Development of the TEthered Mechanism for Persistent Energy Storage and Transmission (TEMPEST) System for the Watts on the Moon Challenge

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NASA's Watts on the Moon Challenge

Technology Gaps

Technology gaps for lunar power infrastructure

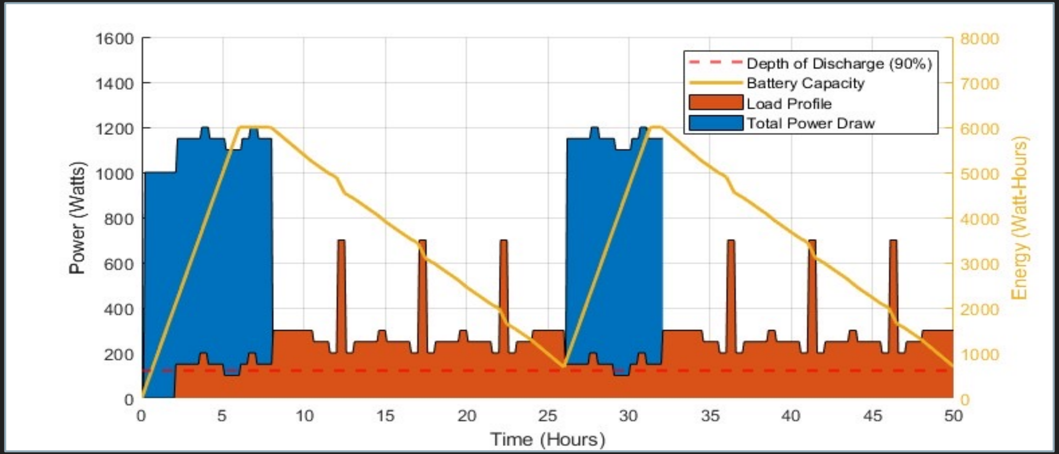
- Low temperature energy storage
- Low-mass/high efficiency energy transmission

Challenge Goals

"NASA's Watts on the Moon Challenge seeks solutions for energy distribution, management, and/or storage that address NASA technology gaps and can be further developed for space flight and future operation on the lunar surface."

Summary of Challenge Design Requirements

- Transmit Power 3km into Lunar PSR (30 meters extrapolated to 3km)
- Supply Power according to given load profile
- Operate under simulated Lunar conditions
  - 10E-3 Torr and ~77K
- Minimize system mass
- Maximize end-to-end efficiency



Watts on the Moon Challenge Supply and Load Profiles

Big Idea 2020 T-REx

NASA’s Big Idea Challenge 2020

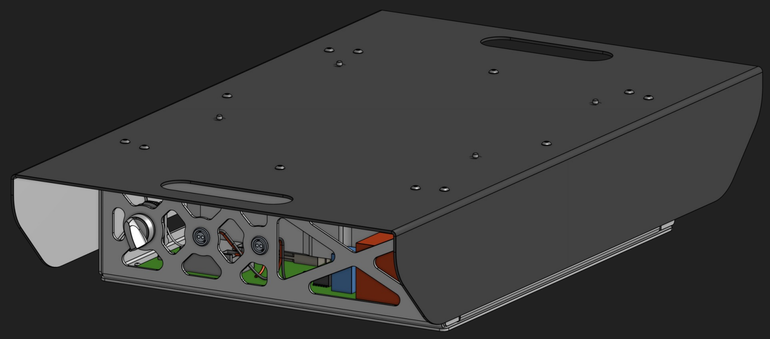
- Rover that traverses into PSR while deploying a superconducting cable to transmit power and communication
- High efficiency solution to powering water processing facilities on lunar surface
- Won “Artemis Award” in NASA BIG Idea Challenge 2020 with the Tethered – permanently shaded Region EXplorer (T-REX)

TEMPEST - Overview

TEMPEST

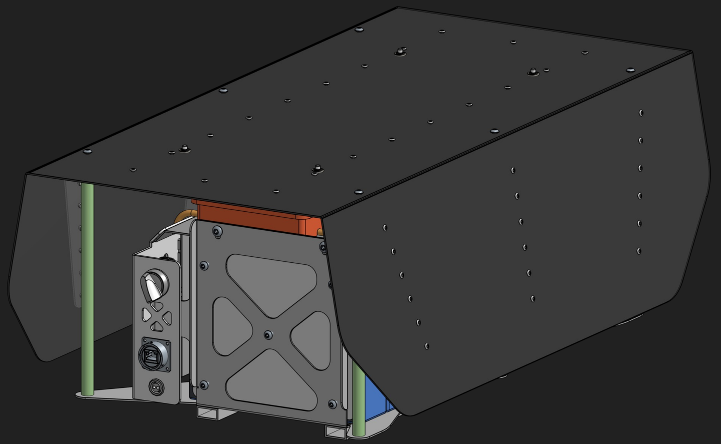
The TEthered Mechanism for Persistent Energy Storage and Transmission (TEMPEST) is a tethered power submission to the Watts on the Moon Challenge. Providing solutions to power conversion, energy storage, thermal management, and tethered transmission technology gaps.

Upstream TEMPEST Module

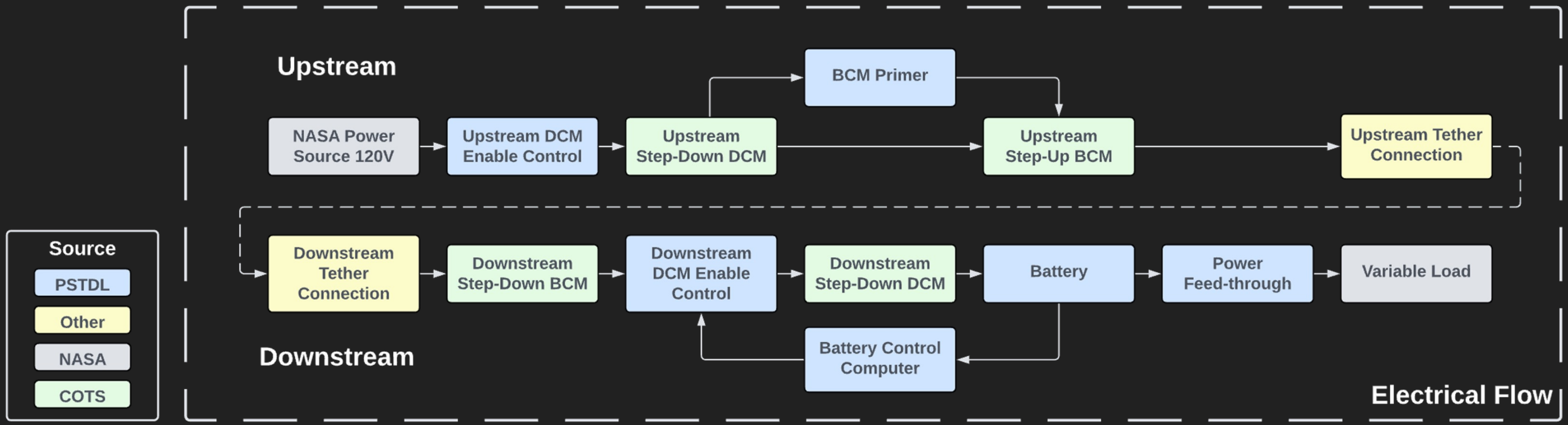


700 VDC

Downstream TEMPEST Module



TEMPEST – DC Power



Electrical Flow Diagram

The electrical subsystem of TEMPEST was designed to minimize complexity while aiming to maximize the reliability of our power delivered. CoTS parts are used where available for conversion and a rigorous testing plan is in progress to qualify our system design for use at NASA Glenn July 2024.

Tethers

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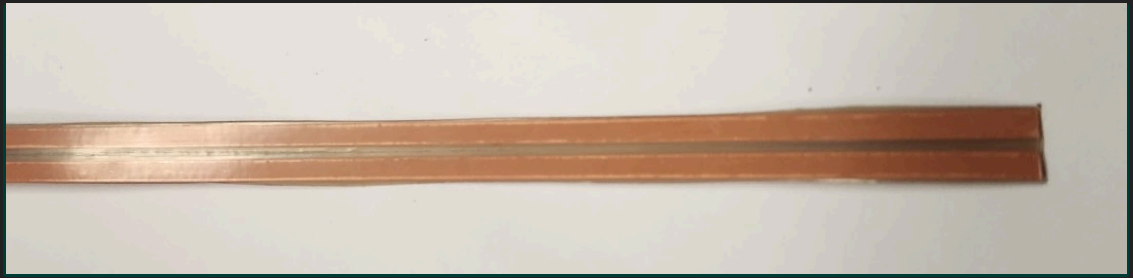
Superconducting Tether

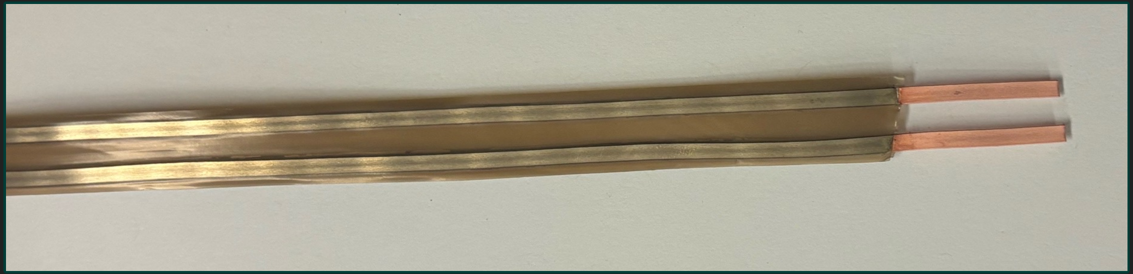
- YBCO superconductor reaches a state of zero electrical resistance when cooled below 92K
- Easily achievable in PSRs, more difficult in TVAC
- Superconductivity enables low voltage, high current power transmission (50 Amps)



Metox/PSTDL Manufactured Superconducting Tether

Flat Aluminum Tether

- Aluminum provides the best mass/resistivity ratio
- Flat tether geometry makes best use of cold radiation environment
- Conductivity increases as temperature decreases
- Scalable in-house manufacturing process developed to produce long lengths of tether



PSTDL Manufactured Flat Aluminum Tether with copper plating

Cryogenic Power Transfer

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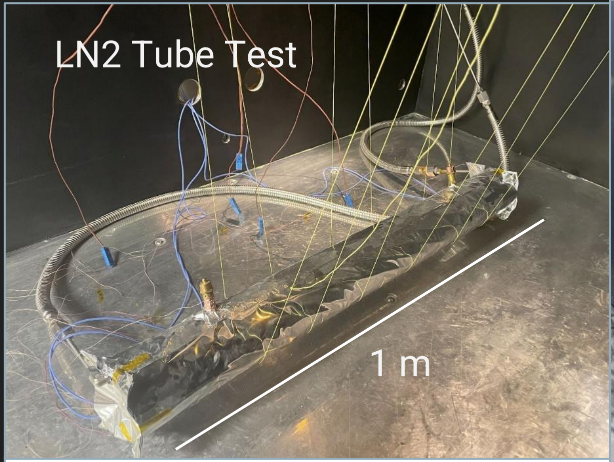
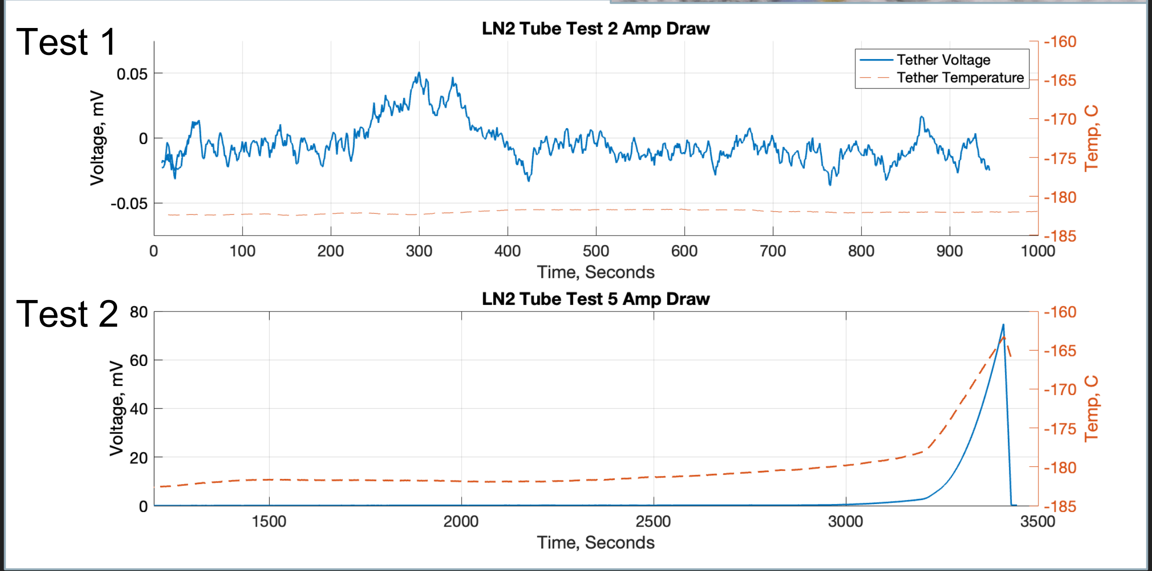
LN2 Tube Test

- Multiple test iterations led to LN2 Tube Test design
- LN2 filled concentric tubes, wrapped in multi-layer insulation create cold radiative environment
- Cryogenic pressure valves ensured vessel temperature
- Regolith within tube acted as a thermal barrier between cooled wall and tether
- Resistivity of tether measured during cooling and power transfer

Superconducting Conclusions

- Tether remained superconducting at 2 Amps (Test 1)
- The 5 Amp test saw temperature rise, beginning at solder junctions (Test 2)
- Improving junction points to reduce temperature rise will increase current capacity
- TEMPEST Team proceeded with aluminum tether due to competition environment





Flat Aluminum Tether Manufacturing

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Rolling aluminum wire to desired dimensions

↓

Wires staged on masking tape

↓

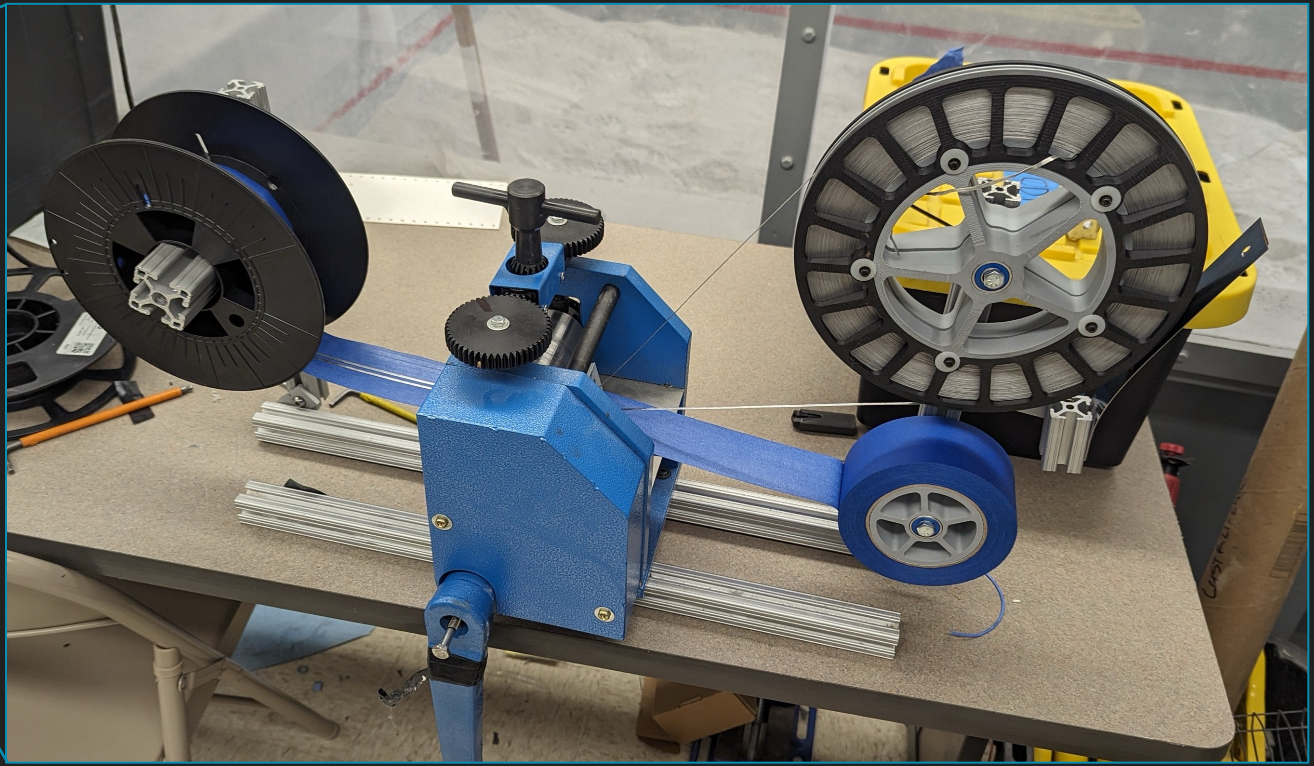
Wire transferred from masking tape to PTFE

↓

Excess tape trimmed to reduce weight

↓

Completed Tether



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Flat Aluminum Tether Manufacturing

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↓

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↓

Completed Tether

Insulation Dimensions	
Thickness	0.1 mm
Conductor Gap	3.0 mm ± 0.5 mm

Conductor Dimensions	
Width	2.3mm ± 0.08mm
Thickness	0.31 mm ± 0.01 mm

Energy Storage

Battery Requirements

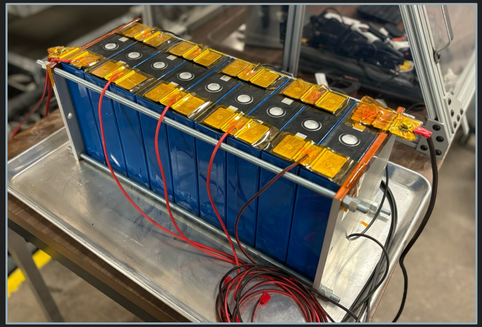
- Output to NASA load at 24-36 VDC
- Supply 5,500 Whrs over 18 hours w/ max draw of 700W
- Maintain >80% capacity over 30 cycles

TEMPEST Battery Specs

Voltage Range	25.2-32.4 VDC
Energy Density	178 Whr/kg
Capacity	6566 Whr
Weight	38kg
Operation Temps	0 to 55 C
Survival Temps	-35 to 100 C

TEMPEST Battery

- Lithium Iron Phosphate (LFP)
- LFP cells are attractive for energy storage applications:
  - Lower cost than other chemistries
  - High specific capacity
  - Cyclic stability and capacity longevity
  - Increased safety from overcharge and puncture
- Challenges of LFPs in space:
  - Lower specific energy
  - Flat discharge curve for SOC tracking

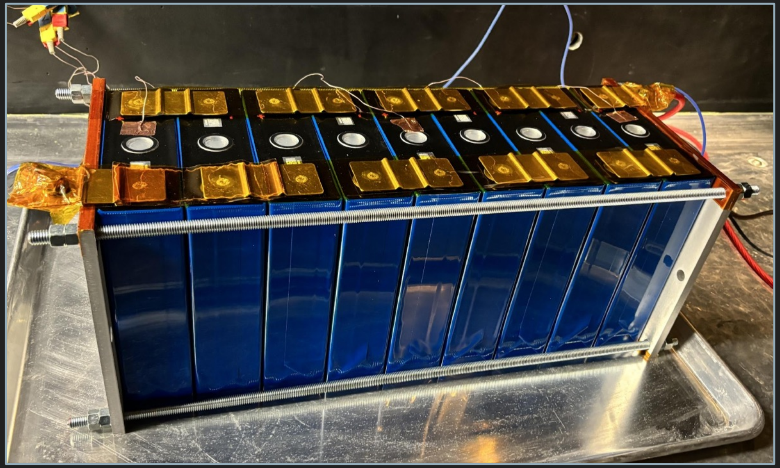


Length	500 mm
Width	174 mm
Height	210 mm

Battery Testing - TVAC

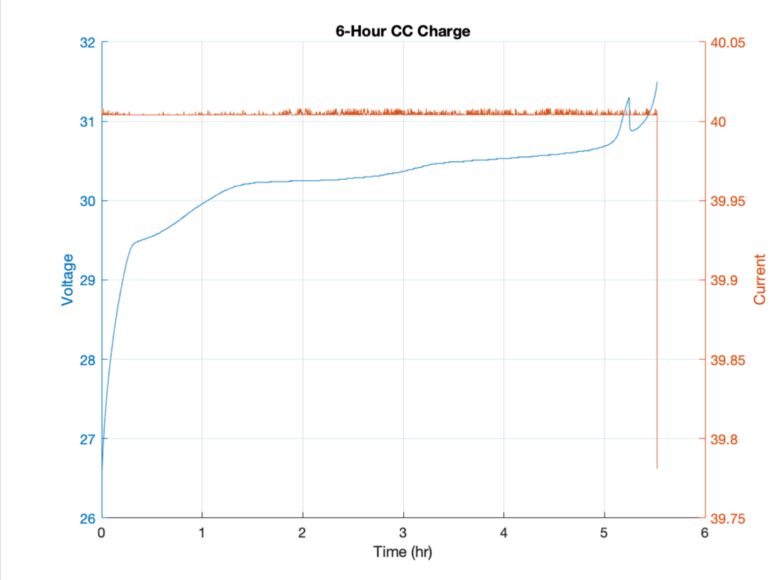
Vacuum Testing

TEMPEST's battery has been demonstrated to perform as expected in vacuum (<10E-6 torr) environments with no outgassing or leakage at full charge/discharge rates, reaching maximum temperatures of 40 degrees C over a 6 hour charge cycle.

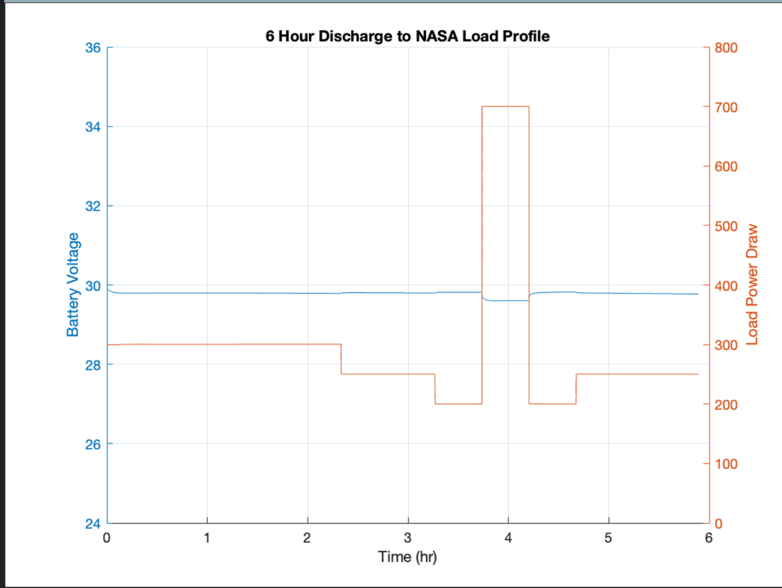


Vacuum Testing of TEMPEST Battery

Battery Charge @ 40A



Battery Discharge @ Watts on the Moon Load



Battery Testing – BMS Development

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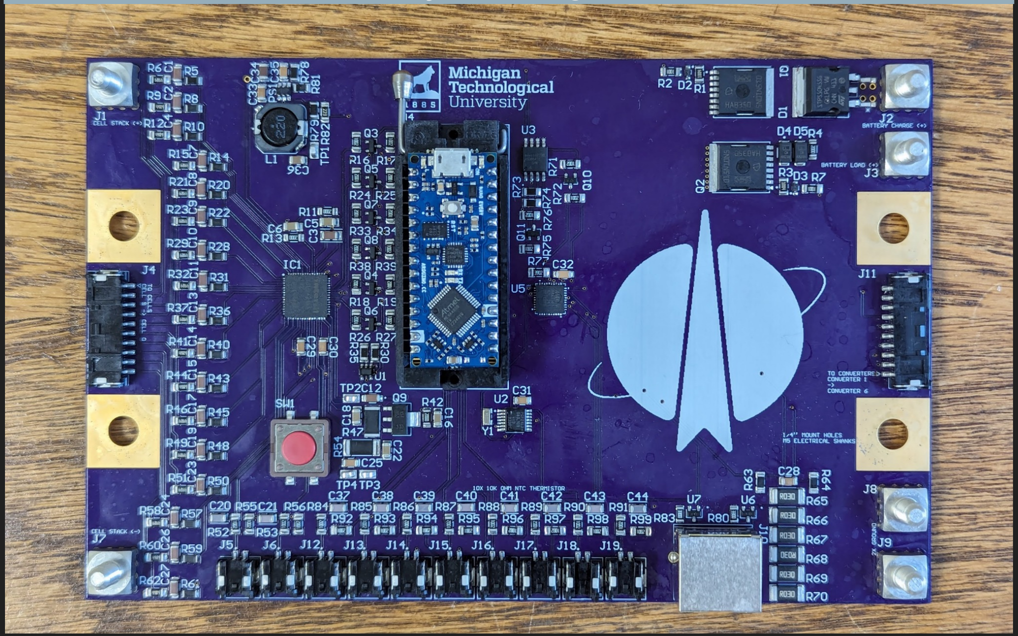
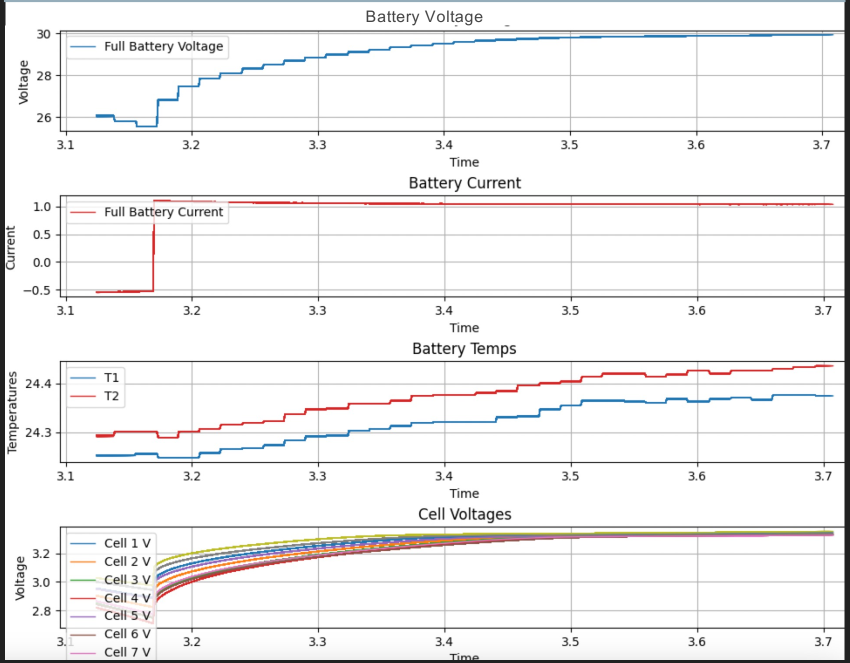
Battery Management

In-house development of a battery management system (BMS) to protect battery from anomalous temperatures, charge/discharge rates, and state of charge. Designing an in-house BMS allows more control over form factor, telemetry gathered, and battery protection decisions

Battery Management



Telemetry Outputs



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TEMPEST – Thermal System

Thermal Switching

- Thermal switches are pistons that expand when heated
- Expansion creates a thermal path from battery to radiator
- Passively thermal system to conserves heat during "night" and reject heat during "day"

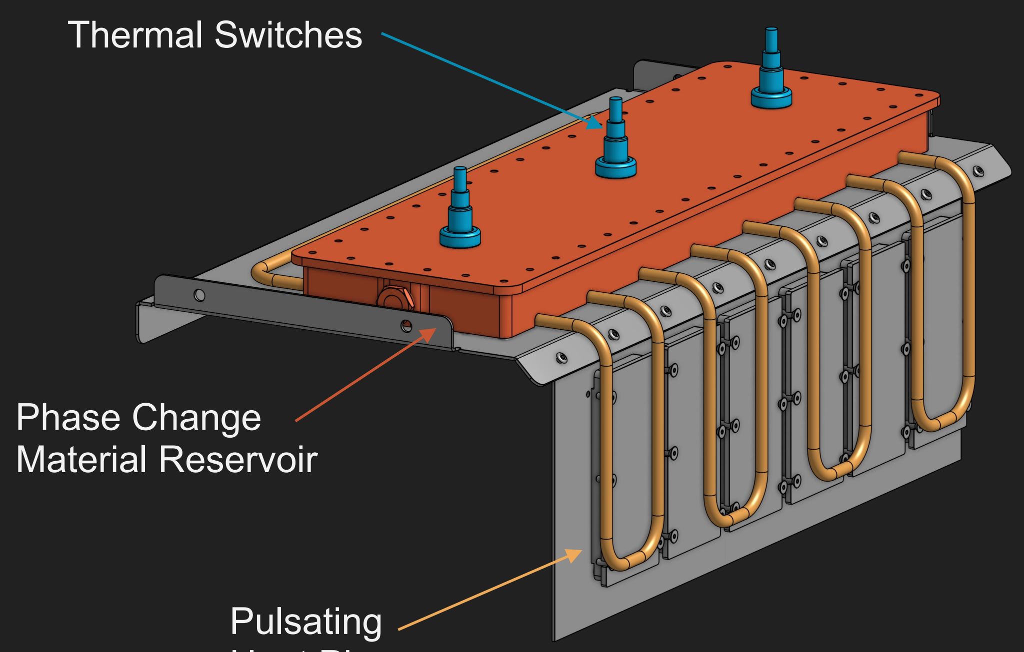
PCM Thermal Battery

- Phase Change Material (PCM)
- Wax-like material to absorb/dispense heat during phase transitions
- Melting temperature of 28-30 °C

Pulsating Heat Pipes

- Pulsating Heat Pipes increase heat transfer between converters and PCM reservoir
- Copper tubes with low pressure water/water vapor
- Utilize slug flow from internal pressure increases

Downstream Thermal System

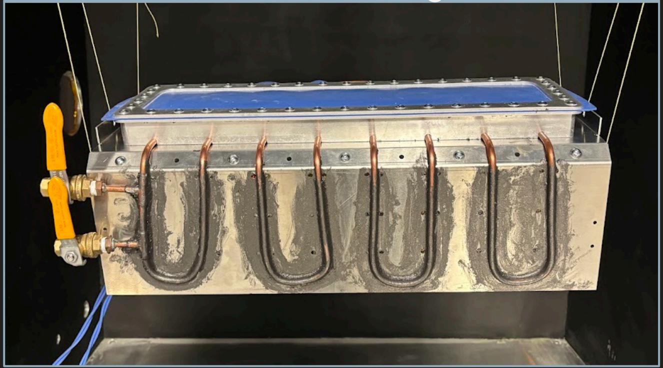


Passive Thermal System – PCM

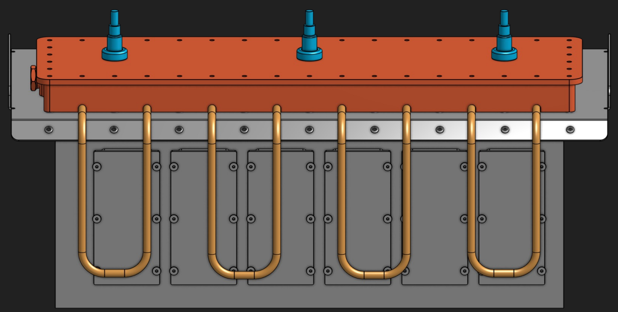
PCM Reservoir

- Both upstream and downstream TEMPEST have PCM
  - 4 kg in Upstream TEMPEST
  - 1 kg in Downstream TEMPEST
- Testing of downstream vessel with fluorosilicone membrane showed dissolved volatiles cause premature membrane actuation due to vacuum pressure

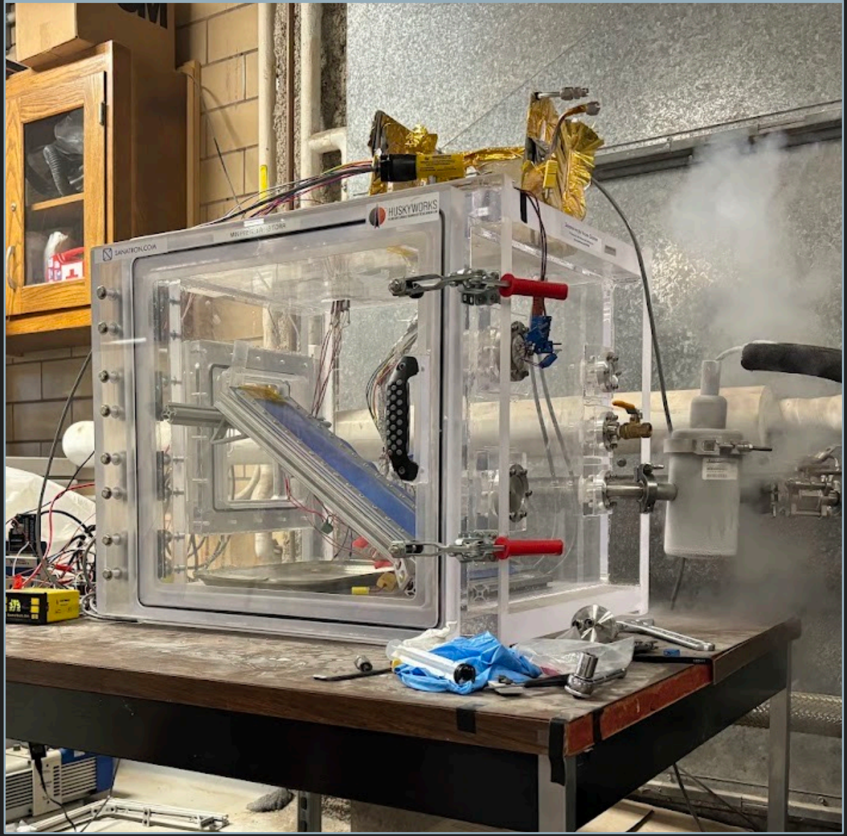
Initial Downstream Thermal System TVAC Testing



Change to Thermal System with Solid Topped PCM Reservoir



PCM Reservoir Filling



Conclusions and Acknowledgements

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Future Work

- Integrated testing at PSTDL vacuum facilities throughout June
- TEMPEST will be demonstrated at NASA Glenn in July

Thanks to TEMPEST Team and more

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