# Lunar Environment Monitoring Station TRL-6 Thermal Vacuum Test Results

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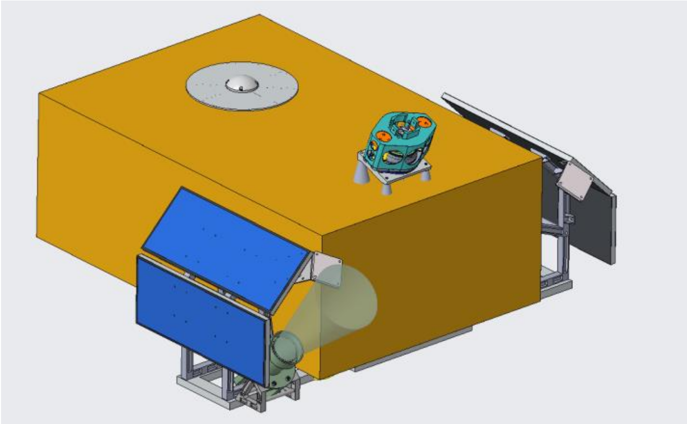
# Paper Availability

- This presentation was also given at the 2023 International Conference on Environmental Systems (ICES).
- The paper can be found at https://ttu-ir.tdl.org/handle/2346/94722

# LEMS Concept

- The Lunar Environment Monitoring Station (LEMS) is a compact, autonomous, and self-sustaining instrument package that will enable long-term, in-situ, monitoring of the lunar exosphere and seismic activity for a nominal duration of 2 years from its deployment on the surface of the Moon.
- Mass Spectrometer: daily measurements of exospheric composition
- Seismometer: continuous monitoring of the Moon’s seismic activity
- Power: on-board batteries and solar arrays for ~3 Watt continuous supply
- Mass: 35 kg CBE
- Comms: weekly downlinks w/ monthly data dump
- Dimensions: 6U
- Operational Environment: 45 deg latitude, capable at other latitudes with design deltas



# Thermal Control Subsystem Design

**Passive Thermal Control**

**High efficiency (e* <0.0028) MLI Thermal Blanket**
**Variable conductance heat switch + OSR radiator**
**Optimized optical coatings**

- All black interior to increase interior heat transfer

**Low Thermal Conductivity Standoffs**

- Retroreflector standoff
- Mass spectrometer breakoff assembly

**Active Thermal Control**

**Cold Op Heaters**

- Operational and survival set points are the same

**Cold Trap Heaters**

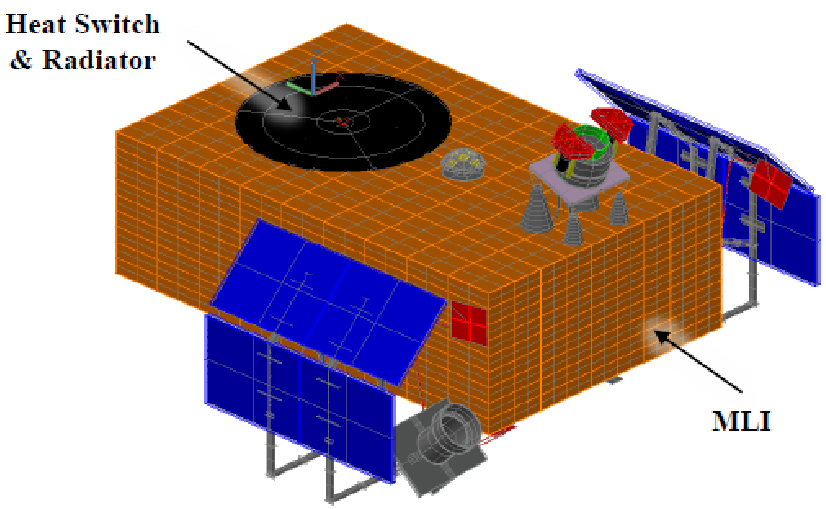
- Cold trap closes through thermal expansion
- Heaters are software controlled

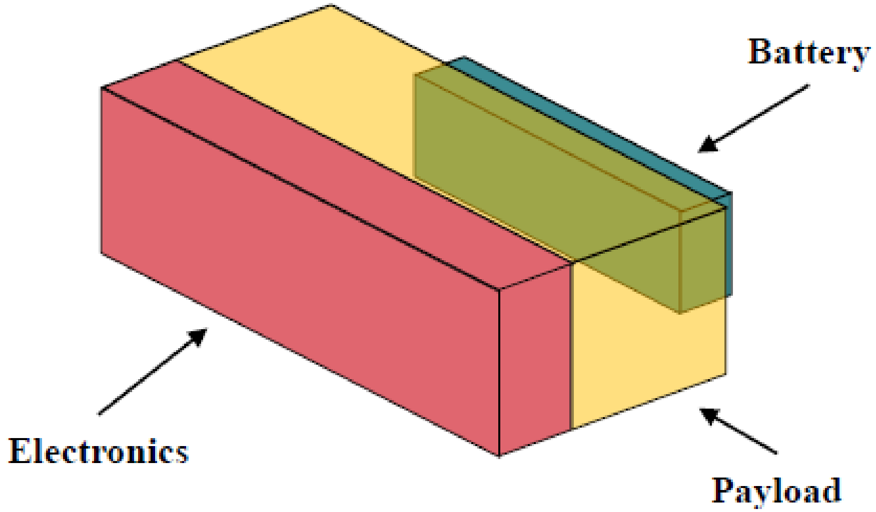
**Launch Lock Legs (not shown)**

- High strength legs for launch, low thermal conductivity legs for surface operations

**Temperature Telemetry**

**Interior components monitored with thermistors**
**Exterior components monitored with PRTS**



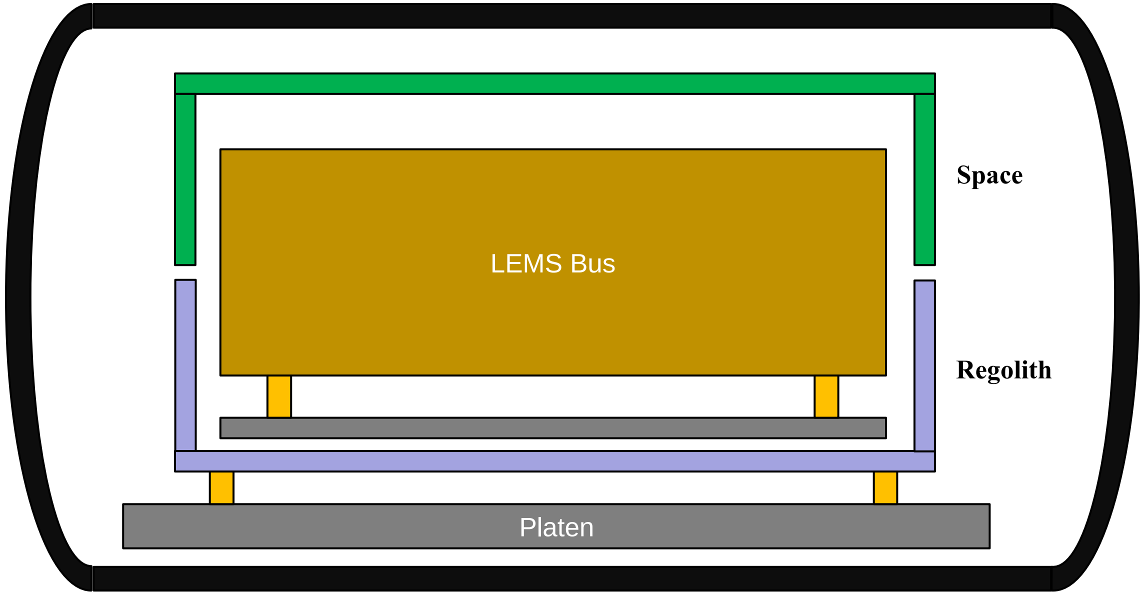
# Test Requirements Overview

To verify the operability of the LEMS command electronics, mass spectrometer, and thermal control system at stacked worst case hot and cold environmental conditions seen on the lunar surface at a latitude of 45 degrees.

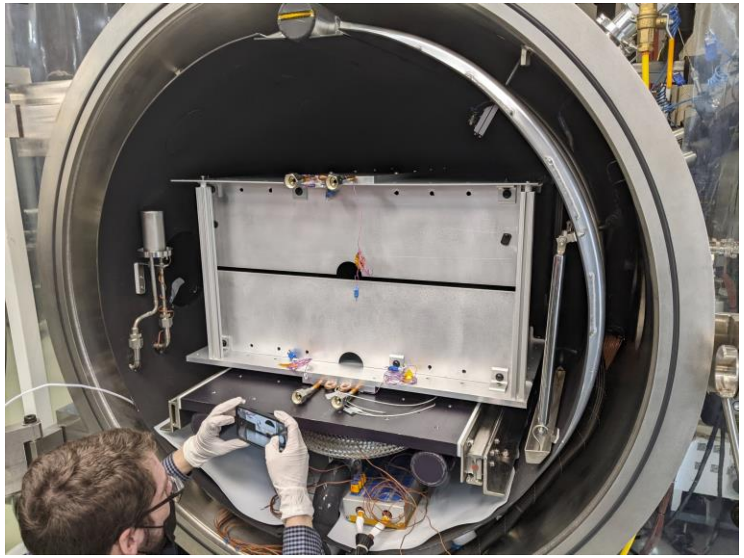
- Verify steady state operation of the avionics box at worst case hot and cold environmental conditions
  - 5 CPTs at temperatures from +50C to -30C demonstrate operability of avionics, PSE, and QMS electronics in flight-like conditions
- Take thermal balance measurements at worst case hot environmental conditions
  - Due to control loop issues with the sink plates, a balance was NOT achieved at Hot Op
- Take thermal balance measurements at worst case cold environmental conditions to verify survivability of TCS during Lunar night
  - $E_{night} = mC_p \Delta T + E_{elec} + \frac{dT}{dt} t_{night} m C_p$
  - $E_{battery} > E_{elec} + \frac{dT}{dt} t_{night} m C_p$
  - Thermal energy requirements on the battery ($E_{battery}$) were measured to be 1178.2 Wh
  - The total Lunar eclipse heat leak ($E_{night}$) was measured to be almost exactly 1407.3 Wh
- Measure test article specific heat capacity
  - LEMS’ specific heat capacity was measured to be 757.4 J/kgK

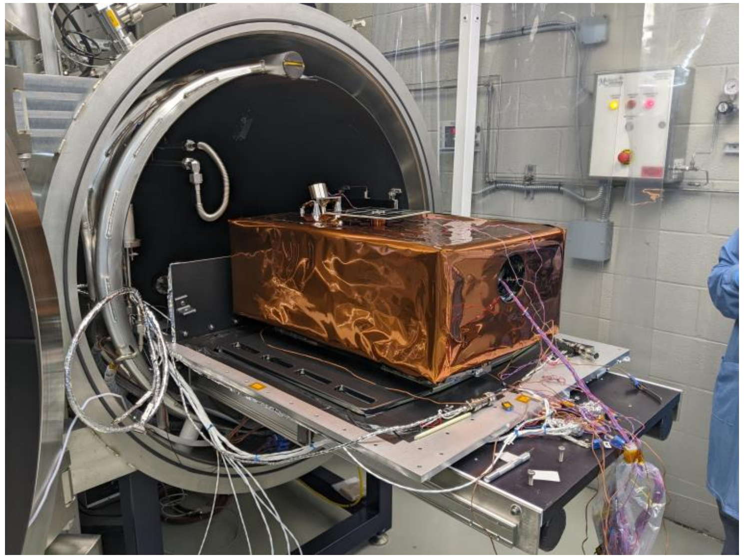
# Test Design Overview

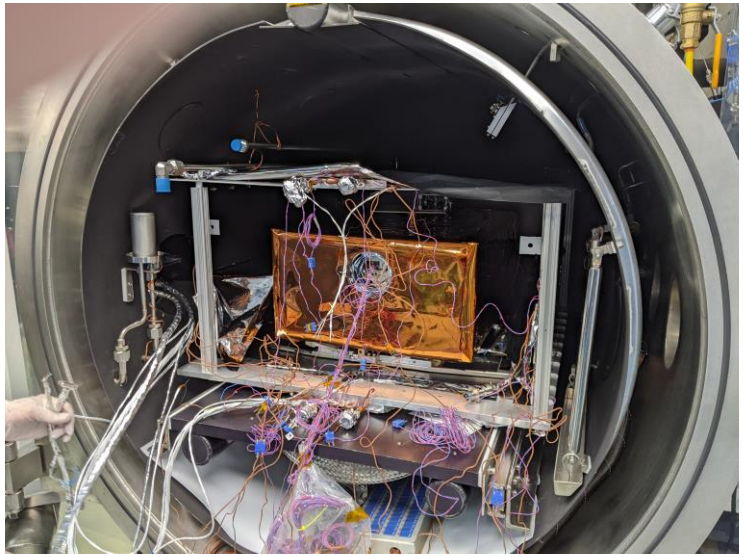
- Thermal vacuum chamber at Genesis Engineering
  - <1e-5 Torr
  - Temperature controlled shroud and platen
  - QCM, cold finger, cold plate
  - 60 temperature channels
- Radiative surface sink plates
  - Two “tubs” to simulate the regolith and space temperatures for the thermal blankets, radiator, and launch lock mechanism
  - LN2 and heaters controlled tub temperatures
  - Isolated from chamber plate
- 0Q Heaters on GSE Harnessing

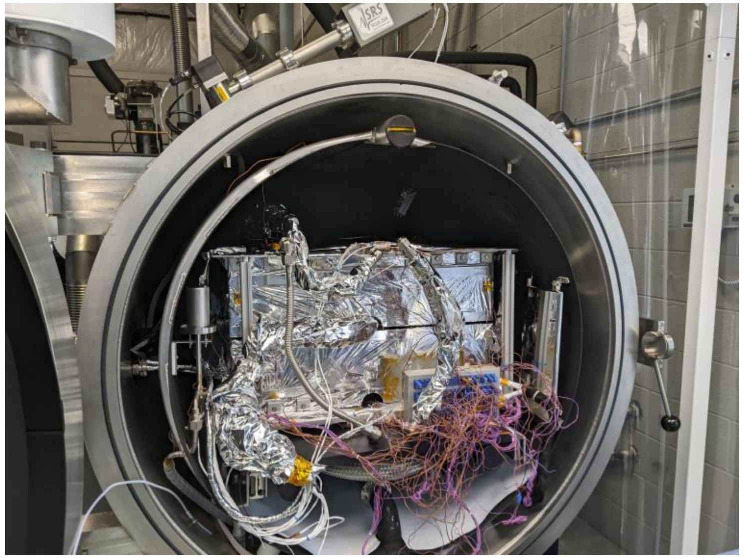


# Chamber Integration







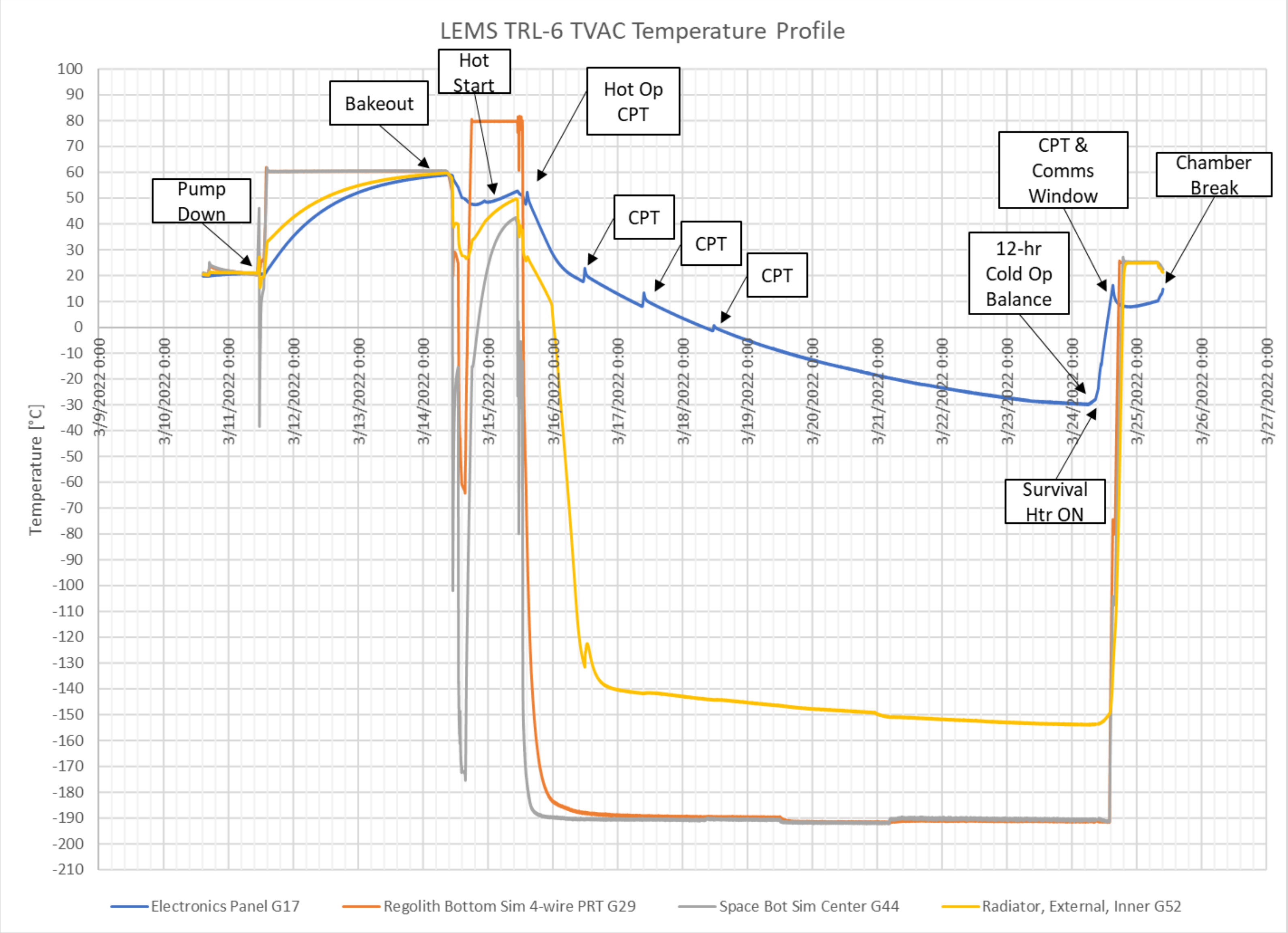


From left to right:

- Fit check
- GSE cooling plate assembly
- LEMS installed on GSE in TVAC chamber
- Harness and thermocouple connection
- Final close out

# Thermal Test Profile

- CPT: 33 min
  - Start-up: 3 min
  - Comm: 10 min
  - QMS: 20 min
- Battery Preheating: 5 hours
- Data Dump: 2 hr



# Thermal Mass Measurement

- Following Cold Op CPT all internal electronics were turned on to measure the thermal heat capacity of the system.
- Power input measured from power supplies and corrected using harness loss assumptions
- Interface leakage estimated as the cold op conductance multiplied by the measured delta T
  - Linear extrapolation of heat leaks does not account for $T^4$ effects from blanket radiation so the maximum dT was used from the sampled range
- Mass is the sum of all internal components (excluding the blanket and external standoffs like the launch lock legs and breakoff standoffs)
- $C_p = \frac{Q_{diss} - Q_{leak}}{m\left(\frac{dT}{dt}\right)} \left[\frac{Wh}{K}\right] = 5.726\,\frac{Wh}{K} = \mathbf{757.4}\,\frac{\mathbf{J}}{\mathbf{kgK}}$
  - Linear regression has a high correlation ($r^2 > 0.99$) to internal sensors indicating use of $Q = mc_p\Delta T$ to measure $c_p$ is reasonable

| TC Name | Ref Des | DAQ Des | Temperature [°C] | | | Linear Regression | |
|---|---|---|---|---|---|---|---|
| | | | Start | End | delta | linest [K/h] | $r^2$ |
| Launch Lock Leg 1, internal | G1 | TC101 | -14.88 | 4.45 | 19.34 | 7.476 | 0.998 |
| Launch Lock Leg 2, internal | G2 | TC102 | -18.02 | 0.65 | 18.67 | 7.336 | 0.999 |
| Launch Lock Leg 3, internal | G3 | TC103 | -20.94 | -3.47 | 17.47 | 7.098 | 1.000 |
| Launch Lock Leg 4, internal | G4 | TC104 | -131.93 | -131.96 | -0.02 | 0.030 | 0.018 |
| Breakoff, Internal 1 | G9 | TC109 | -17.33 | 1.37 | 18.70 | 7.372 | 0.999 |
| Heat Switch, internal | G11 | TC111 | -18.28 | -0.62 | 17.66 | 7.231 | 0.999 |
| Breakoff, Internal 2 | G13 | TC113 | -11.22 | 8.44 | 19.66 | 7.579 | 0.995 |
| GSE Harness, Internal | G15 | TC115 | -20.81 | -3.61 | 17.20 | 6.904 | 1.000 |
| Electronics Panel | G17 | TC117 | -14.24 | 4.39 | 18.63 | 7.380 | 0.999 |
| Battery | G18 | TC118 | -21.35 | -3.93 | 17.41 | 7.069 | 1.000 |
| Thermal Leg 1, Bottom Panel | G21 | TC121 | -13.98 | 5.50 | 19.48 | 7.503 | 0.997 |
| Thermal Leg 2, Bottom Panel | G22 | TC122 | -17.83 | 0.88 | 18.71 | 7.376 | 0.999 |
| Thermal Leg 3, Bottom Panel | G23 | TC123 | -20.51 | -2.91 | 17.60 | 7.036 | 1.000 |
| Thermal Leg 4, Bottom Panel | G24 | TC124 | -21.23 | -3.86 | 17.38 | 7.035 | 1.000 |
| **LEMS Internal Avg** | | | **-26.29** | **0.91** | **16.98** | **7.291** | **0.999** |
| **LEMS Internal Avg, without TC104** | | | **-17.48** | **0.91** | **18.39** | **7.287** | **1.00** |

| Case | Temperature [°C] | | | Heat Dissipation [W] |
|---|---|---|---|---|
| | Internal | External | dT | |
| Cold Op Balance | -30.3 | -189.5 | 159.2 | 2.999 |
| Cp Meas. Start | -17.5 | -189.9 | 172.5 | 3.249 |
| Cp Meas. End | 0.9 | -189.8 | 190.7 | 3.593 |

# Cold Operational Thermal Balance

- Thermal balance criteria from GEVS: GSFC-STD-7000b requires temperature stability of **4.5e-3 K/day** (see backup)
- Instead, LEMS uses a thermal balance criteria derived from the objective to measure nighttime power consumption.
  - $E_{battery} > E_{elec} + \frac{dT}{dt} t_{night} m C_p$
  - Electrical heat dissipation = 1178.2 Wh
- Linear regression was performed to on balance data to determine balance criteria were met
  - Average $r^2$ on critical sensors = 0.858 due to high noise (~0.1 C) relative to rate of change

| TC Name | Ref Des | DAQ Des | Temperature [°C] | | Linear Regression | |
|---|---|---|---|---|---|---|
| | | | Start | End | Slope [K/h] | $r^2$ |
| Launch Lock Leg 1, internal | G1 | TC101 | -30.63 | -31.28 | -0.058 | 0.923 |
| Launch Lock Leg 2, internal | G2 | TC102 | -29.93 | -30.65 | -0.058 | 0.776 |
| Launch Lock Leg 3, internal | G3 | TC103 | -29.80 | -30.58 | -0.058 | 0.839 |
| Launch Lock Leg 4, internal | G4 | TC104 | -128.25 | -132.46 | 0.024 | 0.010 |
| Breakoff, Internal 1 | G9 | TC109 | -30.30 | -30.74 | -0.056 | 0.822 |
| Heat Switch, internal | G11 | TC111 | -29.66 | -30.46 | -0.056 | 0.747 |
| Breakoff, Internal 2 | G13 | TC113 | -29.96 | -30.47 | -0.058 | 0.898 |
| Electronics Panel | G17 | TC117 | -29.18 | -29.87 | -0.058 | 0.767 |
| Battery | G18 | TC118 | -29.91 | -30.64 | -0.056 | 0.907 |
| Thermal Leg 1, Bottom Panel | G21 | TC121 | -30.00 | -30.86 | -0.057 | 0.906 |
| Thermal Leg 2, Bottom Panel | G22 | TC122 | -30.87 | -31.58 | -0.056 | 0.902 |
| Thermal Leg 3, Bottom Panel | G23 | TC123 | -29.62 | -30.30 | -0.056 | 0.910 |
| Thermal Leg 4, Bottom Panel | G24 | TC124 | -29.95 | -30.58 | -0.056 | 0.905 |
| **LEMS Internal Avg** | | | **-37.543** | **-38.497** | **-0.051** | **0.793** |
| **LEMS Internal Avg, sans TC105** | | | **-29.984** | **-30.667** | **-0.057** | **0.858** |

| Power Supply | Meas. Avg. Voltage [V] | Meas. Avg. Current [A] | Meas. Avg. Pwr [W] | 28V Harness Corr.[W] | External Seismometer Power Corr. [W] | 12V Seismometer Supply Corr. [W] | Corr. Power [W] |
|---|---|---|---|---|---|---|---|
| 4 | 28.0 | 0.1153 | 3.228 | -0.011 | -0.364 | -0.002 | 2.851 |
| 3 | 28.0 | 0.0053 | 0.148 | 2.230E-06 | - | - | 0.148 |
| Totals | | | 3.376 | -0.011 | -0.364 | -0.002 | 2.999 |

# Acknowledgments


- Planetary Science Division / Science Mission Directorate at NASA Glenn Research Center Development and Advancement of Lunar Instrumentation for funding this development effort.
- The rest of the LEMS team for their effort and support in the design, integration, and testing of the LEMS system for TRL-6 TVAC with notable efforts by Rick Mills, Rebecca Austin, Emmanuel Hernandez, and Ryan Wilkinson.
- Sierra Nevada Space for loaning the heat switches used in the test.
- QUEST Thermal Group for the design and construction of the blanketing.
- Jason Budinoff at Visioneering for the design and integration of the launch lock mechanism.
- Rommel Zara for his mentorship, expertise, and advice throughout the development of the LEMS thermal control system.
- Lunar QuickMap (https://quickmap.lroc.asu.edu), a collaboration between NASA, Arizona State University & Applied Coherent Technology Corp, for the use of imagery from the Lunar surface.

# Lessons Learned

- LEMS TCS DesignInclude method of verifying thermal conductance of variable conductance interfaces (e.g.launch lock mechanism, heat switch). Options include breaking electrical contact, measurement of electrical capacitance.
- Lunar thermal design ***is***cryogenic thermal design. Fight Mechanical and Electrical for every mW.
- TVAC Testing
  - Account for measurement uncertainty in thermal balance and heat flow tables
    - Uncertainty in the energy dissipated from stored heat due to the temperature rate of change during Cold Op balance was **20.5%**of the total available energy
- Measure Thermal Conductance of Individual Components
  - TRL-6 testing precluded component level testing of the launch lock mechanism and breakoff standoffs
- All unique GSE radiative and conductance thermal sinks need to have independent control
  - By nature of the TVAC chamber that was selected, only one LN2 loop was available
  - Select a chamber that has all the required interfaces without additions. DIY chamber hardware costs time and money
- Include scheduling of LN2 and other chamber consumables in thermal test plan
  - Test depleted LN2 stores every 2-3 days. Airgas was not originally scheduled to deliver over the weekend
- 24 hour staffing is a blessing but LEMS was unable to staff around-the-clock due to cost