LIVE: Thermal Management Systems
NASA Space Technology Mission Directorate
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 inter-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)

**Power Systems**
- Transport heat from source to power conversion system
- Reject waste heat efficiently (lightweight radiators with long-life, dust tolerant coatings)

**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 ($\alpha/\varepsilon$) of 0.21)

**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**

<table>
<thead>
<tr>
<th>Technology Area</th>
<th>SoA (Flight Heritage)</th>
<th>Current NASA Investments (Technologies in Development)</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Heat Rejection</td>
<td>Turn Down Ratio ~3:1 (Human class)</td>
<td>✓</td>
<td>Turn Down Ratio &gt; 12:1</td>
</tr>
<tr>
<td></td>
<td>Turn Down Ratio ~30:1 (Rover class)</td>
<td>✓</td>
<td>Turn Down Ratio &gt; 100:1</td>
</tr>
<tr>
<td>Advanced Radiators</td>
<td>19 kg/m² (Deployable)</td>
<td>✓</td>
<td>&lt; 6 kg/m² (Deployable)</td>
</tr>
<tr>
<td></td>
<td>6 kg/m² (Body Mounted)</td>
<td>--</td>
<td>&lt; 3 kg/m² (Body Mounted)</td>
</tr>
<tr>
<td>Thermal Control Coatings</td>
<td>α = 0.35, ε = 0.87 after 5-year life</td>
<td>✓</td>
<td>α &lt; 0.25, ε &gt; 0.88 after 10-year life</td>
</tr>
<tr>
<td>Advanced Heat Pipes</td>
<td>Medium heat fluxes</td>
<td>✓</td>
<td>High heat fluxes</td>
</tr>
<tr>
<td></td>
<td>Moderate temperature operation</td>
<td>✓</td>
<td>Low temperature operation</td>
</tr>
<tr>
<td>Dust Tolerant Thermal Systems</td>
<td>Intolerant (oversized)</td>
<td>✓</td>
<td>90% pristine surfaces after 10-year life</td>
</tr>
<tr>
<td>Freeze Tolerant Thermal Components</td>
<td>0.067” ID Tube (Radiator)</td>
<td>✓</td>
<td>&gt; 0.125” ID Tube (Any TCS component)</td>
</tr>
<tr>
<td>Advanced Heat Exchangers</td>
<td>Standard Manufacturing</td>
<td>✓</td>
<td>Non-standard manufacturing for optimization</td>
</tr>
<tr>
<td>Novel Heat Transfer Fluids</td>
<td>Two fluid loops</td>
<td>--</td>
<td>Efficient, non-toxic, freeze resistant single loop</td>
</tr>
<tr>
<td></td>
<td>Traditional working fluids</td>
<td>--</td>
<td>Fluids with improved thermophysical properties</td>
</tr>
<tr>
<td>Cold Tolerant Mechanisms</td>
<td>Heated lubrication</td>
<td>✓</td>
<td>Cold tolerant lubrication or lubrication-free</td>
</tr>
<tr>
<td>Advanced Cooling for Electronics</td>
<td>6.5 W/in², 30 kg/m²</td>
<td>✓</td>
<td>&gt; 12 W/in², &lt; 9 kg/m²</td>
</tr>
<tr>
<td>Integrated Structural/Thermal Elements</td>
<td>Independent elements</td>
<td>✓</td>
<td>Integrated elements with reduced system mass</td>
</tr>
<tr>
<td>Advanced Modeling Techniques</td>
<td>Independent analysis</td>
<td>✓</td>
<td>Integrated analysis</td>
</tr>
</tbody>
</table>
### 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
<table>
<thead>
<tr>
<th>Applications: Surface, SmallSats, Aerospace, and Planetary Missions</th>
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<tr>
<td><strong>Existing Funding:</strong></td>
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</tr>
<tr>
<td>▪ STMD, SMD, &amp; SST Investments</td>
<td>▪ STMD &amp; SMD Investments</td>
</tr>
<tr>
<td>▪ Advancements in - hybrid, oscillating, and variable conductance heat pipes (including advanced manufacturing techniques)</td>
<td>▪ Advancements in – variable view factors, thermal switches, phase change materials, multi-phase flow, thermoelectric regulation</td>
</tr>
<tr>
<td><strong>Planned Funding:</strong></td>
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</tr>
<tr>
<td>▪ NA</td>
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<tr>
<td><strong>Recommendations:</strong></td>
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<tr>
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## 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.

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<tr>
<td></td>
<td>TRL 1-3</td>
<td>TRL 4-6</td>
</tr>
<tr>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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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

- $\alpha$ – solar absorptivity
- $\varepsilon$ – 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