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Power Hibernation: Surviving the Extreme Cold Lunar Environment

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Power Hibernation: Surviving the Extreme Cold Lunar Environment



Lunar Power Hibernation is an approach to dramatically extend capabilities and duration of low-cost robotic lunar missions by exploiting the common 18650 Li-Ion battery cell's ability to tolerate and recover from extreme cold of the lunar night.

Power Hibernation: Surviving the Extreme Cold Lunar Environment

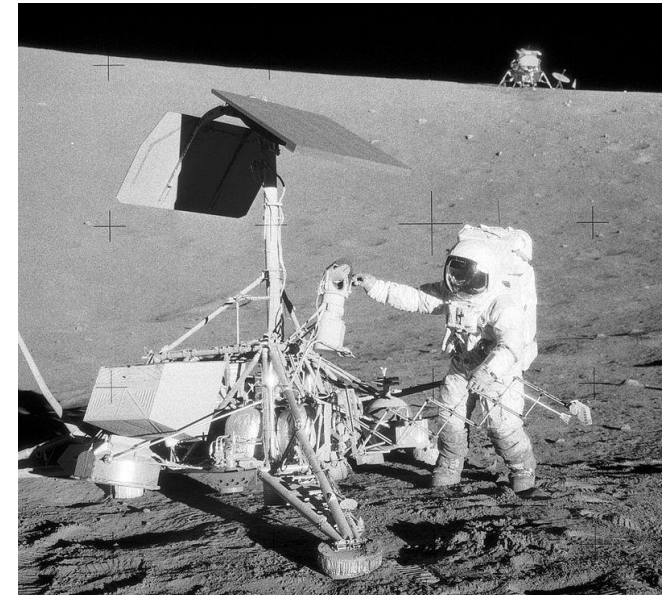


Batteries have always been assumed to be the weak link in surviving the lunar night.

- Recent studies show that common lithium-ion cells can survive the night
- Success depends on safely restoring the power system at lunar dawn

Surveyor Missions Experience (1966-1968)

- Surveyor was not designed for Night Survival
- RTG technology still under development
- Multiple Surveyors did indeed survive the night
 - Used Silver-Zinc Batteries
 - Most Surveyor missions partially survived beyond one lunar cycle.

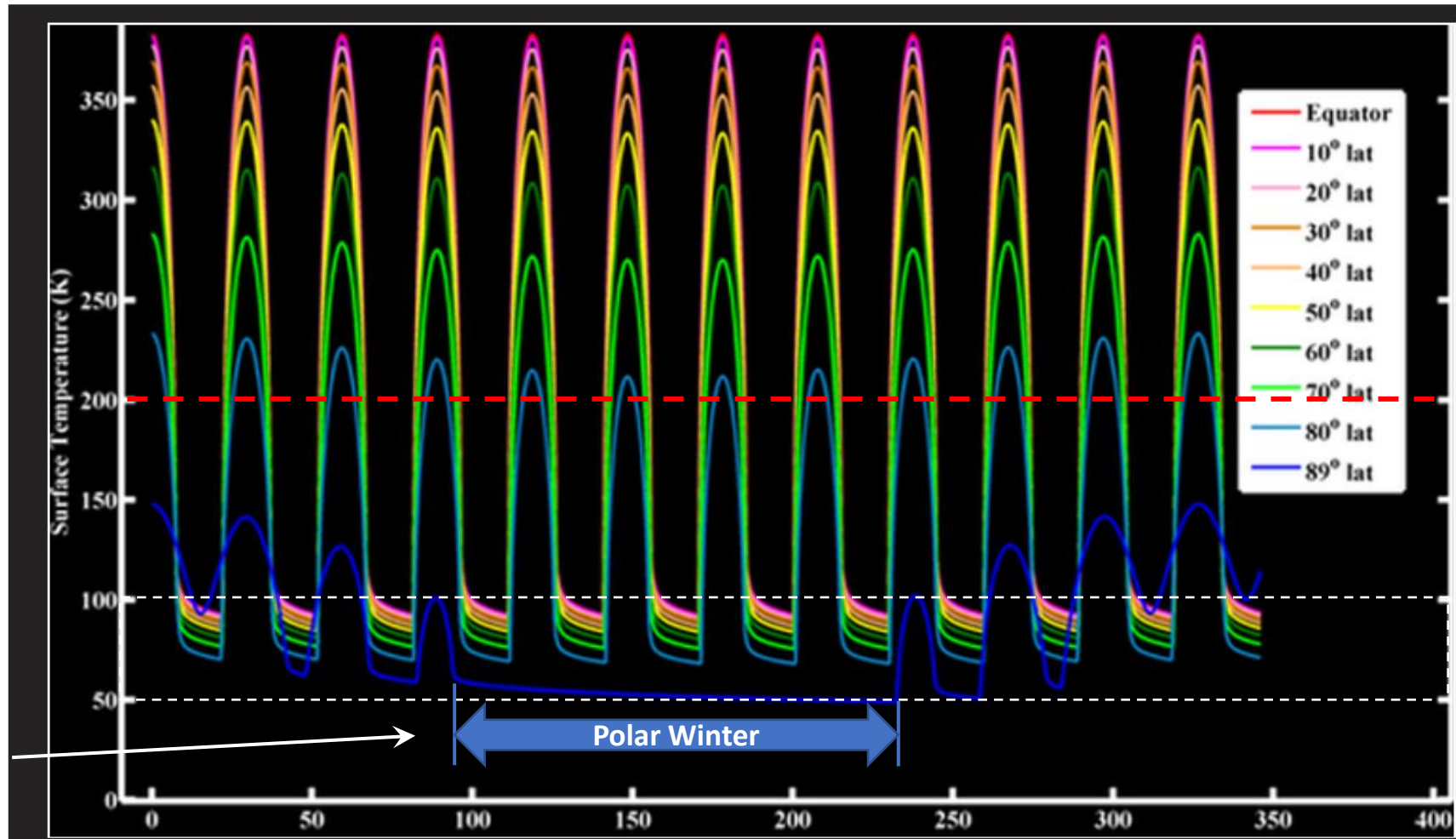


NASA Photo

LRO DIVINER: Lunar Day/Night Temperature Range by Latitude



Thermal model calculations of monthly and annual lunar surface temperature variations at various latitudes.



← Li-Ion Battery
Approx. Freeze
Temperature

← --- Lunar Night
Temperatures are
extremely cold
everywhere

Polar Winter
4 ½ months

Permissions per Dr. N Petro/NASA GSFC and Dr. D Paige/UCLA

Environment and Mission Constraints



Extreme Thermal and Illumination Environment

- Day high temperatures span from 100K to near 400K based on latitude
- Night low temperatures span 50-100K for all latitudes
- Non-polar latitudes night durations ~354 hours
- Polar Regions have very low sun angle,
 - Seasonal Variations (sun drops below horizon in lunar “polar winter” for ~4 ½ Months)
 - Illumination affected by site elevation and topographical features casting shadows

Commercial Lunar Payload Services (CLPS)

- CLPS landers/robotics provide single lunar day of operation
- CLPS landers are low cost, short development cycle
- Hibernation may be a viable option for robotic survival and extending operating life
- Hibernation success depends on exploiting cold tolerant and cryo-capable components

Li-Ion Low Temperature Survival



Published work suggested that Li-Ion Cells can survive extreme cold

- 2018 ISRO investigated 18650 Li-Ion cell passive lunar night survivability.
- Evaluated 3 manufacturers of 18650 Li-ion cells.
- Subjected them to 14-day lunar night at -160°C (in vacuum)
- Cells recovered charge capacity with no apparent damage or degradation

Batteries viewed as the weak link in terms of night survival

- If a battery survives the night, it will enable spacecraft survival
- The Li-Ion cells must pass through a freeze-thaw cycle
- NASA Glenn decided to investigate and verify the survival claims

Cell Hibernation Investigation at NASA Glenn

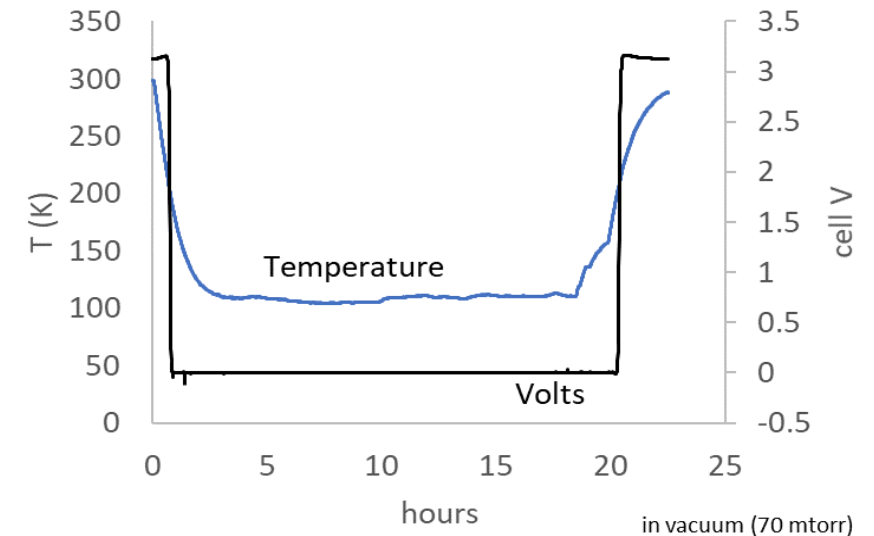
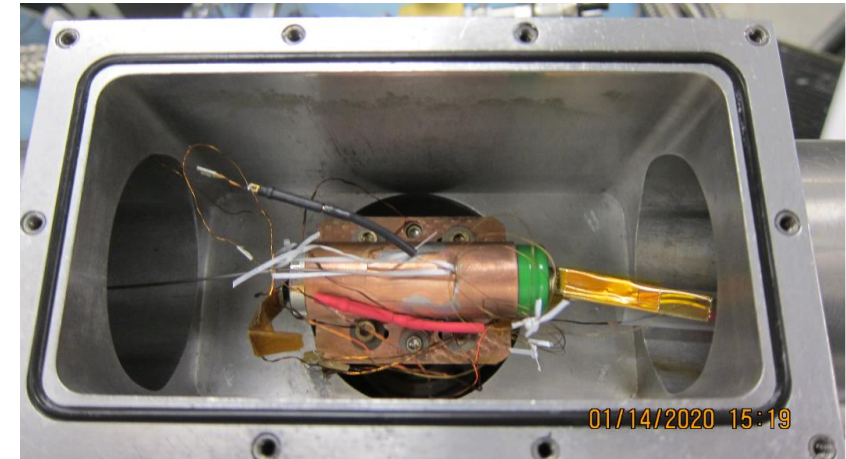


Preliminary Tests Performed at 1 Atmosphere

- Chilled to 80K (-193°C) (3 of 5 Survived)
- Strongly suspect seal leak and trapped LN₂
- 20 mg trapped LN₂ can rupture the pressure relief disc.

Test Setup for full vacuum

- Vacuum chamber pressure at ~70 mtorr
- Cryocooler chilled and held near 100K.
- Eliminated pressure reversal and LN₂ Intrusion
- Voltage dropped to zero below 200K
- Voltage recovers when warmed above 200K
- 4 of 4 cell trials in vacuum were successful



Hibernation and Dawn Operations



Power Hibernation:

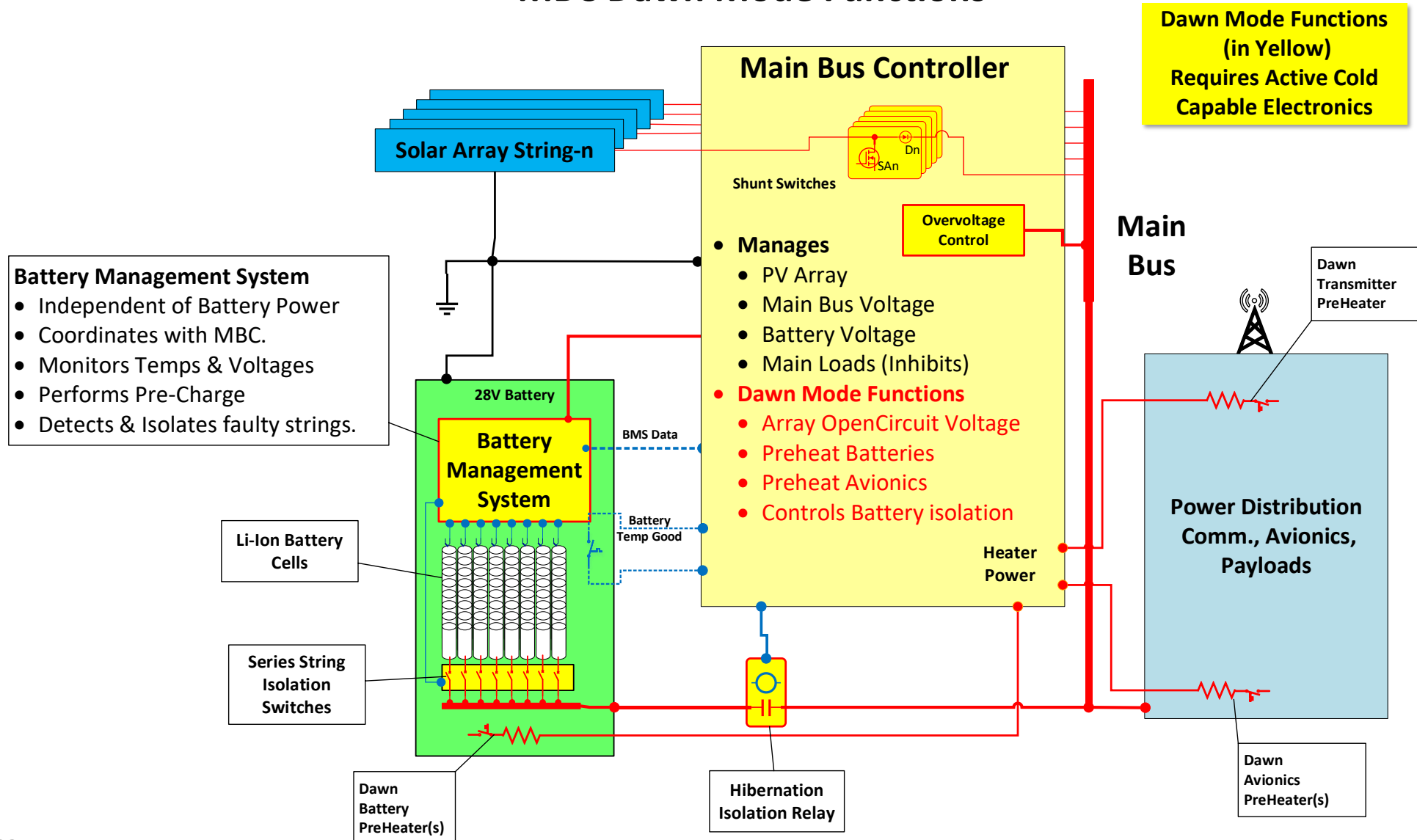
Point Arrays toward Dawn, Shut-Down Loads, Isolate Battery, Wait for Dawn

Lunar Dawn Controls: (first illumination, coldest temperature)

- Dawn Mode controls activate on solar array power alone (*Battery still Isolated*)
- Majority of systems are *still hibernating*.
- Dawn Mode must actively manage array output.
- Dawn Mode manages thermal conditioning (Pre-Heaters) for battery and avionics
- Battery Management System (also operates in extreme cold)
 - Monitor battery temperatures and voltages during Dawn Pre-heat phase.
 - Perform pre-thaw diagnostics and isolate potential faults
 - At normal temperature BMS pre-charges battery to match main bus voltage
- Reconnect Battery to Main Bus- **Dawn Mode Complete!**
- Clears “Power Inhibits” allowing system to boot-up as normal

Power Hibernation Architecture

MBC Dawn Mode Functions



Cold Tolerant Electronics for Hibernation



Cold Tolerant: The ability to passively tolerate extreme cold without damage

- All electronic systems (power, avionics and communications) must be cold tolerant.
- Avionics will need to extend the qualification testing range.
- Cold tolerance is primarily dependent on electronic device and circuit level packaging.
- **Device Level:** Generally, individual device packages have shown a tolerance of cold
- **Circuit Level:** (PC Board Substrate):
 - Fiberglass reinforced plastic (FRP) circuit board material is remarkably cold tolerant.
 - Minimize Thermal Stress by minimizing spatial temp gradients
 - Minimize temperature rate of change (dT/dt.)
 - Lunar environment temperatures change slowly (few degrees/hour)
- NASA has succeeded in modifying COTS circuits for cryogenic operations.
 - Usually requires replacement of temperature sensitive elements (electrolytic capacitors)
 - Redesigning circuits as hi-rel modules using ceramic substrates usually not necessary.

Cryo-Capable Electronics for Hibernation



Cryo-Capable: The ability provide stable operation in extreme cold

- Restoring power at Lunar Dawn requires “Cryo-Capable” electronics.
- **Device Level Cryo-Capability**, depends on semiconductor temperature dependent properties and device type. (Most individual devices work at cryo temperatures)
- **Circuit Level Cryo-Capability**, depends on stability of device interactions, involve multiple materials and device types with differing response to temperature. Circuits stable at normal temperature may be unstable in extreme cold temperatures.
- Cryo-Capability is most challenging for Analog Circuits (Power, RF Comm, Instrumentation)
- Analog Circuits: Analog signal regulation, modulation, amplification, filtering etc.
 - Ideally, each device is insensitive to temperature.
 - **In Reality**, many devices will need temperature compensation.
 - Resistors and capacitors are available in materials with flat temperature response.
 - Inductors relying on magnetic core materials tend to become lossy at low temperatures.

Cryo-Capable Electronics Technology

Temperature 20°C to -196°C (293K to 77K)



Power switching device testing in LN₂

Silicon (Si)

- Sensitivity to temperature
- On-Resistance $R_{ds(ON)}$ improves at low temps

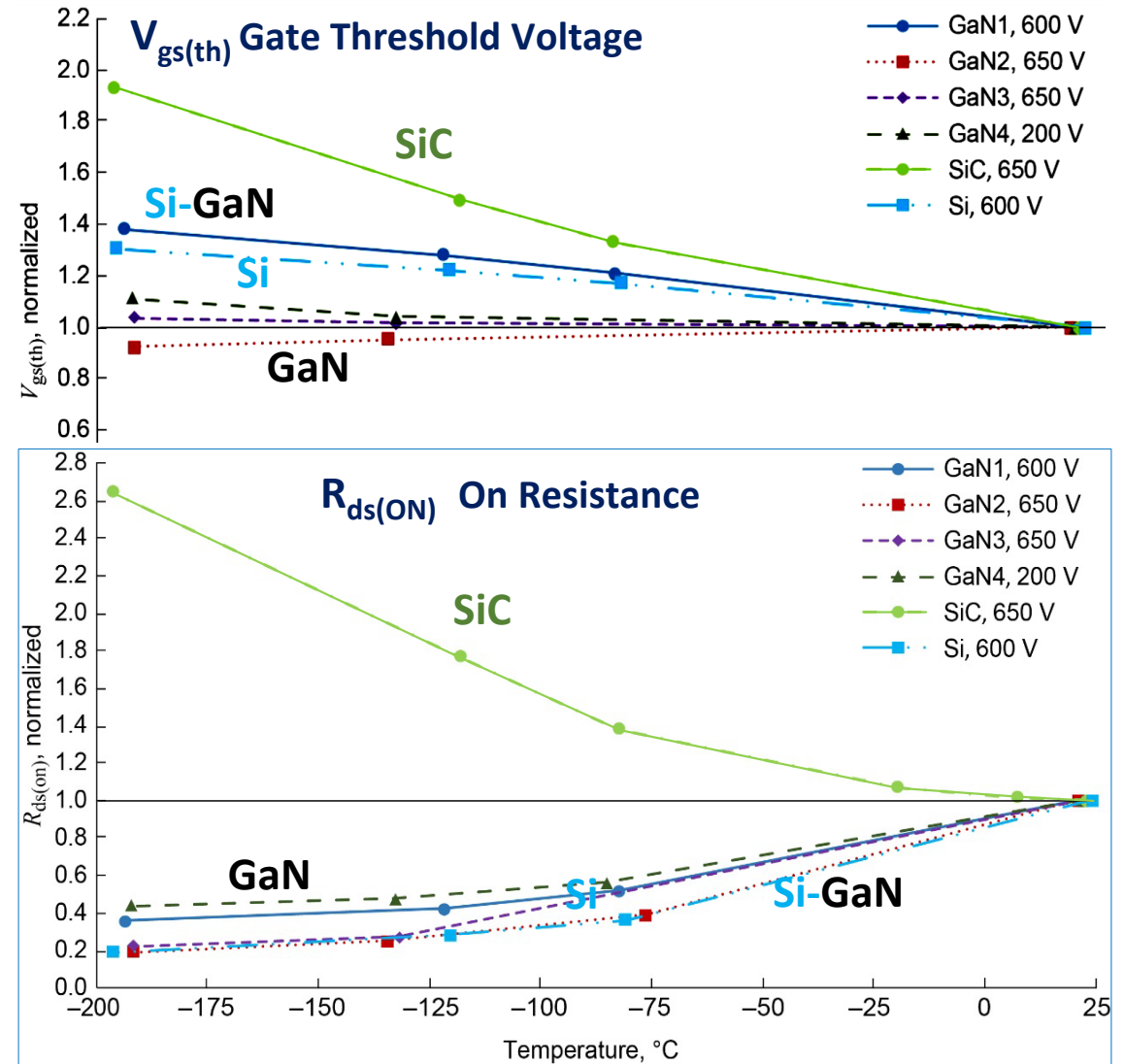
Silicon-Carbide (SiC)

- Very sensitive to Temperature
- On-Resistance $R_{ds(ON)}$ degrades at low temps
- Evidence of “Carrier Freeze-Out”

Gallium-Nitride (GaN):

- Low sensitivity to temperature
- On-Resistance $R_{ds(ON)}$ improves at low temps
- GaN is best for this temperature range

Figures Courtesy of Marcelo Gonzalez NASA Glenn

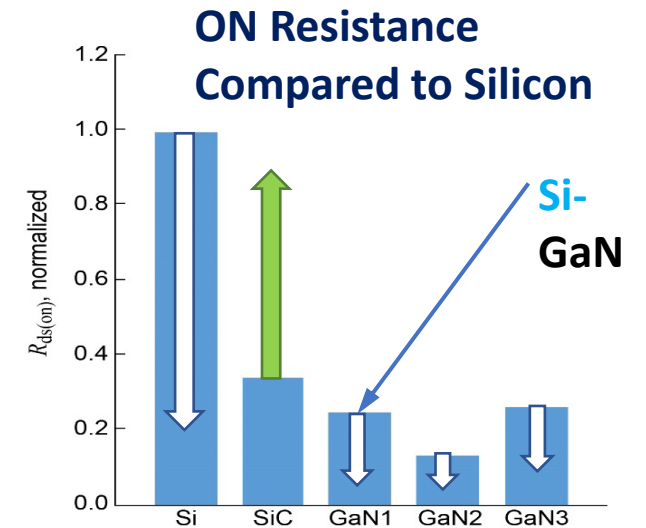


Cryo-Capable Electronics Technology



Silicon Devices:

- Silicon dominates digital applications and most analog applications
- Wide availability, low cost, huge Body-of-Knowledge
- Silicon digital devices demonstrated down to 4K.
- Changes in characteristics over the temperature range requires compensation.



Figures Courtesy of Marcelo Gonzalez NASA Glenn

Need Collaboration Hibernation Battery Development



Further Li-Ion Cell work

- Li-Ion Batteries are “Cold Tolerant”: passively survive the cold without loss of capability.
- NASA preliminary testing was limited to mostly one source
- Further Testing to include cells from lots certified for human space flight
 - Strategic procurements of 40,000-60,000 cell lots
 - Controlled supply “Chain of Custody”
 - Establish Statistical Confidence
- Evaluate alternate cell formats (20700, 21700)
- Establish State-of-Charge guidelines
 - Thermal runaway is less likely below 40% SOC
 - **Note:** Cells are safest when frozen (nail tests) but could become a hazard when thawed.
- Investigate pre-thaw Fault Detection
 - Detect and isolate a fault in frozen state if possible
 - Modulate temperature rise to dissipate faulted cell energy slowly.

Need Collaboration Hibernation Electronics Development



Most Avionics need only Passively Tolerate the extreme cold.

- Avionics will need additional qualification testing to prove passive tolerance
- Conventional FRP circuit board material is remarkably cold tolerant.
- Lunar environment changes slowly (few degrees/hour)

Active Cryo-Capable Electronics primarily for restoring power.

- Silicon is not ideal but will work if proper compensation is applied.
- GaN has low sensitivity to temperature and excellent low-temperature performance.
 - Need GaN applied to more analog applications.
 - Further investigate other materials. (GaAs, SiGe)
- Need **New** inductor core materials with low loss at cryo temps.
- Need cryo-temperature device models. (CoolSpice)

Summary



Hibernation Enables Low-Cost Missions Achieve Multi-Lunar Cycles

- 18650 Li-Ion cells demonstrated a night survival capability
- “Passive Hibernation” approach minimizes changes to existing hardware
- Reduces dependency on costly radioisotope heat and power sources
- Reduces dependency on pre-established power infrastructure
- Applicable to lunar robotic systems including ISRU and human missions
- Hibernation improves survival and recovery options in contingency situations
- **Ultimately:** *Hibernation technologies will lead to more robust robotic systems that are actually designed for the Lunar Environment.*

Thanks for Listening



**Power Hibernation:
Surviving the Extreme Cold Lunar Environment**

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