing of novel coatings from JSC & collaborators (torch, microscopy, hypervelocity & low velocity impact, emissivity)

Collaborators: SpaceX, Sierra Space, Oak Ridge National Lab, NASA GRC, NASA KSC / TPSF

STMD Shortfalls:

- 1567: Entry Capabilities for Small-Scale and Commercial Spacecraft
- 1572: Performance-Optimized Low-Cost Aeroshells for EDL Missions
- 1624: Advanced Thermal Management Technologies 37

# Additive Manufacturing for Thermal Protection Systems (TPS)

## Description:

- Goal: Significantly improve and automate the manufacturing processes of Thermal Protection Systems (TPS) used on human-rated spacecraft and robotic missions with the intention of reducing cost and improving quality and system performance.

## Strategic Alignment:

Technology Taxonomy: TX 9.1.1, Thermal Protection Systems; TX 12.1.4, Materials for Extreme Environments; TX 12.4.1, Manufacturing Processes; TX 14.3.2, Thermal Protection Systems

## Technology Maturation Plan / Roadmap:

- Technical feasibility has been demonstrated for small capsules. Next, scale-up the technology for 1-meter class vehicles. Then, continue to advance to TRL 6.
- Three AMTPS Workshops have been hosted (and fourth in March 2026) to obtain inputs from industry and DoD to guide future planning and solicit collaboration.

## Infusion / Commercialization Potential:

- Industry and DoD are pursuing this technology, but it is in its infancy.
- Commercial space is expanding and will need technologies to reduce manufacturing costs.
- NASA Human Mars missions will need to reduce cost and mass of TPS on large entry vehicles.

## Related Projects (Past & Present):

- A STMD CIF project, 3D Printing Heat Shields, was funded FY18-20 and technical feasibility at a small scale was demonstrated. An ~11-inch diameter sphere/cone heat shield was 3D printed and delivered to University of Kentucky for use on their capsule and was flown on Cygnus NG-16.
- A STMD ECI project, Additively Manufactured TPS, started in FY21 and continued through FY23. Manufacturing demonstration units were fabricated, and new material formulations were developed. Multiple re-entry experiments were flown from the ISS via U of Kentucky KREPE Program

## Partnership Opportunities:

- Collaboration with Oak Ridge National Lab and U of Kentucky
- Continue to pursue partnerships with DoD and industry.



# Accessible and Low-Cost High Enthalpy Testing, including CO<sub>2</sub> Capability

## The Challenge:

- High-speed flight for routine access to space and for defense require high-temperature materials.
- Development and qualification of those materials and the design of hypersonic vehicles requires testing in high enthalpy facilities, such as an arc jet.
- Current facilities are large, expensive and not routinely accessible: NASA Ames/CA and AEDC/TN.
  - One mid-level facility (LCAT) is owned by Boeing with limited availability.
- CO<sub>2</sub> has not been widely applied in high enthalpy facilities, but will be required for future Mars missions

## Large Facilities

High-Power: 20 to 75 MW

Large range of test articles & conditions

High Cost

Accessibility Poor

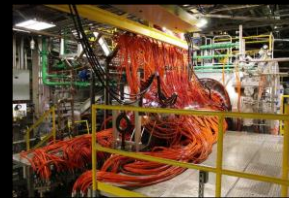
### NASA Ames

20 MW & 75 MW  
Segmented Heaters  
1 to 14+” diameter test articles  
Enthalpy – Up to 12,000 BTU/lbm  
Stag. Pressure – Up to 6 atms  
Test Gas – Air, N<sub>2</sub>



### AEDC

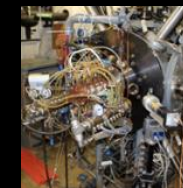
30, 45, 70 MW  
Segmented & Huels heaters  
1 – 24” diameter test articles  
Enthalpy – Up to 8, 500 BTU/lbm  
Stag. Pressure – up to 100 atm  
Test Gas - Air



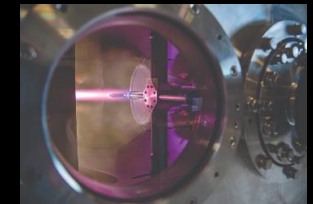
## Small Facilities

15 to 400 kW

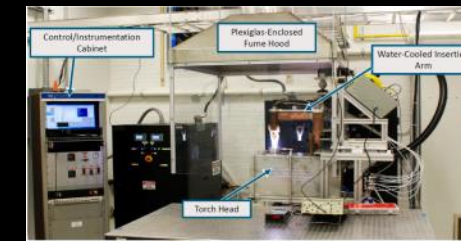
Small Test Articles 1-2” D  
Air, N<sub>2</sub>, CO<sub>2</sub> (low pressure)  
Varying levels of accessibility



HyMETS LaRC (Segmented)



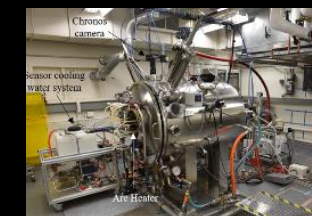
350 kW PlasmatronX at UIUC (ICPT)



50 kW UT-Austin (ICPT)



30 kW U. of Vermont (ICPT)



30 kW mARC II NASA ARC (Segmented)



Ablative TPS

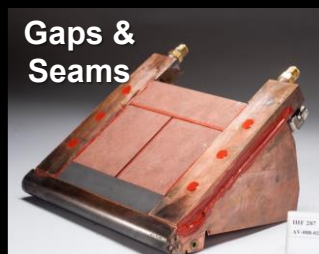


C/C and CMCs

Proposed facility would be used for material evaluation, screening, and qualification as well as testing of systems-level design.



Ceramic TPS



Gaps & Seams

## Need: Mid-Level Testing Facility

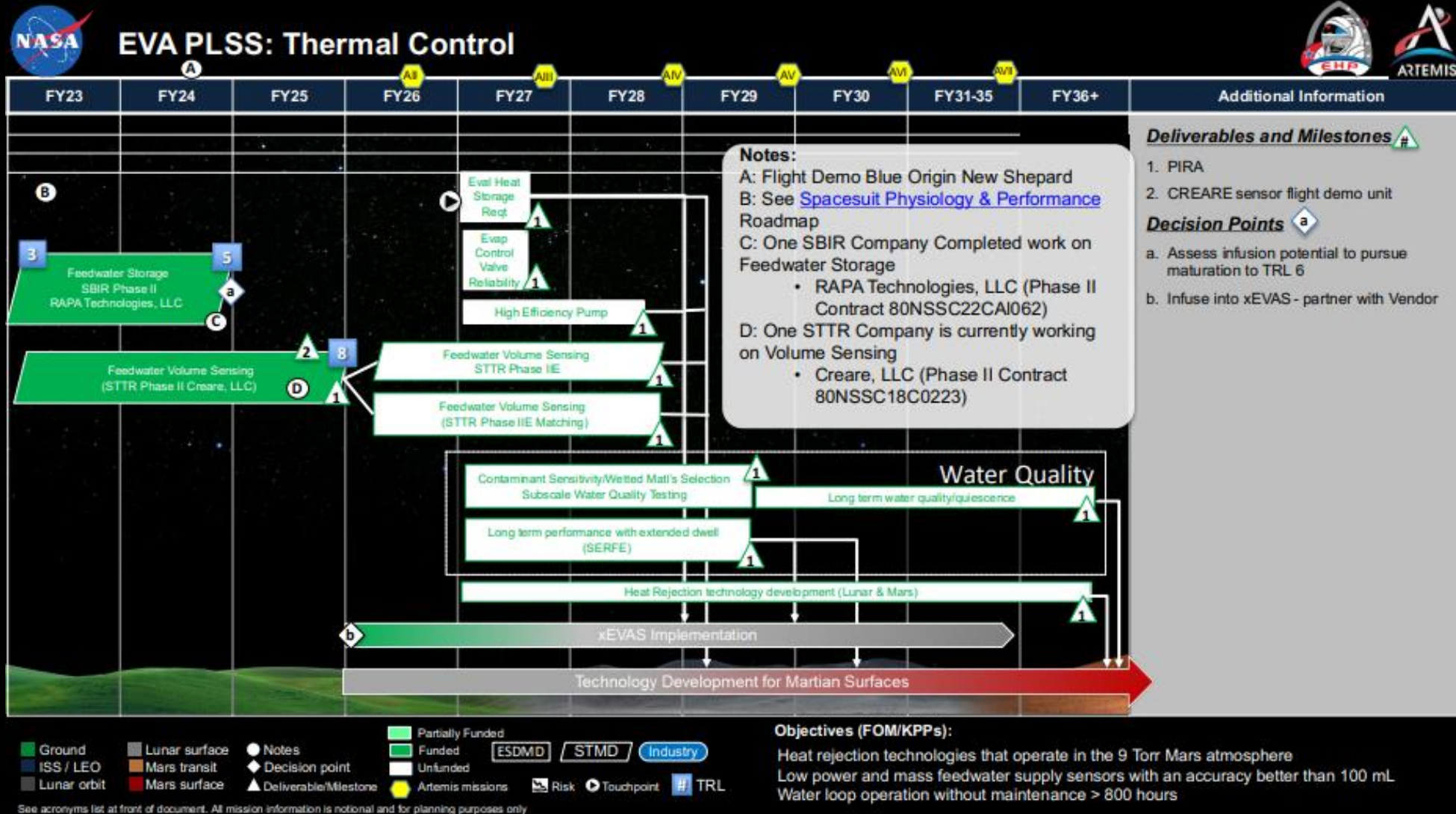
1. Power from 500 kW to 5 MW
2. Focus on common size test articles (~4”)
3. Reduce costs and address accessibility
4. CO<sub>2</sub> capability for human & robotic Mars missions

# Portable Life Support System (PLSS) Thermal Gaps

- Mars Surface EVA Suit
- Heat Rejection for Mars EVA Suit in Non-vacuum Applications
- Mars EVA Suit Environment Thermal Insulation



# EVA Thermal Control Roadmap from ICES Paper ICES-2025-61



# EVA and PLSS Thermal Gaps

- Mars EVA is a challenge with significant gravity driving the need for lighter weight thermal technologies
- Technology gaps include lightweight radiators, variable emissivity radiators, freeze tolerant radiators, variable insulation for suit and other technologies listed below
- Per ICES-2025-61, development includes Liquid Cooling Garments, studies on long duration water and materials compatibility, heat rejection technologies that do not use consumables or can be used in a Martian environment, and thermal control valves.
- NASA Funded “EVA PLSS: Thermal Control” Investments:
  - Feedwater Storage – Water is one of the primary consumables for a life support system that uses evaporation for cooling. A reliable, and gravity independent, technique for measuring the amount of water remaining is critical to monitoring the duration of an EVA. Volume Sensor for Flexible Fluid Reservoirs in Microgravity. Flight Demo on New Shepard launch, December 18, 2023. (Creare, LLC)
  - Feedwater Volume Sensing – High-Purity, Defined-Envelope pressure Bladder. (RAPA Technologies, LLC)

# EVA and PLSS Thermal Gaps

- Proposed Activities per ICES-2025-61: “EVA PLSS: Thermal Control”
  - **Evaluate Heat Storage Requirement** – Crew members generate variable amounts of heat during an EVA based on their activity levels. There are requirements for energy storage in the crew (as monitored by core body temperature) if their metabolic output exceeds the cooling capability of the life support system. Refinement of this requirement could enable sizing reductions for thermal control hardware.
  - **Evaporator Control Valve Reliability** – The xEMU SWME uses a backpressure control valve to meter the water evaporation rate and thereby the cooling provided to the crew. The xEMU design experienced many issues with linear actuator reliability where the motor would jam, making the control valve inoperable. This task would look at designs that provide more reliable actuation while still meeting the flow rate and pressure drop requirements.
  - **High Efficiency Pump** – Continued development and evaluations of water pumps with lower power requirements is desired.
  - **Contaminant Sensitivity/Wetted Materials Selection Subscale Water Quality Testing/Long Term Water Quality and Quiescence/Long Term Performance with Extended Dwell** – Water quality issues have plagued the ISS EMU and other life support systems throughout NASA’s history. xEMU-based technology development efforts for SWME and the SWME Express Rack Flight Experiment (SERFE) ISS payload have taken large steps to demonstrate decreased sensitivity to water quality issues and improved materials compatibility as compared to previous systems. However, continued efforts are needed to completely reduce risks associated with water quality. These include sub-scale tests to assess materials or contaminants that might present performance issues to the current thermal control technologies; long term quiescent evaluations with the SERFE Ground Unit where it is tested after long dormant periods (> 2 years), and then additional long-term evaluations as the xEVAS designs are finalized and mission concepts mature.
  - **Heat Rejection technology development (Lunar and Mars)** – The low-pressure CO<sub>2</sub> environment on Mars may degrade the performance of water evaporation-based technologies. In addition, non-venting heat rejection or storage technologies could decrease mission consumables. Low TRL heat rejection technologies need to be continually evaluated for potential benefits.
  - **Feedwater Volume Sensing** – Continue development of the volume sensor for flexible fluid reservoirs in microgravity. (Create, LLC). Flight demo on New Shepard, December 18, 2023, launch.

***To enable Mars EVA, reduced on-back carry mass of thermal control equipment is required***

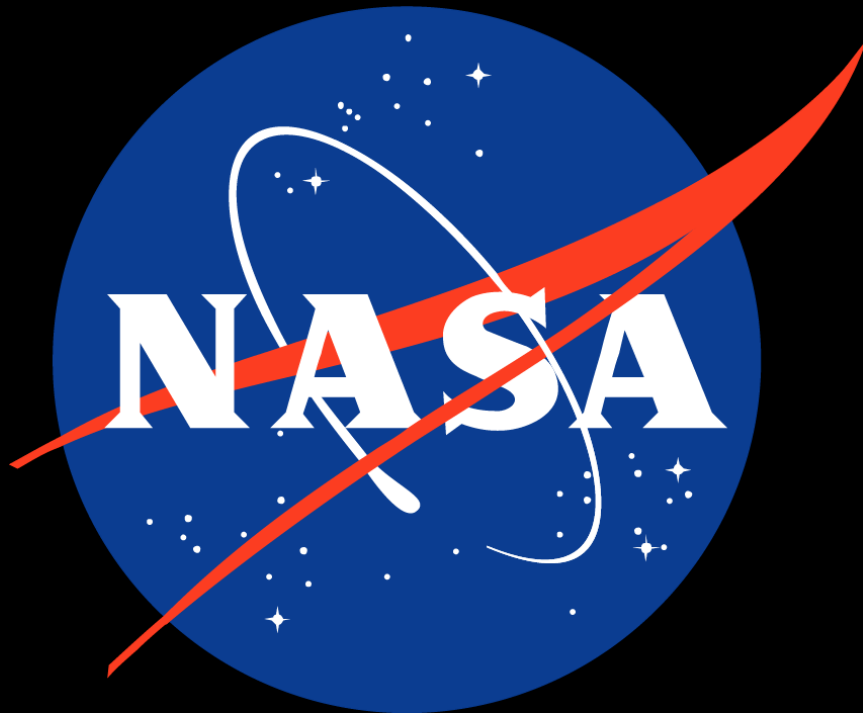
# JSC Thermal Systems Future



- Human spaceflight missions
- Sustained presence in Cis-Lunar space
- Mars exploration
- Innovative partnerships and collaborations
- Commercialization



# Acknowledgements



- Nate Olson
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