EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LIVE: Thermal Management Systems
NASA Space Technology Mission Directorate

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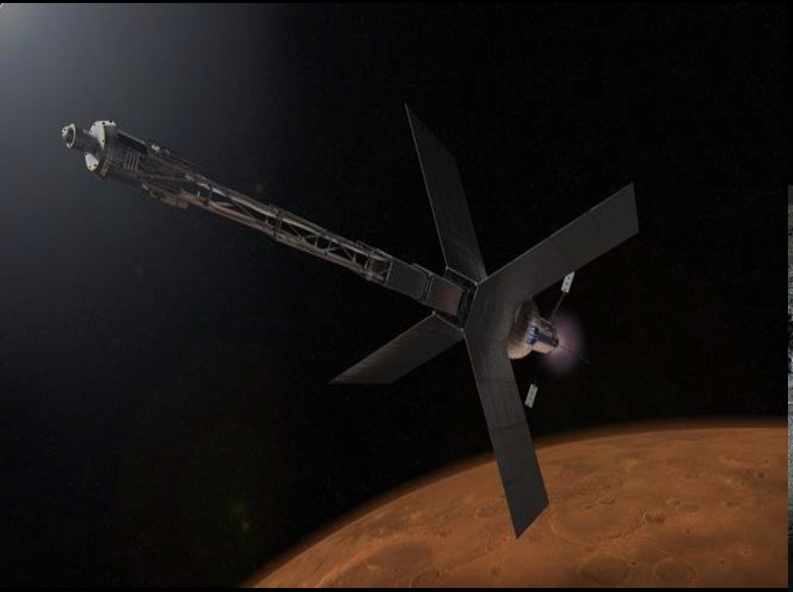
Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Thermal management technologies that enable surviving the extreme lunar and Mars environments

Thermal Control for In-Space Transportation Systems



"Develop nuclear technologies enabling fast in-space transits"

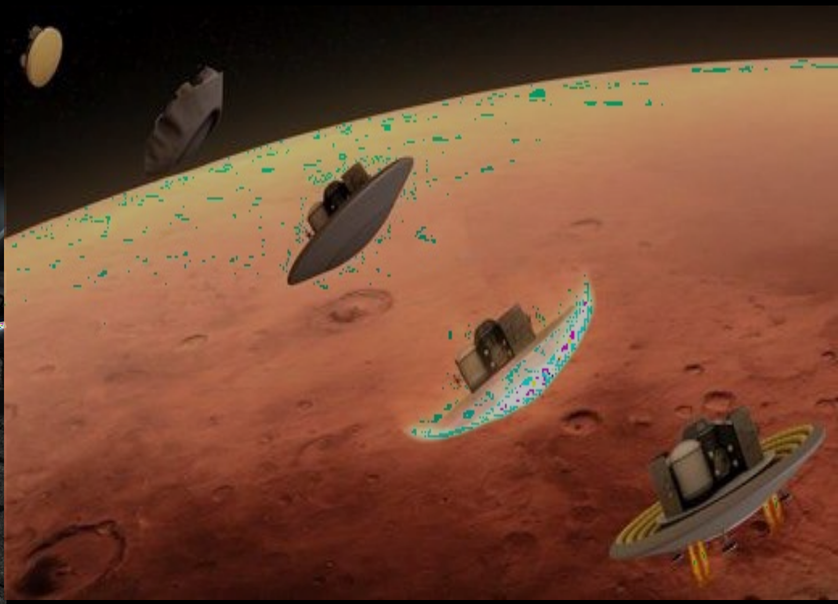
"Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications"

Thermal Control for Surface Environment Survival

"Technologies that enable surviving the extreme lunar and Mars environments"

Science Instrument Survival
Power Systems
Spacesuits
Habitats
Cold Tolerant Mechanisms
ISRU Commodity Production
Mobility Systems

Thermal Control for Entry, Descent, and Landing Systems



"Enable lunar/Mars global access with 20t payloads to support human missions"

"Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies"

Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Envisioned Future (Surface temperatures ranging from 400 K to 35 K)

Spacesuits

Closed-looped heat rejection for extreme temperature variations to minimize consumables

Maintain optical properties in dusty environments (BOL average ratio of solar absorptivity to infrared emissivity (α/ε) of 0.21)

Power Systems

Transport heat from source to power conversion system

Reject waste heat efficiently (lightweight radiators with long-life, dust tolerant coatings)

Science Instrument Survival

Variable Heat Rejection to stay cool in temps up to 400 K while staying warm in temps down to 35 K

Mobility Systems

Variable Heat Rejection to stay cool in temps up to 400 K while staying warm in temps down to 35 K

Freeze & dust tolerant thermal components

Habitats

Variable Heat Rejection to stay cool in temps up to 400 K while staying warm in temps down to 100 K

Contamination-insensitive evaporator/sublimators

Long-life condensing heat exchangers

Efficient, non-toxic, single-loop temp control of crew quarters

Long-term cold food storage to maintain nutrients

Cold Tolerant Mechanisms

Years of continuous operation in temperatures down to 35 K

ISRU Commodity Production/Handing

Water sublimation

Commodity capture

Liquefaction and storage

Commodity management during surface transfers

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Advanced Thermal Management Technologies to Enable Lunar and Martian Missions

Current State of the Art and Progress Toward Goals

Technology Area	SoA (Flight Heritage)	Current NASA Investments (Technologies in Development)			Goal
		TRL 1-3	TRL 4-6	TRL 7-9	
Variable Heat Rejection	Turn Down Ratio ~3:1 (Human class)	✓	✓	--	Turn Down Ratio > 12:1
	Turn Down Ratio ~30:1 (Rover class)				Turn Down Ratio > 100:1
Advanced Radiators	19 kg/m^2 (Deployable)	✓	--	--	< 6 kg/m^2 (Deployable)
	6 kg/m^2 (Body Mounted)				< 3 kg/m^2 (Body Mounted)
Thermal Control Coatings	$\alpha = 0.35$, $\varepsilon = 0.87$ after 5-year life	✓	--	--	$\alpha < 0.25$, $\varepsilon > 0.88$ after 10-year life
Advanced Heat Pipes	Medium heat fluxes	✓	✓	--	High heat fluxes
	Moderate temperature operation				Low temperature operation
Dust Tolerant Thermal Systems	Intolerant (oversized)	✓	✓	--	90% pristine surfaces after 10-year life
Freeze Tolerant Thermal Components	0.067” ID Tube (Radiator)	✓	--	--	> 0.125” ID Tube (Any TCS component)
Advanced Heat Exchangers	Standard Manufacturing	✓	✓	--	Non-standard manufacturing for optimization
Novel Heat Transfer Fluids	Two fluid loops	--	--	--	Efficient, non-toxic, freeze resistant single loop
	Traditional working fluids				Fluids with improved thermophysical properties
Cold Tolerant Mechanisms	Heated lubrication	✓	✓	--	Cold tolerant lubrication or lubrication-free
Advanced Cooling for Electronics	6.5 W/in^2, 30 kg/m^2	✓	✓	--	> 12 W/in^2, < 9 kg/m^2
Integrated Structural/Thermal Elements	Independent elements	✓	--	--	Integrated elements with reduced system mass
Advanced Modeling Techniques	Independent analysis	✓	--	--	Integrated analysis

Current Investments Summary

Novel Heat Transfer Fluids

Applications: Surface Functions

Existing Funding: NONE

Planned Funding:

SBIR Solicitation for Lunar Habitat Applications

Recommendations:

- More STRG Solicitations to increase opportunities for success (ECLSS applications)
- Continue seeding new low TRL work for any application, including fluids in high temp applications, such as fission power
- Invest in solid-state solutions such as leveraging of Shape Memory Alloy elastocaloric properties

Dust Tolerant Thermal Systems

Applications: Surface Functions

Existing Funding:

- STMD & ESDMD Investments
- Advancements In - Electrodynamic Dust Shield applicability to radiators, dust sensors for surfaces

Planned Funding:

- SBIR subtopic focus areas for thermal considerations in dust mitigation

Recommendations:

- Integrate active dust mitigation on optical surfaces and study impacts/effectiveness
- Initiate development of passive solutions
- Expand dust work to include Mars regolith and environments

Advanced Radiators

Applications: Surface, SmallSats, and Planetary Missions

Existing Funding:

- STMD Investments
- Advancements In - Additive Manufacturing, Integration of Advanced Heat Pipes, High temperature heat rejection

Planned Funding:

- ESI22 Development of materials and manufacturing processes for high-temperature radiators

Recommendations:

- Expand surface power radiator portfolio
- Increased collaboration with materials development (integrate advanced materials and processes)

Thermal Control Coatings

Applications: Surface, SmallSats, and Planetary Missions

Existing Funding:

- SMD & STMD Investments
- Advancements In – Dust resistance, optimization of optical properties, variable emissivity

Planned Funding:

- NA

Recommendations:

- Solicitations to address high temperature applications
- Solicitation to extend life of coatings
- Development of fully integrated solutions
- Increased collaboration with advanced materials/processes

Current Investments Summary

Freeze Tolerant Thermal Components

Applications: Surface, SmallSats, and Planetary Missions

Existing Funding:
- STMD Investments
- Advancements In - Advanced manufacturing and multi-phase flow

Planned Funding:
- NA

Recommendations:
- Advancement of existing & previous developments to mid-TRL levels
- Increased collaboration with materials development

Advanced Modeling Techniques

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD Investment
- Advancements In - Human thermal loads, magnetic refrigeration, and cryo systems

Planned Funding:
- NA

Recommendations:
- Solicitations to address integrated thermal loads on-surface
- Structural/thermal modeling advancements
- Incorporate AI/ML for reduced processing times

Integrated Structural/Thermal Elements

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD Investments
- Advancements In – Topology optimization for thermal systems

Planned Funding:
- Thermal SBIR subtopic focus area for thermal topology optimization approved

Recommendations:
- Solicitations to seed new ideas and advance existing developments
- Increased collaboration with ARMD and materials/process developers
- Develop self-sensing and self-healing technologies

Advanced Heat Exchangers

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD, SMD, ESDMD, & ARMD Investments
- Advancements In - Advanced manufacturing, Novel fluid control, evaporative cooling

Planned Funding:
- NA

Recommendations:
- Investments to drive potential solutions toward a flight ready state
- Increase collaboration between Mission Directorates
- Closed-loop systems for EVA

Current Investments Summary

Advanced Heat Pipes

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD, SMD, & SST Investments
- Advancements in - hybrid, oscillating, and variable conductance heat pipes (including advanced manufacturing techniques)

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements (miniaturization and low temp operation)
- Push existing advancements toward tech demo

Variable Heat Rejection

Applications: Surface and Planetary Missions

Existing Funding:
- STMD & SMD Investments
- Advancements in – variable view factors, thermal switches, phase change materials, multi-phase flow, thermoelectric regulation

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements
- Push existing advancements toward tech demo

Cold Tolerant Mechanisms

Applications: Surface and Planetary Missions

Existing Funding:
- STMD & SMD Investments
- Advancements in - magnetic gears, phase change lubricant, bulk metallic glass gears

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements
- Push existing advancements toward tech demo

Advanced Cooling for Electronics

Applications: Surface, SmallSats, Aerospace, and Planetary Missions

Existing Funding:
- STMD Investments
- Advancements in – coldplates, textured cooling loops, dual-channel flow boiling, and microgap coolers

Planned Funding:
- NA

Recommendations:
- Continue seeding new advancements
- Push existing advancements toward tech demo

Planned Development Approach

Order listed shows priorities for new starts due to missing or limited existing investments and descends to top priorities for continued development, demonstration, and infusion.

Technology Area	Current NASA Investments (Technologies in Development)			Recommendation
	TRL 1-3	TRL 4-6	TRL 7-9	
Novel Heat Transfer Fluids	--	--	--	Initiate STRG projects Initiate SBIR projects
Dust Tolerant Thermal Systems	✓	✓	--	Include radiator specific implantation in mid-TRL projects Determine applicability of mitigation tech to thermal systems
Integrated Structural/Thermal Elements	✓	--	--	Initiate SBIR/GCD projects
Advanced Modeling Techniques	✓	--	--	Initiate SBIR/GCD projects
Variable Heat Rejection	✓	✓	--	Integrate maturing tech into demonstrations
Freeze Tolerant Thermal Components	✓	--	--	Initiate SBIR/GCD projects
Advanced Radiators	✓	--	--	Continue new low TRL developments Initiate SBIR/GCD projects
Thermal Control Coatings	✓	--	--	Initiate new low TRL developments Initiate mid TRL developments
Advanced Heat Pipes	✓	✓	--	Integrate maturing tech into demonstrations
Advanced Cooling for Electronics	✓	✓	--	Stay the course – move toward demo
Advanced Heat Exchangers	✓	✓	--	Stay the course – move toward demo
Cold Tolerant Mechanisms	✓	✓	--	Stay the course – move toward demo

Conclusions/Recommendations

- Near-term focus on novel fluids and dust tolerance is required to achieve surface goals
- Late mid-stage investments are crucial for buying down risk for flight program infusion
- Increase collaboration with CLPS, Small Sats, and Flight Opportunities to increase flight demonstration opportunities for maturing technologies
- Thermal Management technologies are highly integrated and support many outcomes and could therefore benefit from increased collaboration among developers
- Development of system-level performance requirements is needed to push component level solutions into integrated system-level solutions
- Continuous infusion of new thermal management ideas can significantly enhance planned architectures leading to enabling of future architectures

Acronyms and Symbols

- α – solar absorptivity
- ε – emissivity
- AI/ML - Artificial Intelligence/Machine Learning
- ARMD – Aeronautics Research Mission Directorate
- BOL – Beginning Of Life
- CIF – Center Innovation Fund
- CLPS – Commercial Lunar Payload Services
- ECLSS – Environmental Control and Life Support Systems
- ESDMD – Exploration Systems Development Mission Directorate
- ESI – Early Stage Innovations
- EVA – Extravehicular Activity
- GCD – Game Changing Development
- HEOMD – Human Exploration and Operations Mission Directorate
- ID – Inner diameter
- ISRU – In-situ Resource Utilization
- LDAR – Lunar Dust Affects on Radiators
- OHP – Oscillating Heat Pipes
- SBIR – Small Business Innovative Research
- SMD – Science Mission Directorate
- SoA – State of the Art
- SOMD – Space Operations Mission Directorate
- SST – Small Spacecraft Technologies
- STMD – Space Technology Mission Directorate
- STRG – Space Technology Research Grants
- TCS – Thermal Control Systems
- TRL – Technology Readiness Level