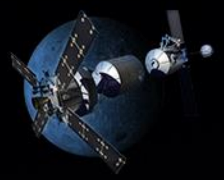


National Aeronautics and
Space Administration

Johnson Space Center Thermal Technology Overview 2026

Tom Leimkuehler, Ph. D.

Active Thermal Technical Discipline Lead, NASA Johnson Space Center

Nate Olson, Adam Sidor, Sydney Taylor, Hee Jong Song, Tommy Chen, Scott Hansen,
Darnell Cowan, Ryan Dippolito, Jon-Michael Tucker

NASA Johnson Space Center

Bruce Conger, Hung Le

Amentum

Human Spaceflight Programs Currently Supported at JSC

International Space Station | Commercial Crew | Commercial LEO | Orion | Gateway | Human Landing System | Extravehicular Activity & Human Surface Mobility

To learn more about JSC capabilities, visit the JSC Front Door:
https://www.nasa.gov/johnson/frontdoor/

Human Spacecraft Thermal Systems Development at JSC

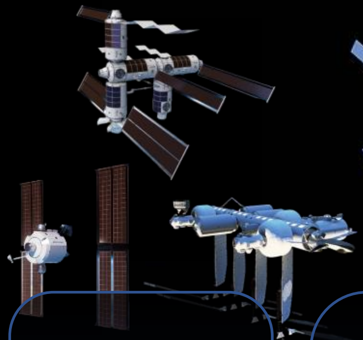
International Space Station

- 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

Commercial Crew

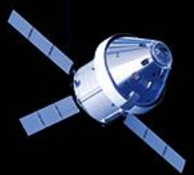
- ATCS
- PTCS
- TPS
- Supplemental cooling during pre-launch, ascent, entry, post-landing

Commercial LEO



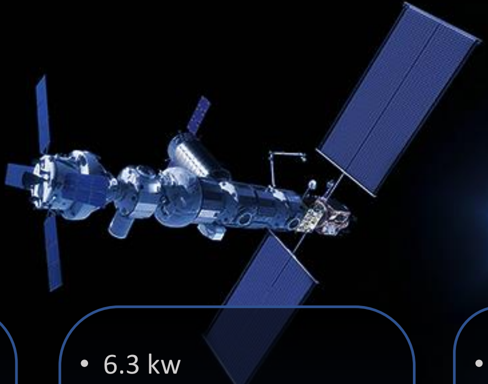
- ATCS
- PTCS

Orion



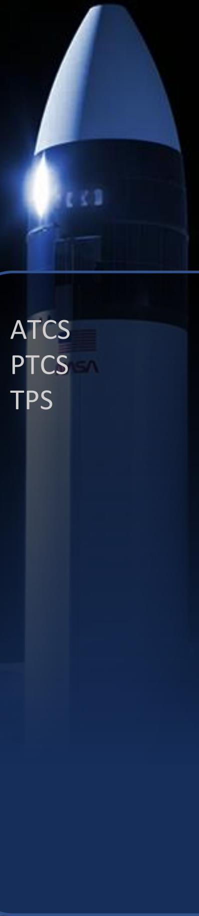
- 5 kW
- Dual pumped loops
  - Internal: PGW
  - External: HFE-7200
- Body-Mounted Radiators
  - $24m^2$
- PCM
- Ammonia Boiler
- Software controlled heaters
- MLI / SiOx tape on CM
- TPS

Gateway



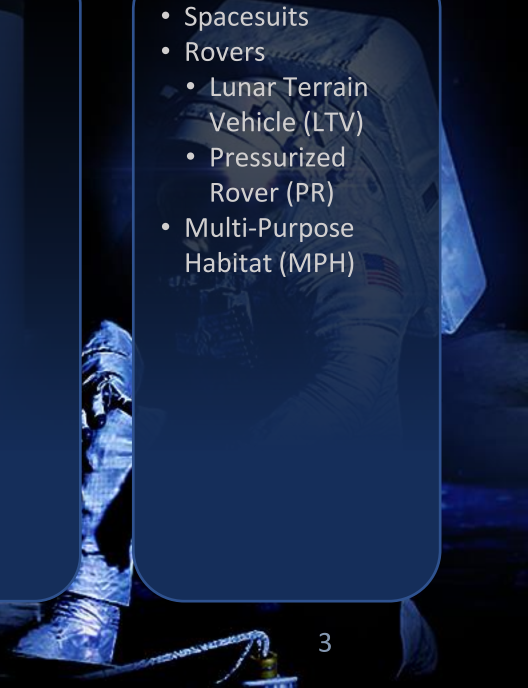
- 6.3 kw
- Dual pumped loops
  - Internal: PGW
  - External: HFE-7200
- Body-Mounted (HALO = $36m^2$) & Deployable Radiators
- Unique challenge due to cislunar environment and 7-day lunar orbit
- Potential lunar dust deposition
- Optical property degradation

Human Landing System



- ATCS
- PTCS
- TPS

Extravehicular Activity & Human Surface Mobility



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

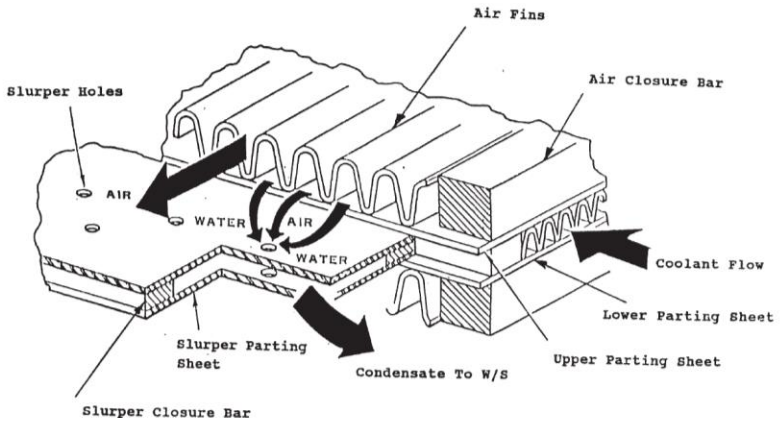
Needs & Current Tech/Flight Development

- 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

Condensing Heat Exchangers (CHX) & Water Separators

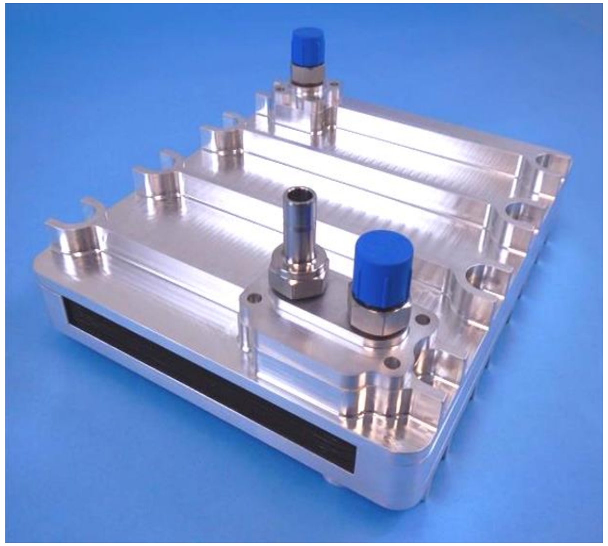
Collins Advanced Coating

- 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 anti-microbial 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

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

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

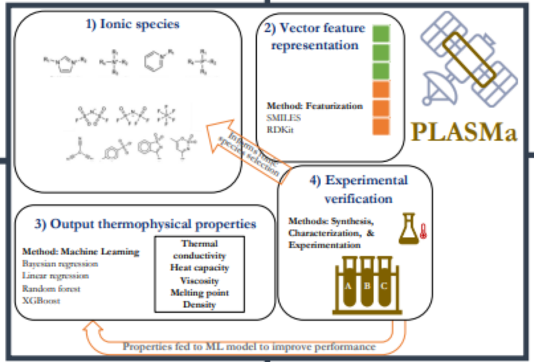
Research Objectives

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...

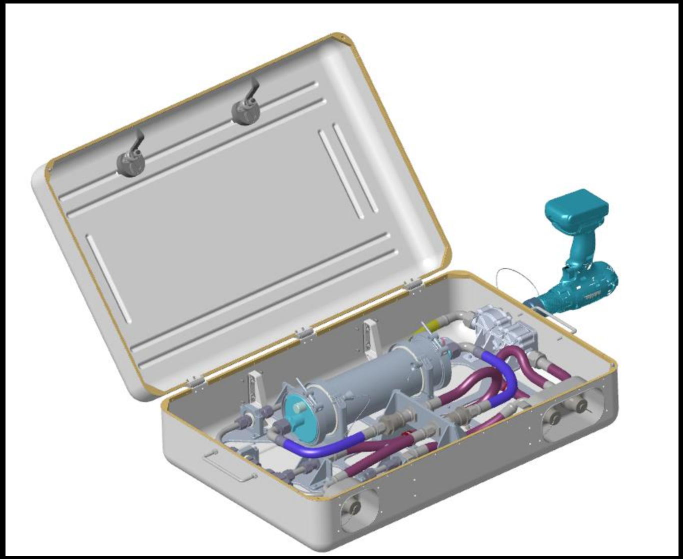
Space Science and Exploration

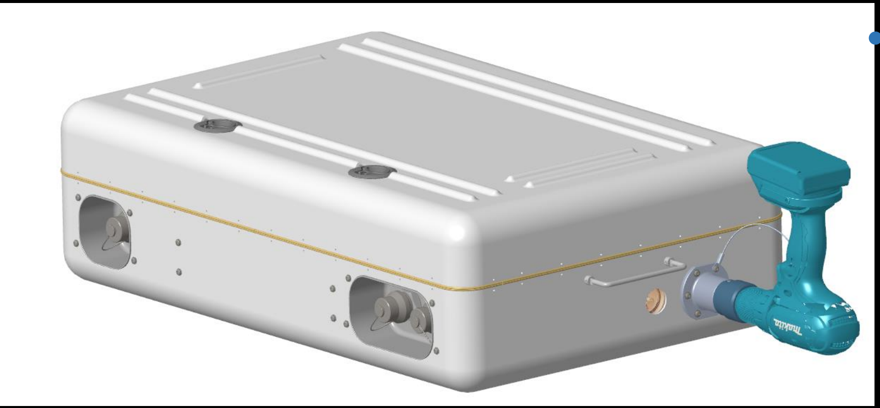
- Safe non-toxic ionic liquids are suitable for future crewed missions
- Enabling technology for lunar surface and deep space thermal systems
- Machine learning for ionic liquid discovery proposed as a fundamentally new technology as part of active thermal control design

"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)

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

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

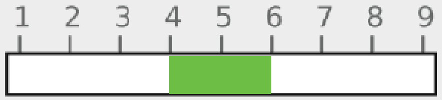
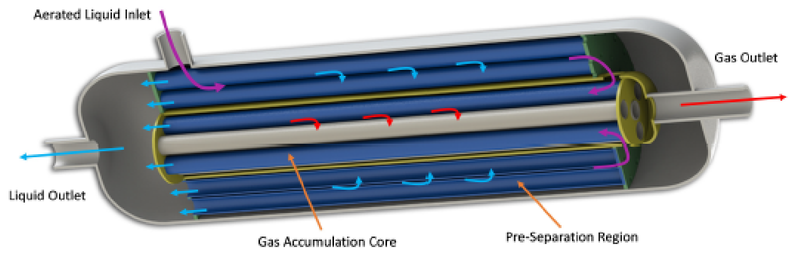


IMAGE TITLE: Creare's Gas Trap Design



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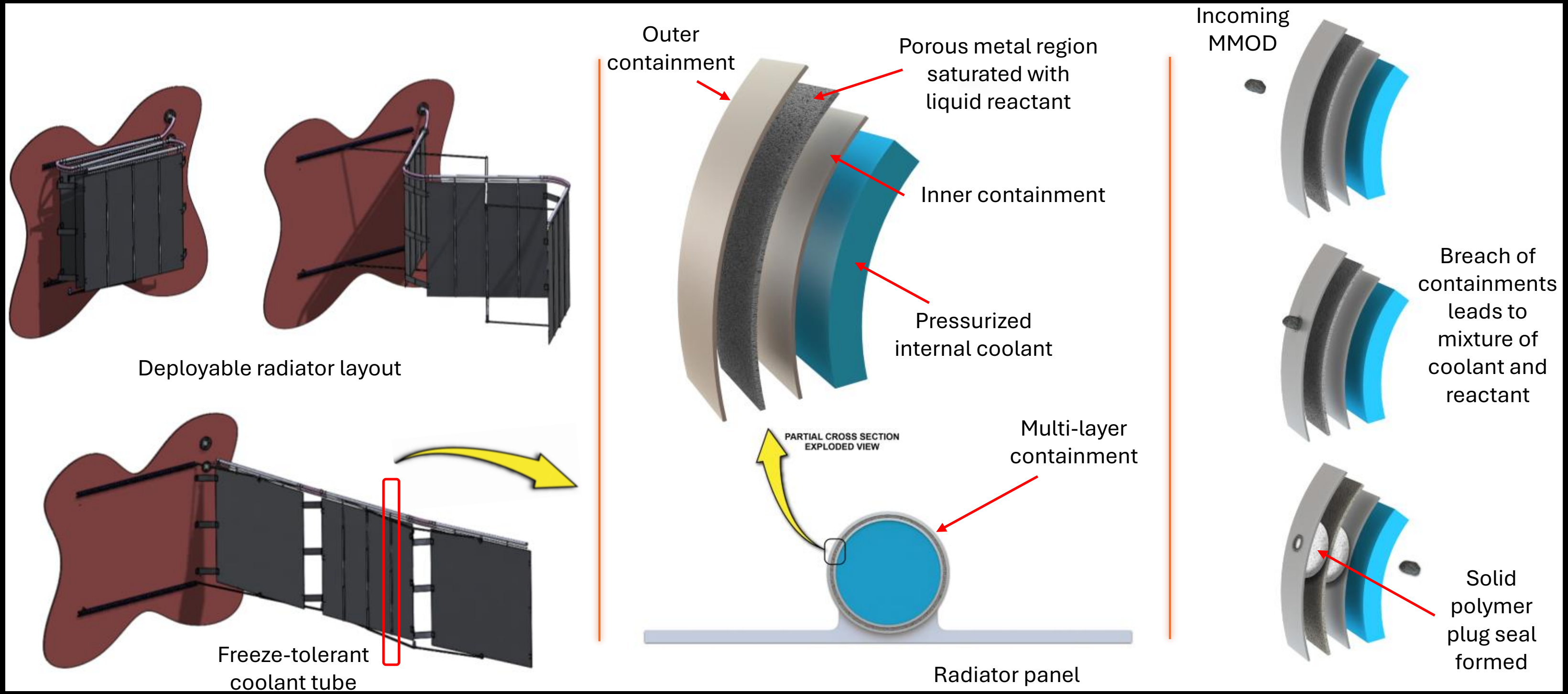
Creare, LLC
EMAIL: tmc@creare.com
PHONE: (603) 643-3800

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

- NASA Phase II SBIR
  - Creare
- 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

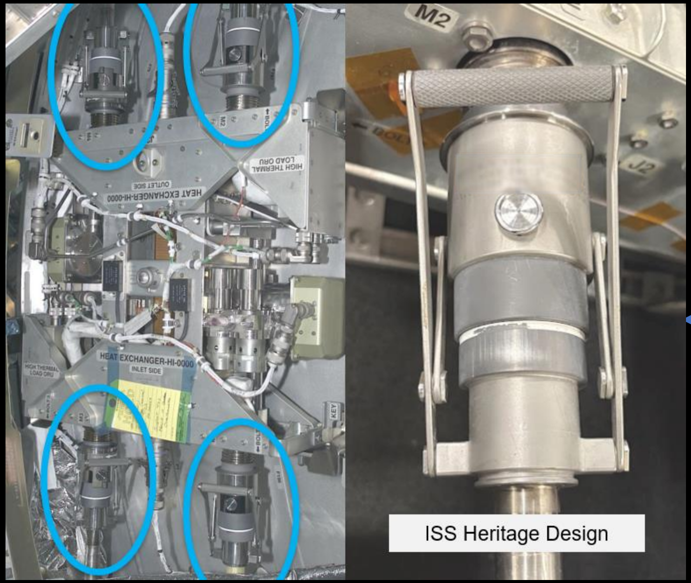


Redesign of EVA Quick Disconnects for Exploration Surface Application

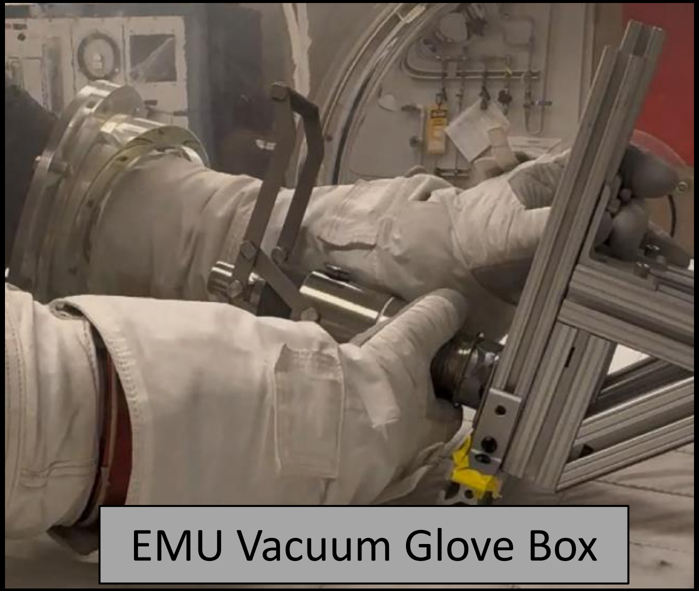
Purpose: Start fundamental redesign work of EVA (Crew Glove) compatible Quick Disconnects for lunar / martian surface application.

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

Insulation and Interfaces – Variable Emittance Coatings Tech Dev

Current Project Objectives:

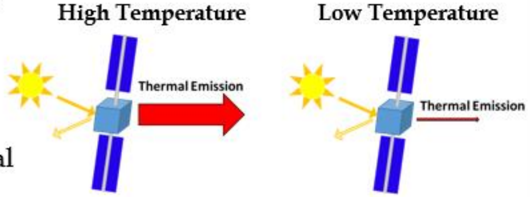
(1) Work with collaborators to fabricate variable emittance samples with reduced transition temperature, high emittance contrast, and low solar absorptance
(2) Develop temperature-dependent FTIR and calorimetry measurements at JSC
(3) Trade study modeling of variable emittance coatings

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

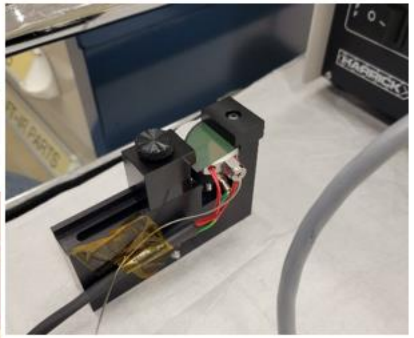
Variable emittance coatings (VECs) could:

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

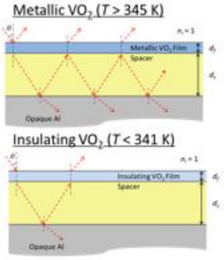


JSC Capabilities:

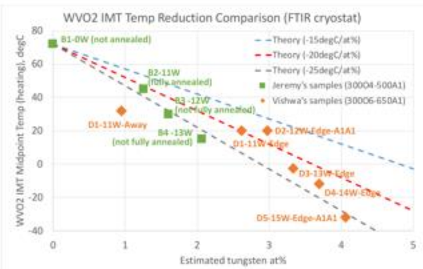
1. Temperature-dependent spectral reflectance and transmittance measurements
2. Calorimetry experiment to measure temperature-dependent heat rejection
3. Thermal modeling of VECs integrated with spacecraft systems
4. Ultimate project goal is to demonstrate ~1 m^2 prototype radiator in TVAC



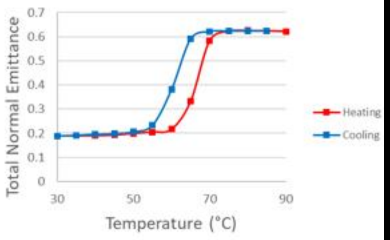
Project Concept and Progress to Date:



Reduced Transition Temp



Undoped VO_2 Emitter
ASU Sample 1



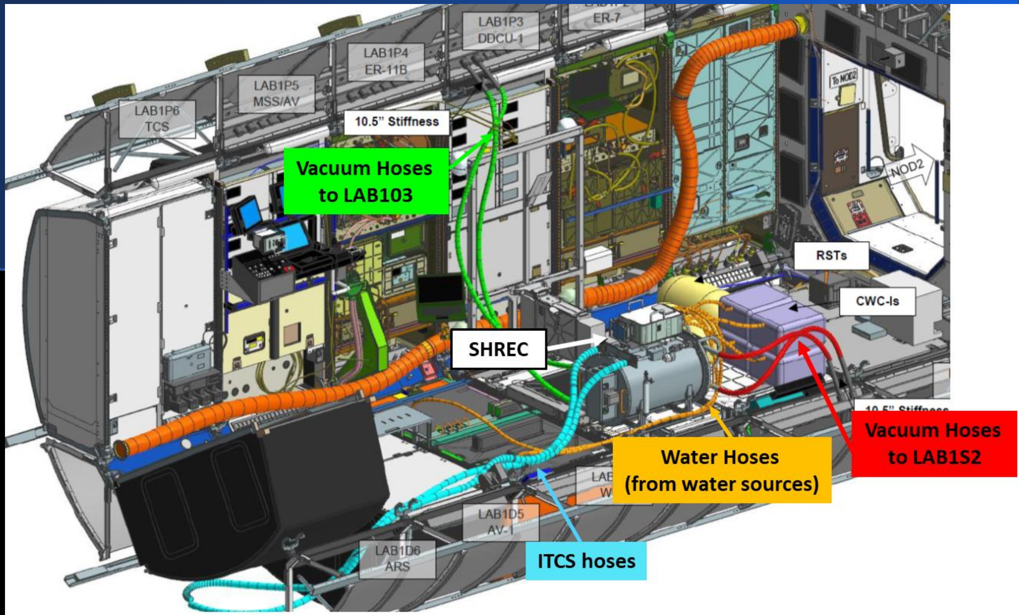
VO_2 changes from an insulator to a metal at 68 °C (undoped), which is used to create temperature-tuned variable emittance devices. PSI, Plasmonics, and ASU have developed samples with reduced transition temperature and significant emittance contrast. Voltage tuned devices can also be developed using electrochromic materials such as Nb_2O_5 (UNT) and WO_3. Novel materials such as GST are also explored (UMN).

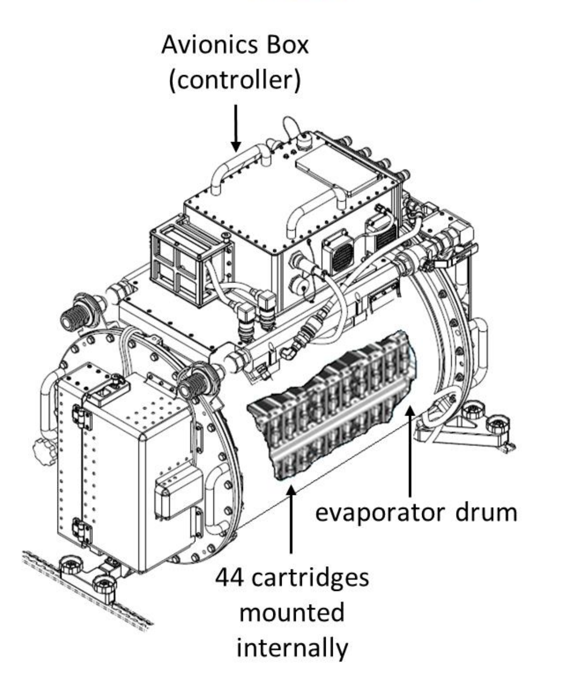
Collaborators and Funding:

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

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

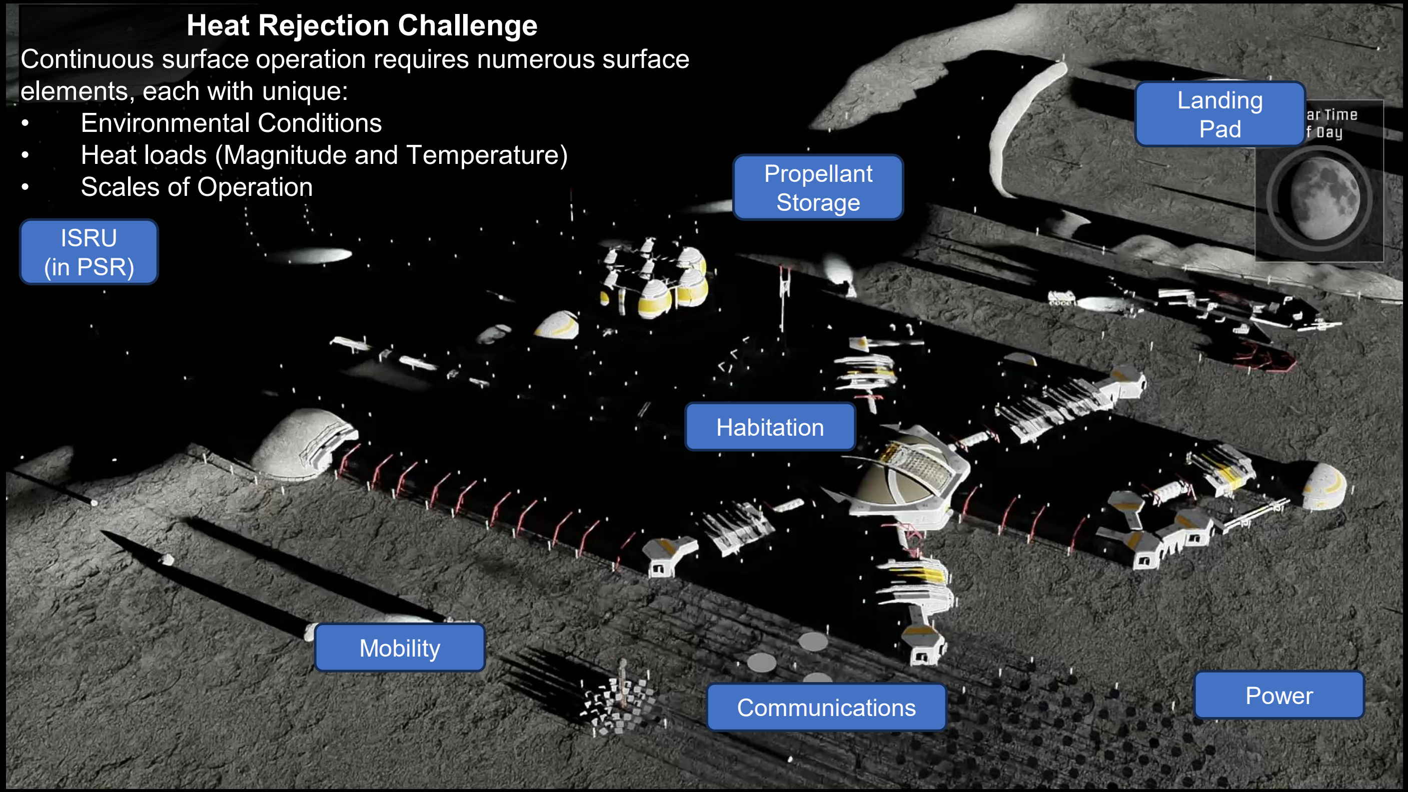




STMD ATC-Explore: *Assessment of Advanced Heat Rejection Systems to Enable and Optimize Exploration Surface Operations*

- **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

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

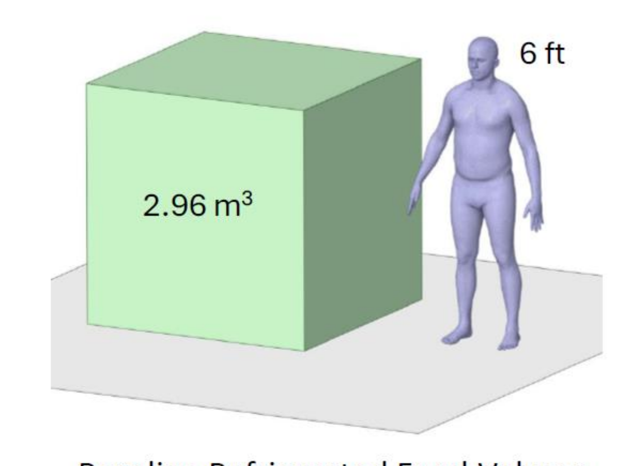
- Mezzo Technologies designed and delivered a Phase Change Material Heat Exchanger Engineering development unit
- The Thermal Systems Branch is partnering with Lockheed Martin to subject the EDU to a full test series
  - Thermal Systems Branch performed leak and functional testing
  - Lockheed Martin’s 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.**

Refrigeration

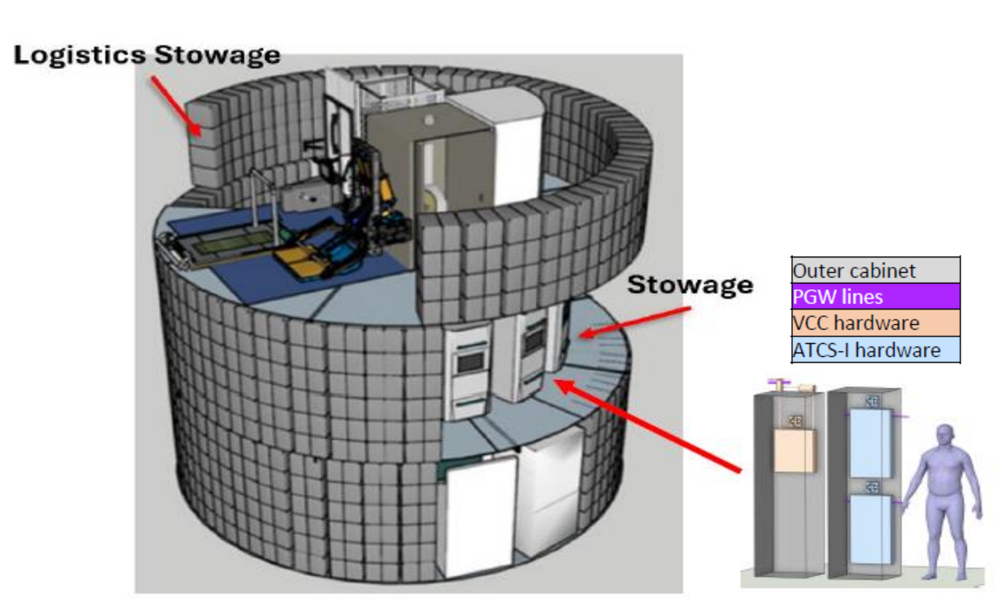
- Refrigeration via heat pumps or other means may be required for storage of food or science samples, or even for cooling of whole habitats in hot environments
  - Temperature requirements range from room temperature down to cryogenic
  - Many different technologies are possible
- JSC manages the cold 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

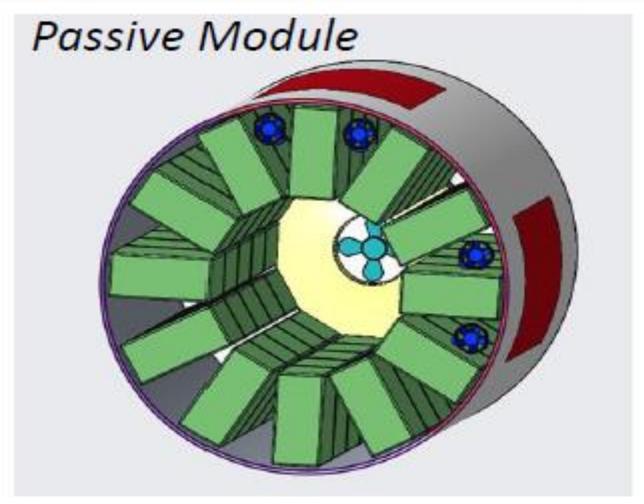
Mars Refrigeration Project

- 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



Baseline Refrigerated Food Volume





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

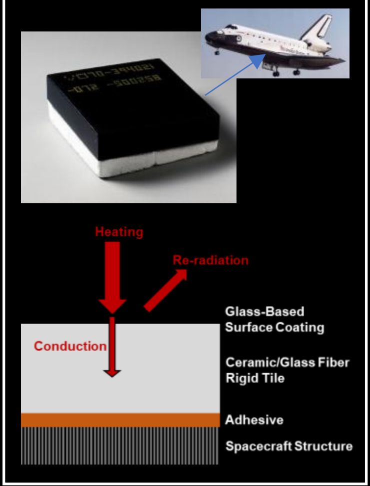
Non-NASA Applications

- 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

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

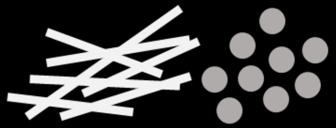
PROTECT will utilize newly emerging materials characterization methods and advanced computational and predictive tools to aid in the design of new reusable TPS for future NASA and commercial industry space vehicles.

Developing improved insulative reusable TPS



Detailed microstructures obtained via micro computed tomography (micro-CT)

+



Properties for constituent materials (fibers, particles)

Thermal conductivity, strength, emissivity, reflectivity, absorptivity, …

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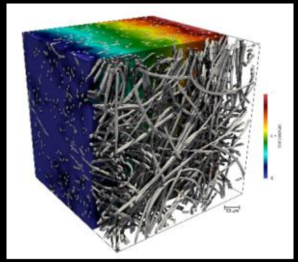


Accurate modeling of key thermal and mechanical properties (conductivity, modulus, strength)

→

Model-informed development of reusable TPS with enhanced performance. **Design, manufacture, and fly our tile on Starship.**

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.

JSC
ARC
GRC
KSC / TPSF

Oak Ridge National Laboratory

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

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:

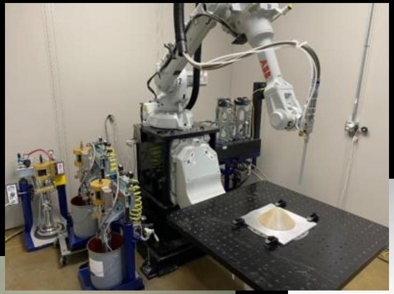
- Industry and DoD are pursuing this technology, but it is in its infancy.
- Commercial space is expanding and will need technologies to reduce manufacturing costs.
- NASA Human Mars missions will need to reduce cost and mass of TPS on large entry vehicles.

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:

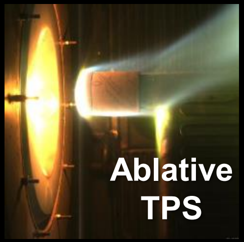
- Collaboration with Oak Ridge National Lab and U of Kentucky
- Continue to pursue partnerships with DoD and industry.



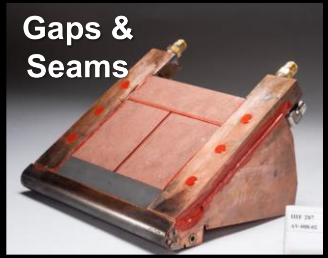
Accessible and Low-Cost High Enthalpy Testing, including CO_2 Capability

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_2 has not been widely applied in high enthalpy facilities, but will be required for future Mars missions



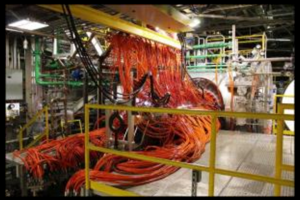
Proposed facility would be used for material evaluation, screening, and qualification as well as testing of systems-level design.



Large Facilities

High-Power: 20 to 75 MW
Large range of test articles & conditions
High Cost
Accessibility Poor

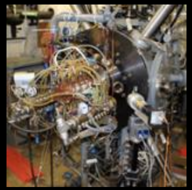
NASA Ames
20 MW & 75 MW
Segmented Heaters
1 to 14+" diameter test articles
Enthalpy – Up to 12,000 BTU/lbm
Stag. Pressure – Up to 6 atms
Test Gas – Air, N_2



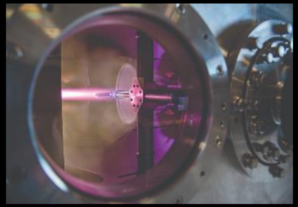
AEDC
30, 45, 70 MW
Segmented & Huels heaters
1 – 24" diameter test articles
Enthalpy – Up to 8, 500 BTU/lbm
Stag. Pressure – up to 100 atm
Test Gas - Air

Small Facilities

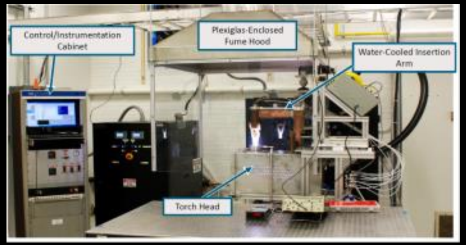
15 to 400 kW
Small Test Articles 1-2" D
Air, N_2, CO_2 (low pressure)
Varying levels of accessibility



HyMETS LaRC (Segmented)

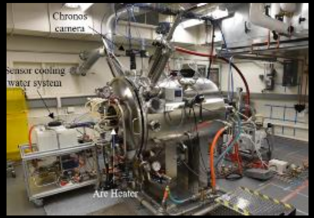


350 kW PlasmatronX at UIUC (ICPT)



50 kW UT-Austin (ICPT)

30 KW U. of Vermont (ICPT)



30 kW mARC II NASA ARC (Segmented)

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_2 capability for human & robotic Mars missions

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

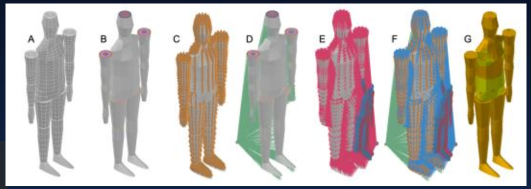
Human Thermal Modeling Development

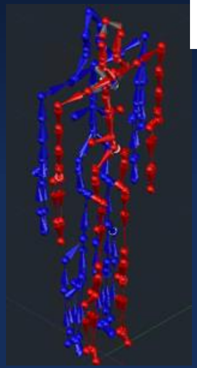
Polaris Dawn, 2023-24

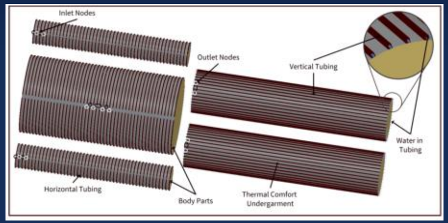
Custom version of METMAN to support testing and mission simulations

NSTGRO, 2022-26

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

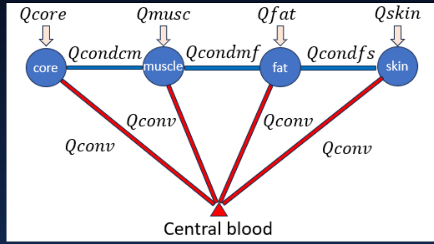


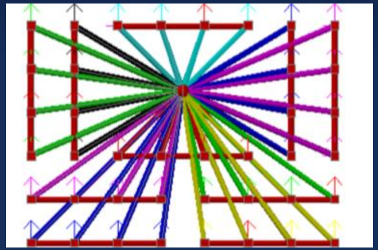




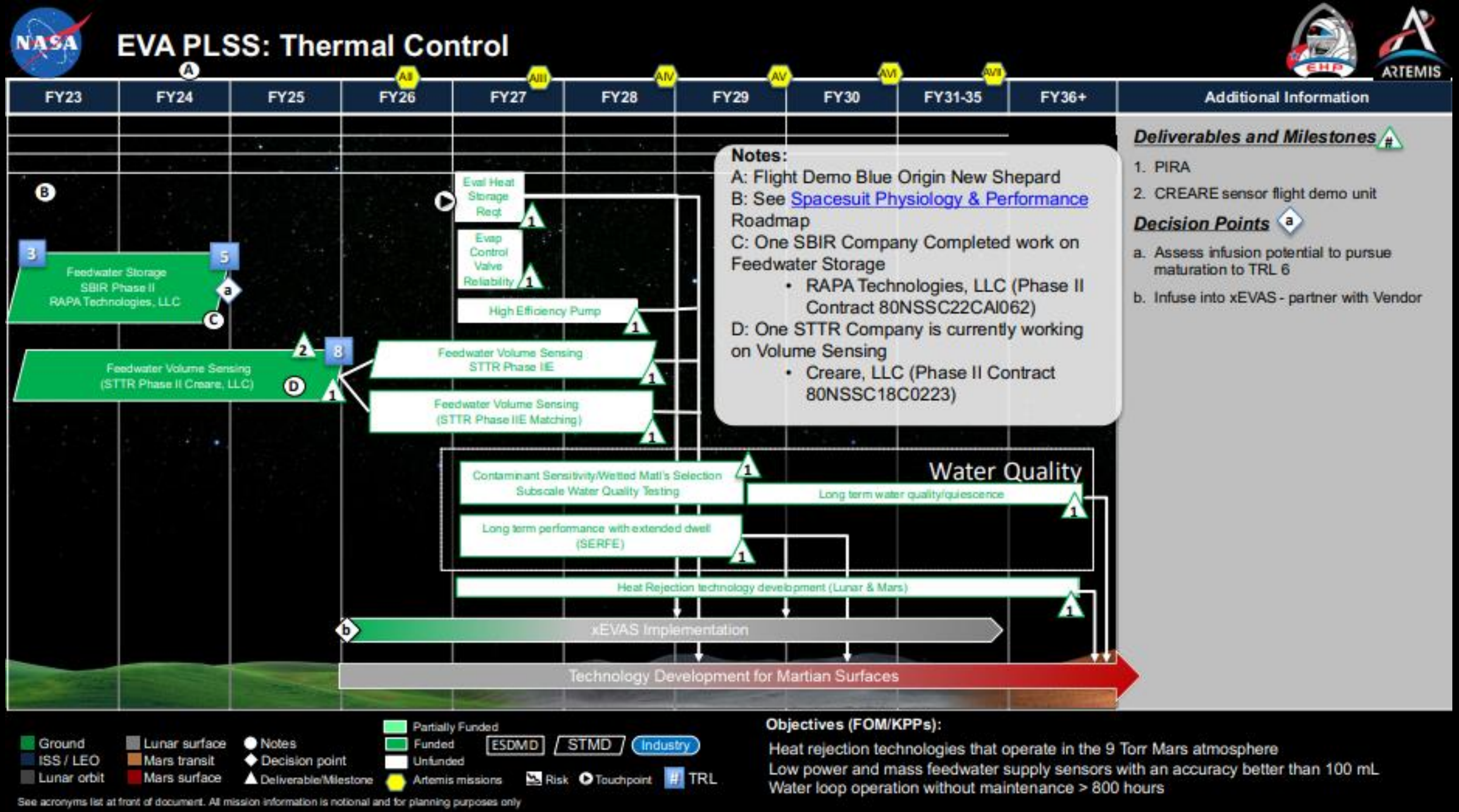
NESC, 2024-2025

Thermal Desktop® version of METMAN for accessibility & compatibility





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)

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 and on the Lunar surface
- Mars exploration
- Innovative partnerships and collaborations
- Commercialization

Acknowledgements

- Nate Olson
- Adam Sidor
- Sydney Taylor
- Tommy Chen
- Hee Jong Song
- Bruce Conger
- Cinda Chullen
- Darnell Cowan
- Ryan Dippolito
- Scott Hansen
- Hung Le
- Jon-Michael Tucker
- David Westheimer
- Jeannie Corte