National Aeronautics and Space Administration

Cryogenically-Operable Electronics for Surviving the Lunar Night

Space Power Workshop
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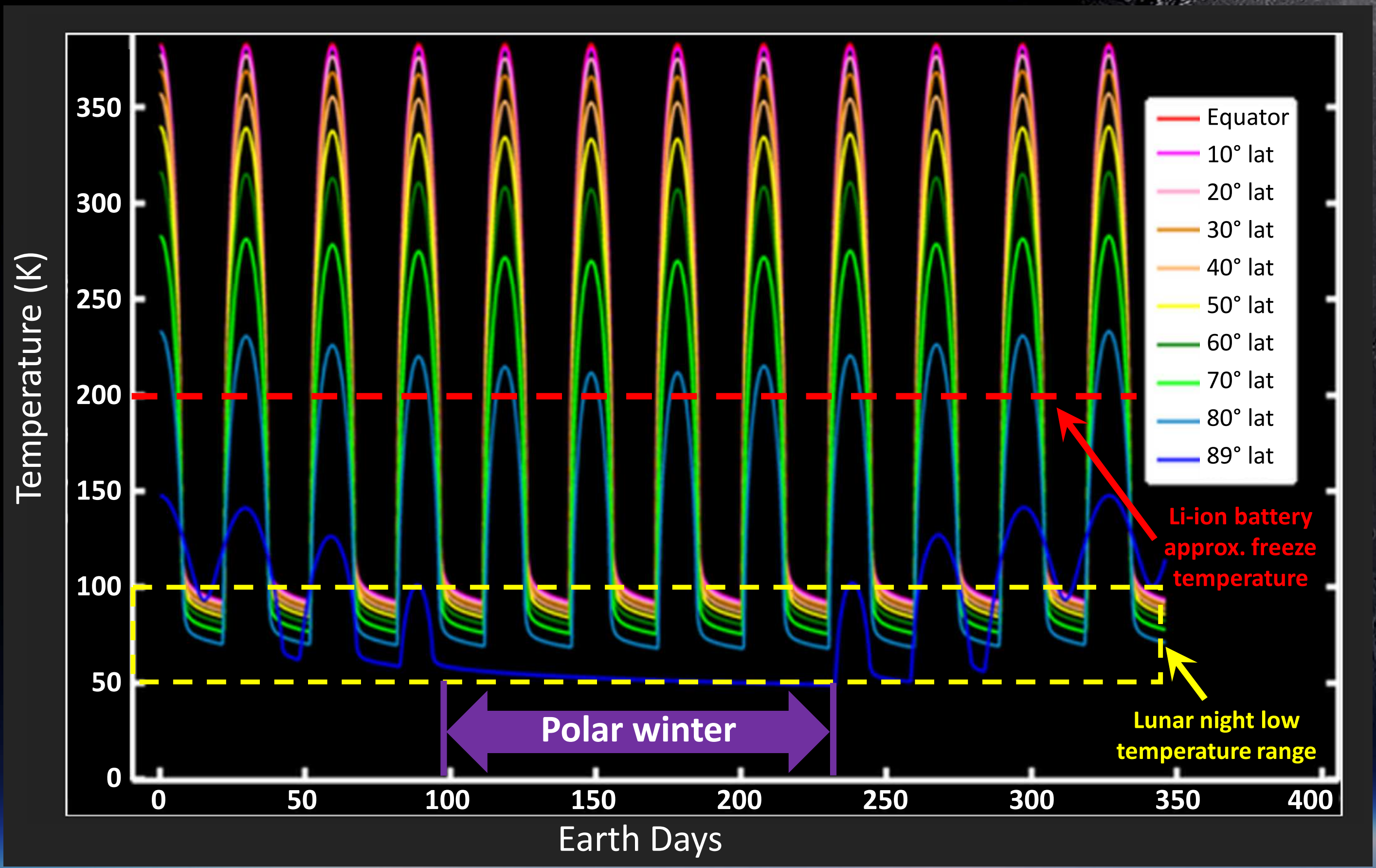
The Extreme Lunar Environment



Thermal model calculations of monthly and annual lunar surface temperature variations at various latitudes.
Image permissions per Dr. N Petro/NASA GSFC, Dr. D Paige/UCLA

Day:

- **150-400 K high temperatures based on latitude**

Night:

- **50-100 K low temperatures**
- **~14.75 Earth days duration (non-polar latitudes)**

Polar Winter:

- **50 K low temperature**
- **~135 Earth days duration**

Current Lunar Night Survivability Options

Commercial Lunar Payload Services (CLPS): commercially-developed lunar landers to provide a low-cost delivery to the lunar surface

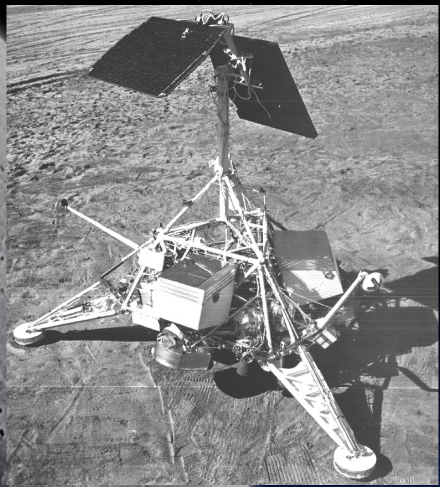
- Currently, all CLPS missions are solar powered, and lunar night survival will likely be a requirement in the future
- Existing non-nuclear survival options require generating and/or retaining heat throughout the night
  - Heaters powered via large mass batteries
  - Generating heat via consumable chemicals
  - At poles, there are areas with longer periods of sunlight, but not 100% illumination
- Example: Lunar Terrain Vehicle (LTV) estimates 15 to 30 kWh just to heat overnight, which would represent 100 to 200 kg of extra battery mass!

Lunar Terrain Vehicle (LTV) concept art. *Image Credit: NASA*

The Hibernation Option

Lunar Power Hibernation: disconnect the batteries, allow all systems to freeze, then enter a controlled thaw at dawn

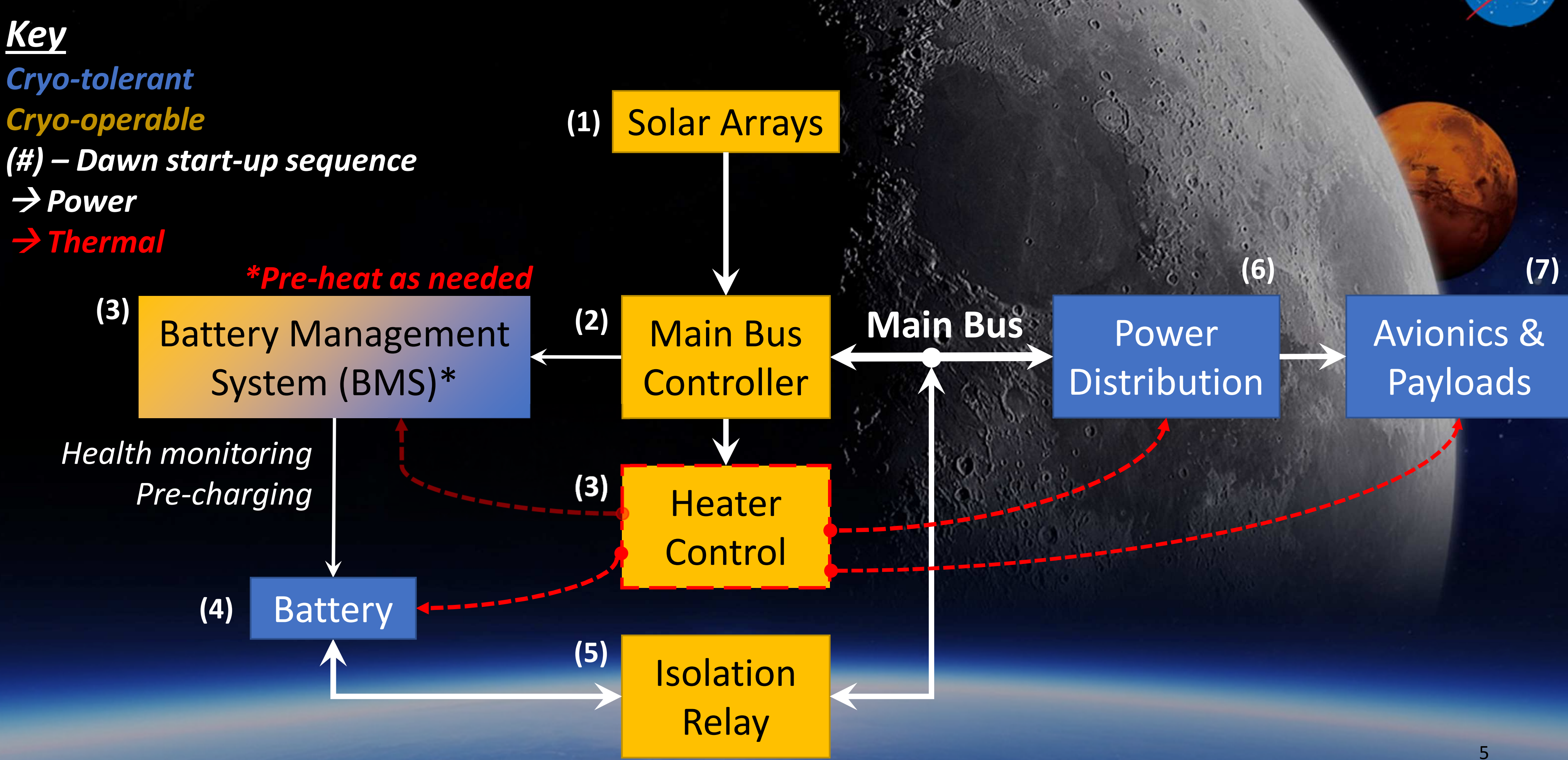
- All on-board systems must be cryogenically tolerant
- Some electronics must be cryogenically operable
- Huge benefits if implemented
  - **Low cost:** obtainable with COTS electronics
  - **Low mass:** extra battery power not required
  - **Low impact:** only require bootstrap power systems to be cryogenically operable
  - **Increases capability:** a single night survival doubles mission length
- Feasibility has been demonstrated



Surveyor 1. *Image Credit: NASA*

Smart Lander for Investigating Moon (SLIM) lander. *Image Credit: JAXA*

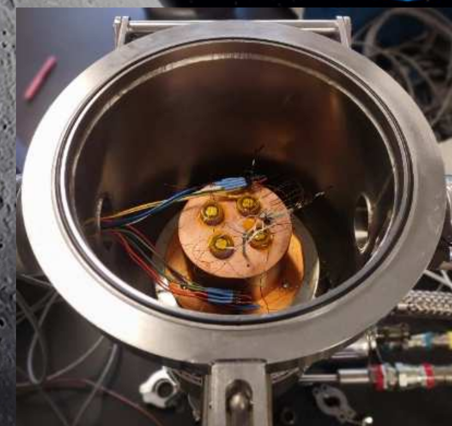
Sample Dawn Start-Up Sequence



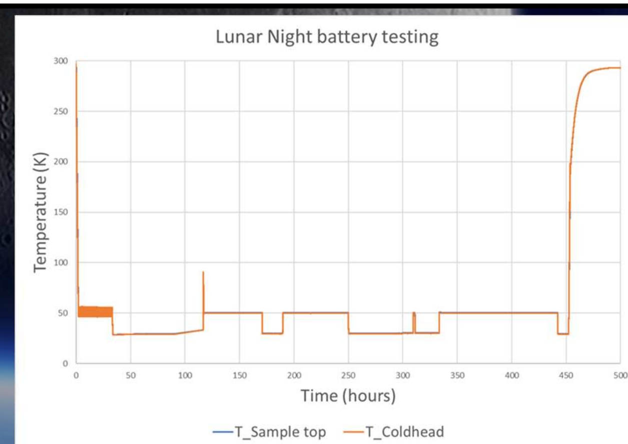
Battery Technology for Power Hibernation

NASA Glenn is testing lithium-ion batteries across multiple freeze/thaw cycles

- Operating Li-ion cells while frozen is not possible; disconnecting the battery from the bus before freezing prevents improper charging/discharging cells
- Tests have been conducted with high-energy COTS cells (LG INR18650-M36 and Molicel INR18650-M35A)
- Tested single cells at 50 K with 0%, 20%, and 40% state-of-charge under multiple lunar hibernation sequences
- Tested series-connected and parallel-connected cell string configurations



Four Li-ion cells inserted into a copper cold block for cryo testing.

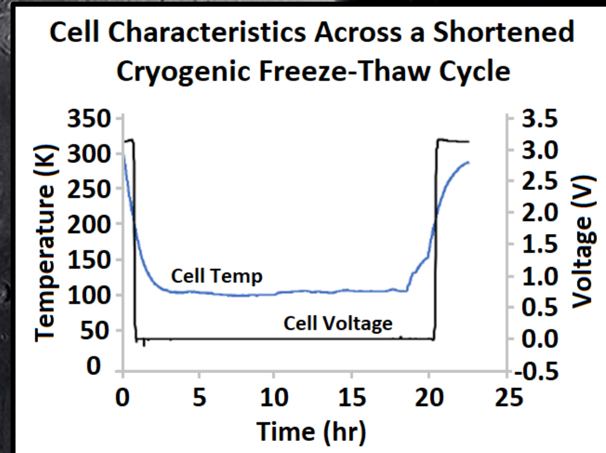


Temperature profile of cells over simulated lunar night.

Battery Test Results

Preliminary data shows tested COTS cells are cryo-tolerant in a vacuum

- Cells consistently survived cryogenic exposures under vacuum at ~50 K with 14-day dwells
- Cells recover open circuit voltage, show no distinguishable mass loss, and have minimal impact to discharge capabilities after returning to operational temperatures
- Future work: Explore higher states of charge, additional measurements and tests, more lunar night cycling



Before Low-T					*After Low-T*				*Change*			
Date	Cell Number	State of Charge	Mass, g	Discharge Capacity, Ah	Date	Cell Number	Mass, g	Discharge Capacity, Ah	Δ Mass (g)	Δ Mass (%)	Δ Capacity (Ah)	Δ Capacity (%)
Strategic Reserve Cells												
6/21/2023	527	0%	45.934	3.3516	7/5/2023	527	45.8652	3.3485	-0.0688	-0.1%	-0.0031	-0.1%
6/21/2023	528	20%	45.835	3.3689	7/5/2023	528	45.8926	3.3310	0.0576	0.1%	-0.0379	-1.1%
6/21/2023	529	40%	45.892	3.3601	7/5/2023	529	45.7972	3.3402	-0.0948	-0.2%	-0.0199	-0.6%
6/21/2023	530	40%	45.777	3.3631	7/5/2023	530	45.8280	3.3405	0.0510	0.1%	-0.0226	-0.7%
8/10/2023	531	0%	45.864	3.3425	8/24/2023	531	45.8641	3.3105	0.0001	0.0%	-0.0320	-1.0%
8/10/2023	532	20%	45.911	3.3668	8/24/2023	532	45.9009	3.3351	-0.0101	0.0%	-0.0317	-0.9%
8/10/2023	533	40%	45.975	3.3624	8/24/2023	533	45.8822	3.3357	-0.0928	-0.2%	-0.0267	-0.8%
8/10/2023	534	40%	45.647	3.3465	8/24/2023	534	45.7355	3.3176	0.0885	0.2%	-0.0289	-0.9%

Power Electronics Technology for Hibernation

Revival from hibernation requires power electronics that survive and operate in cryogenic vacuum conditions

Cryo-tolerance is essential for passive night survival

- Circuit board and device packaging must tolerate repeated exposure to extreme low temperatures (thermal–mechanical stress)
- Physical size of boards and devices can influence reliability

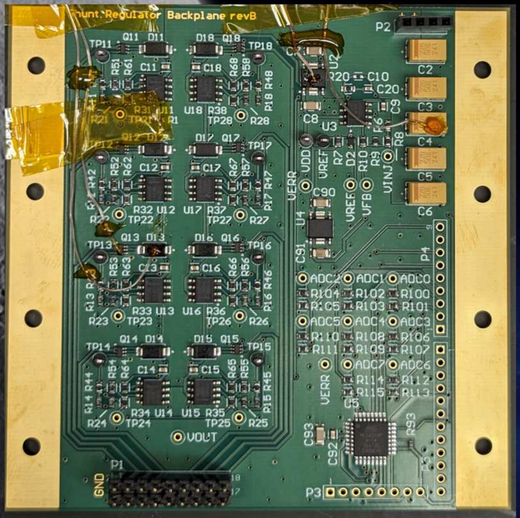
Cryo-operable electronics assures reliable power recovery at lunar dawn

- Cryo-operability requires stable "cold start" operation at 50 K
- Begins operation when solar arrays are first illuminated
  - Capable of managing power on solar array output alone
  - Preheats batteries and passive avionics for restart
  - May perform battery diagnostics and pre-charging

Power Electronics Technology for Hibernation

NASA Glenn has developed a cryo-operable power supply demonstrator with COTS components

- Sequential Switching Shunt Regulator (S3R) module capable of regulating power to external loads via eight "solar strings"
- Designed with component types that have been shown to be operable at low temperatures
- Accomplishments:
  - Stable operation throughout temperature ramp from 300 K down to 50 K
  - Cold start capability at 57 K after cold soak
  - Continued operation for over 100 hours
- Current work:
  - Evaluating cryo-operability of microcontrollers

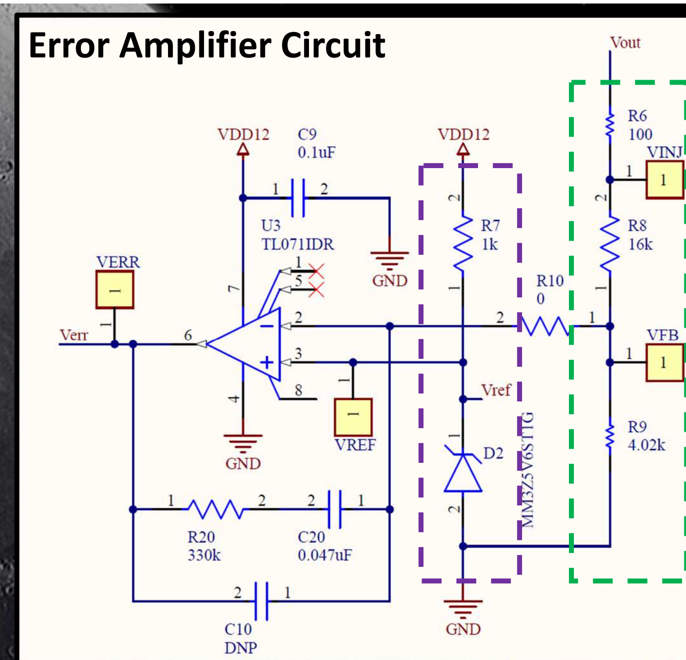


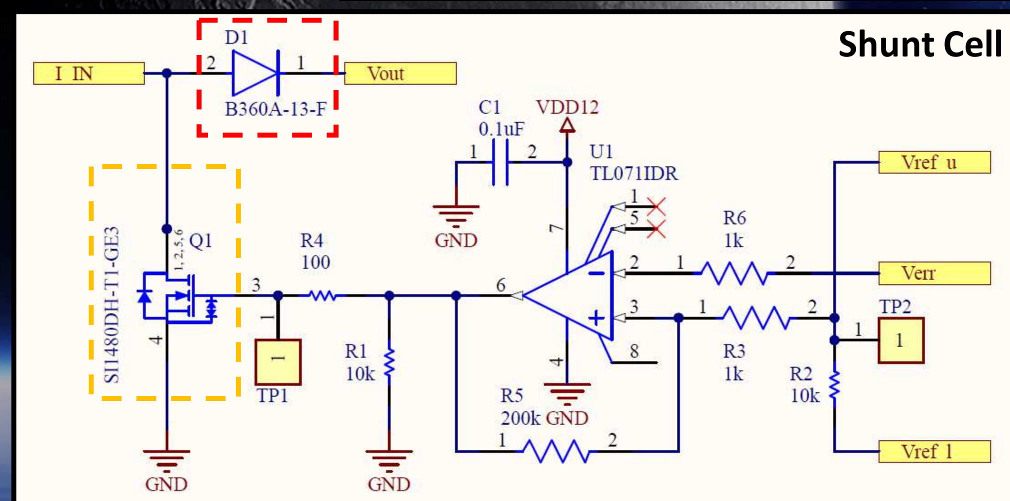
S3R circuit board, revision B.

Cryogenic vacuum chamber setup.

S3R Board

- Feedback and error amplifier
  - Voltage reference (Zener diode)
  - Voltage feedback (thick film resistors)
  - Comparator (JFET op-amp)
- Eight shunt "cells" – one for each solar string
  - Array shunting FET (silicon MOSFET)
  - Blocking diode (silicon Schottky diode)
  - Comparator circuit (JFET op-amp)
- Auxiliary power
  - 12 V linear regulator (CMOS LDO)
- Output capacitance
  - Tantalum capacitors, 5x 22 uF

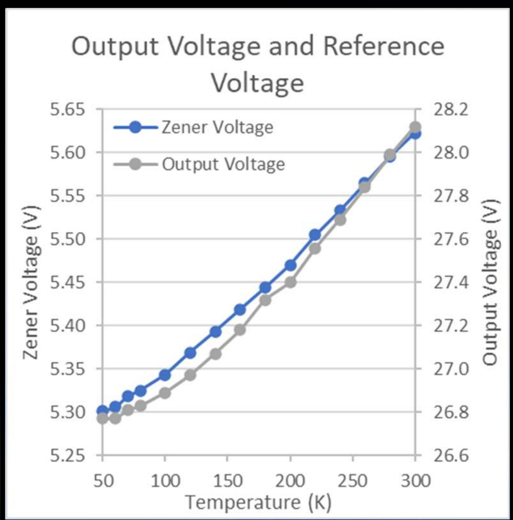


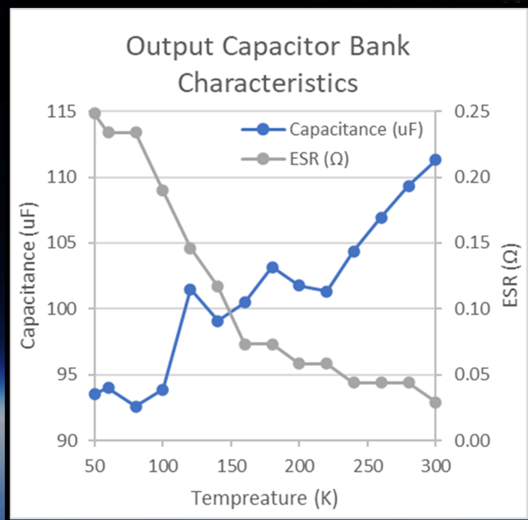


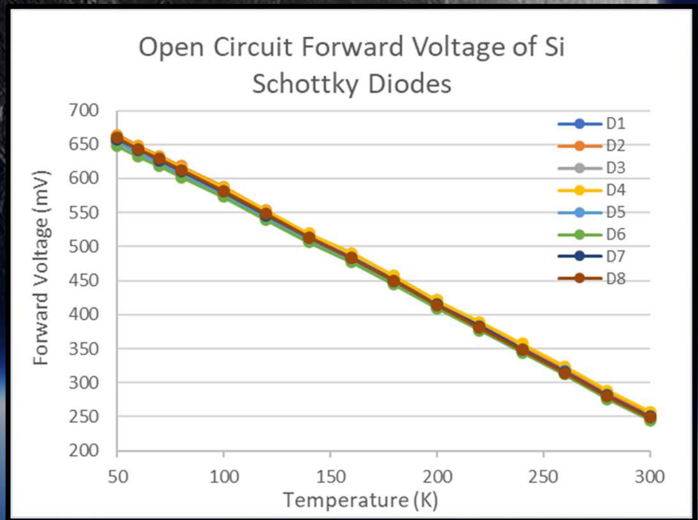
Electronics Test Results

Stable operation across the temperature range and tested load profiles

- Output voltage drops with temperature due to drifting Zener voltage
- 12 V linear regulator was stiff for the entire temperature range
- Capacitor bank ESR increases and capacitance decreases w/ lower temps
- Forward voltage of Schottky diodes rises approximately 250% at cryo



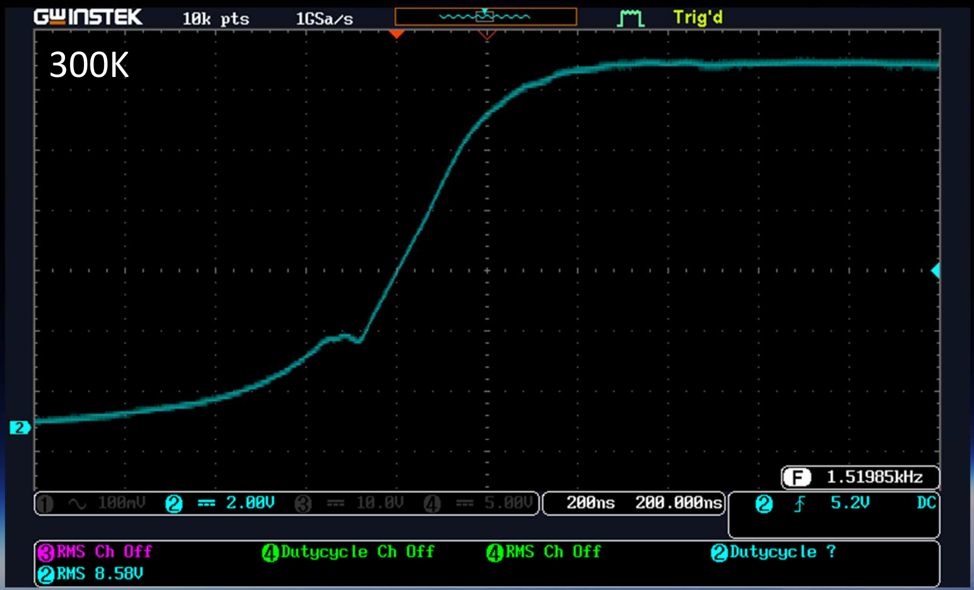




Electronics Test Results

Gate Drive Signal at Steady State

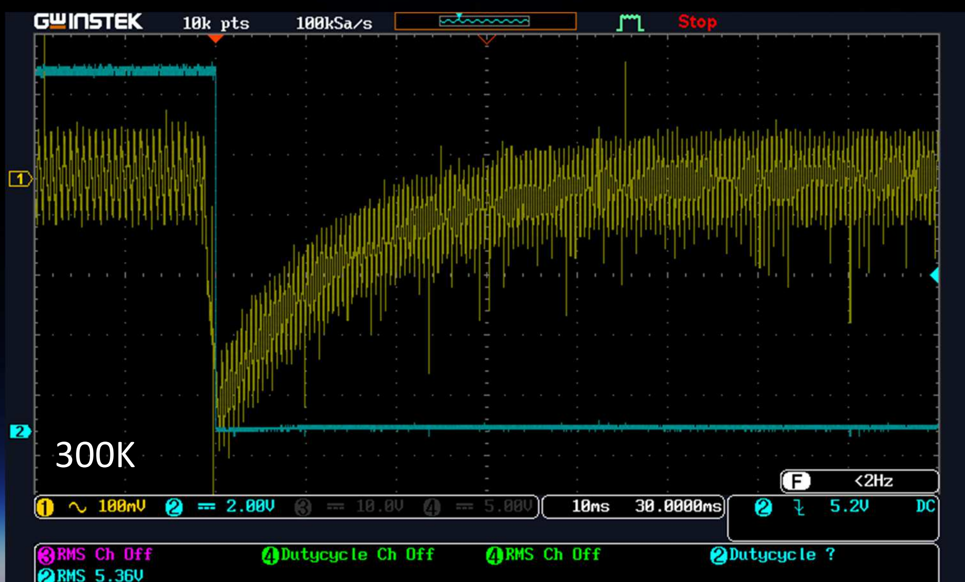
- Channel 2: FET3 (Si1480DH MOSFET) gate drive voltage from TL071 op-amp
- Test Condition: ~20 W load on main bus; String 3 is the active switching cell
- Results: Minimal change in operation

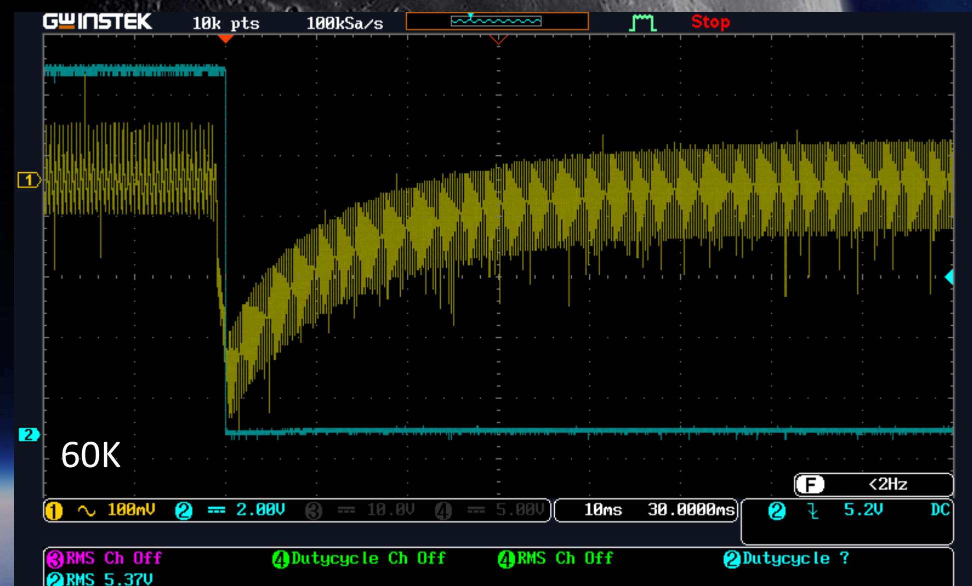


Electronics Test Results

Heavy Load Transient

- Channel 2: FET3 gate drive voltage; Channel 1: Output bus voltage, AC coupled
- Test Condition: No load on bus, ~30 W load on bus at trigger
- Results: Minimal change in operation

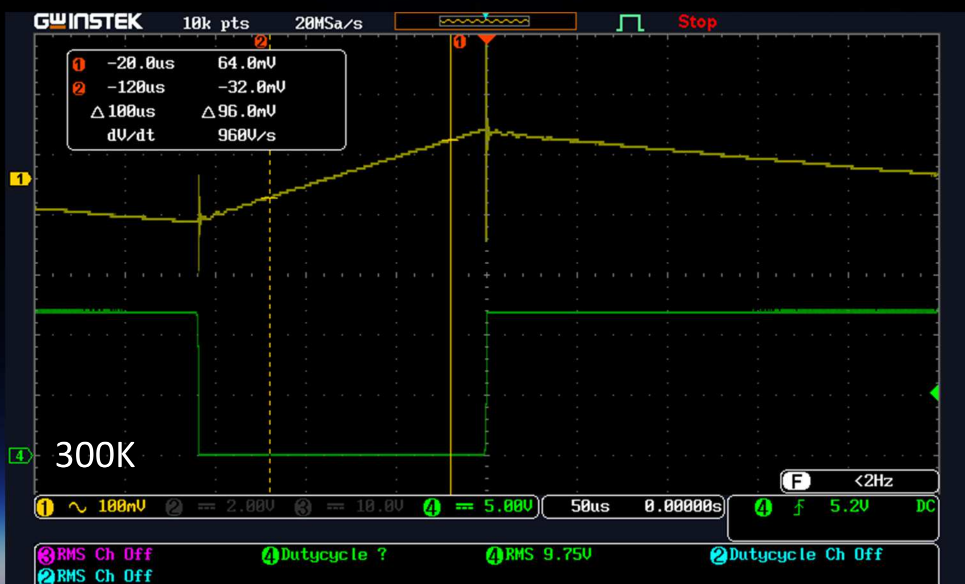


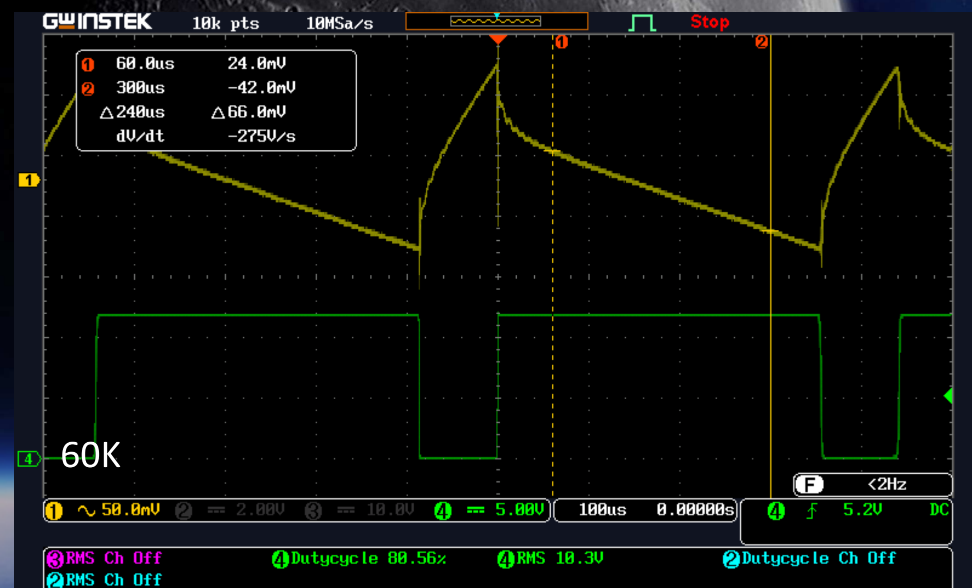


Electronics Test Results

Bus Voltage at Light Load

- Channel 1: Output bus voltage, AC coupled; Channel 4: FET8 gate drive
- Test Condition: No load on bus, only load is <1 W for auxiliary power
- Results: At cryo, cap bank ESR increases ~500% and capacitance decreases ~16%





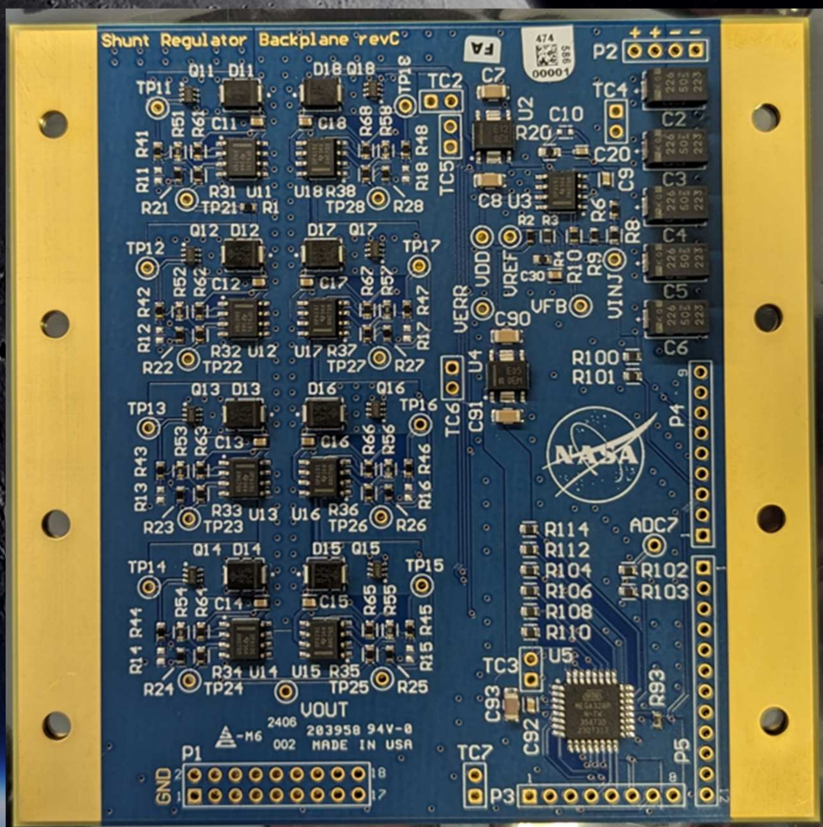
Forward Work

Lessons learned to improve design

- Use resistor divider for voltage reference
- Investigate different families of op-amps
  - OPA191 CMOS op-amps
- Investigate different bulk capacitor types
  - Solid polymer tantalum electrolytics
- Add layers/thickness to increase heat sinking and minimize local heating effects

Software integration on S3R board

- Collect telemetry on-board, including temps
- Program rudimentary “dawn mode” by commanding dummy loads



S3R circuit board, revision C.

Hibernation Technology Contributions

- Utilizing cryo-operable and cryo-tolerant electronics to revive frozen Li-ion cells will enable reliable operation of low-cost robotic missions over multiple lunar cycles
- Hibernation integration will have huge benefits with low risk
  - **Low cost:** attainable with COTS electronics
  - **Low mass:** extra battery power not required
  - **Low impact:** only require bootstrap power systems to be cryogenically operable
  - **Increases capability:** a single night survival doubles mission length

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