



Power Architecture for Hibernation and Dawn Mode Operations

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Power Architecture for Hibernation and Dawn Mode Operations



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.

- Surveyor Experience
- Lunar Thermal Environment and Mission Constraints.
- Li-Ion Low Temperature Survival
- Power Hibernation Architecture Assumptions
- Power Hibernation Sequence
- Cryo-Temperature Electronics Technology
- Power Hibernation Architecture Development

Surveyor Experience: Surviving the Lunar Night



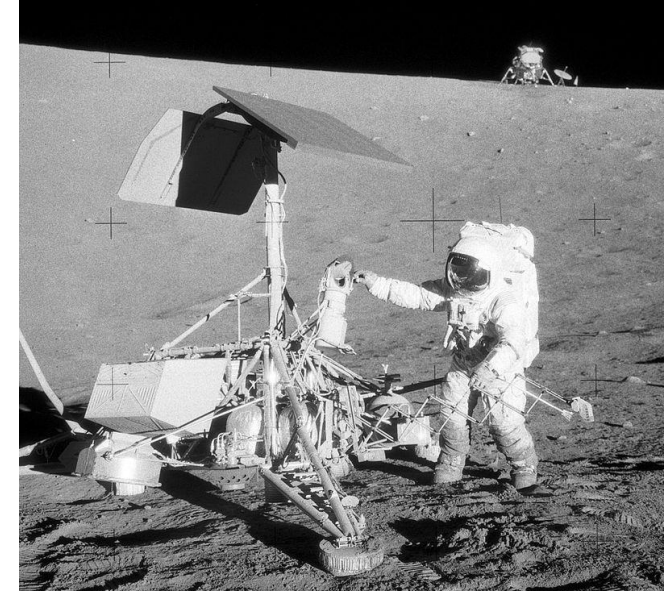
Common Misconception: “Spacecraft batteries cannot take extreme lunar night temperatures and will die”. ***This is Not True***

- *New evidence shows that common lithium-ion cells can survive.*
- *Successful Hibernation depends a power system’s ability to safely restore itself 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
 - Surveyor 1 operated fully/partially for 6 lunar cycles
 - Each mission responded differently

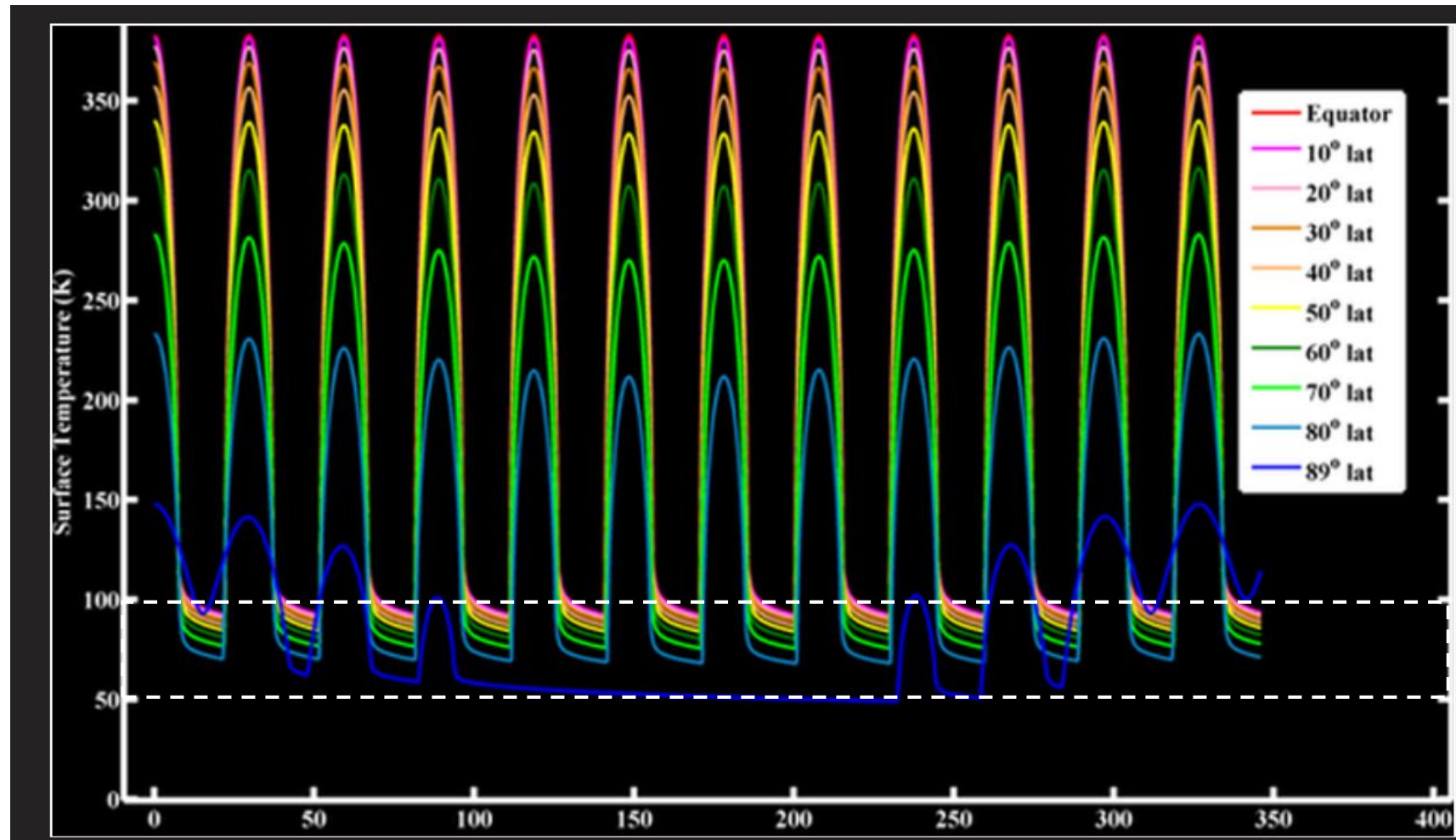
NASA Photo



LRO DIVINER: Lunar Day/Night Temperature Range by Latitude



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



**Lunar Night
Temperatures are
extremely cold
everywhere**

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

Environment and Mission Constraints



Extreme Thermal Environment

- Day temperatures span from 100K to near 400K based on Latitude
- Night temperatures fall within a 50-100K range regardless of latitude.
- Non-Polar latitudes night durations ~354 hours
- Polar Regions have very low sun angle, varying sun/shade cadence and durations
 - Site elevation combined with near/far topographical features casting shadows
 - Seasonal Variations (sun drops below horizon in lunar winter)

Low-Cost Mission Constraints

- Commercial Lunar Payload Services (CLPS) landers to less than one lunation
 - (29 ½ day lunar cycle, Sunrise to Sunrise).
- For Non-Polar missions, hibernation is the most viable option

Li-Ion Low Temperature Survival Corroborating Evidence



Indian Space Research Organization (ISRO) published work on Hibernation

- 2018 ISRO investigated 18650 Li-Ion cell passive lunar night survivability.
 - Evaluated 3 manufactures 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
- ISRO published a power architecture concept for Hibernation
- Its not clear if hibernation capability was on-board Chandrayaan-2 lander
 - *(It is clear that they were thinking about it.)*
- Growing interest in “Flash-Freezing” of Li-Ion batteries for transportation safety

18650 Li Ion Cell Investigation at NASA Glenn



Initial Tests Performed at 1 Atmosphere

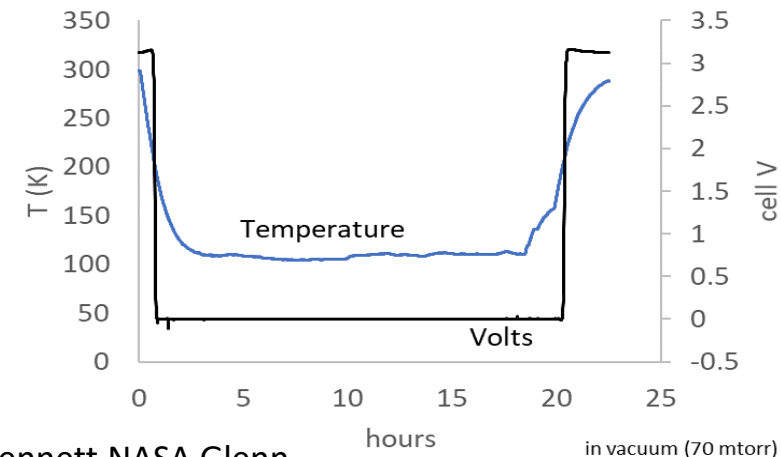
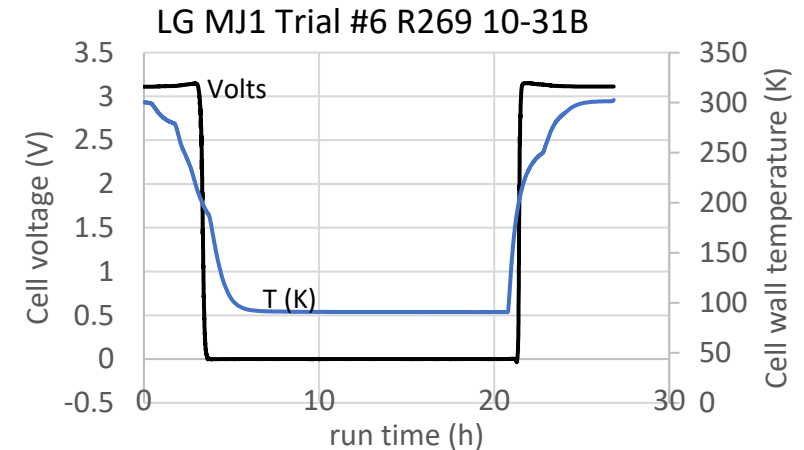
- LN_2 Vapor chilled to 80K (-193°C)
(3 of 5 Survived)

Refined Tests Performed in Vacuum

- 70 millitorr
- Cryocooler chilled to 100K (-173°C)
- All units Survived

Li-Ion 18650 cells

- Voltage drops to 0 volts near 200K (-70°C)
- Voltage recovers above 200K
- No apparent degradation
- NASA GRC Confirms Lunar Night Survivability



Figures Courtesy of W. Bennett NASA Glenn

Power Hibernation Architecture Assumptions



Lowest Temperatures occur just before Lunar Dawn

- Non-polar latitudes we assume night is ~354 hours.
- Polar Regions subject to multiple short (Dusk-Dawn) cycles.
 - Low Sun Elevation, Terrain Obscuration and Seasonal Variations
 - Polar day-time high temperatures are still below 200K

Assume that Li-Ion Batteries will survive the Lunar Night

- Batteries Passively Survive the cold without loss of capability
- Batteries must be isolated from main bus prior to Dawn.
- Requires “Active Cold Capable Controls” to manage the Battery Recovery.
 - Pre-Heating and Pre-Charging are required
 - Battery resumes operation when temperatures and voltages return to normal

Power Hibernation Architecture Assumptions



Solar Arrays expected to Survive and Generate Power at Lunar Dawn.

- Photovoltaic Arrays are tolerant of cryogenic temperatures.
- PV Arrays at cold temps will cause high open-circuit voltages.
 - Array Over-Voltage protection required.
 - Requires Cold Capable Controls to manage array power

Assume Avionics Passively Survives

- Avionics will need to be qualified to passively survive lunar night temperatures
- Not required to operate below normal temps
- Requires external Cold Capable Controls to manage temperature recovery.

Power Hibernation Architecture Assumptions



Main Bus Control (MBC) is Active at Cryo-temps:

- Main (Power) Bus Control incorporates “Dawn Mode” functions
- MBC Dawn Mode
 - Must be capable of activating and operating at low temps
 - MBC must operate when flight computers are unavailable
 - Manages PV Arrays and Main Bus Voltage
 - Manages Battery State (through Battery Management System)
 - Enables/Disables System Loads via Power Inhibits. (Avionics and Payloads)

Hibernation and Dawn Operations



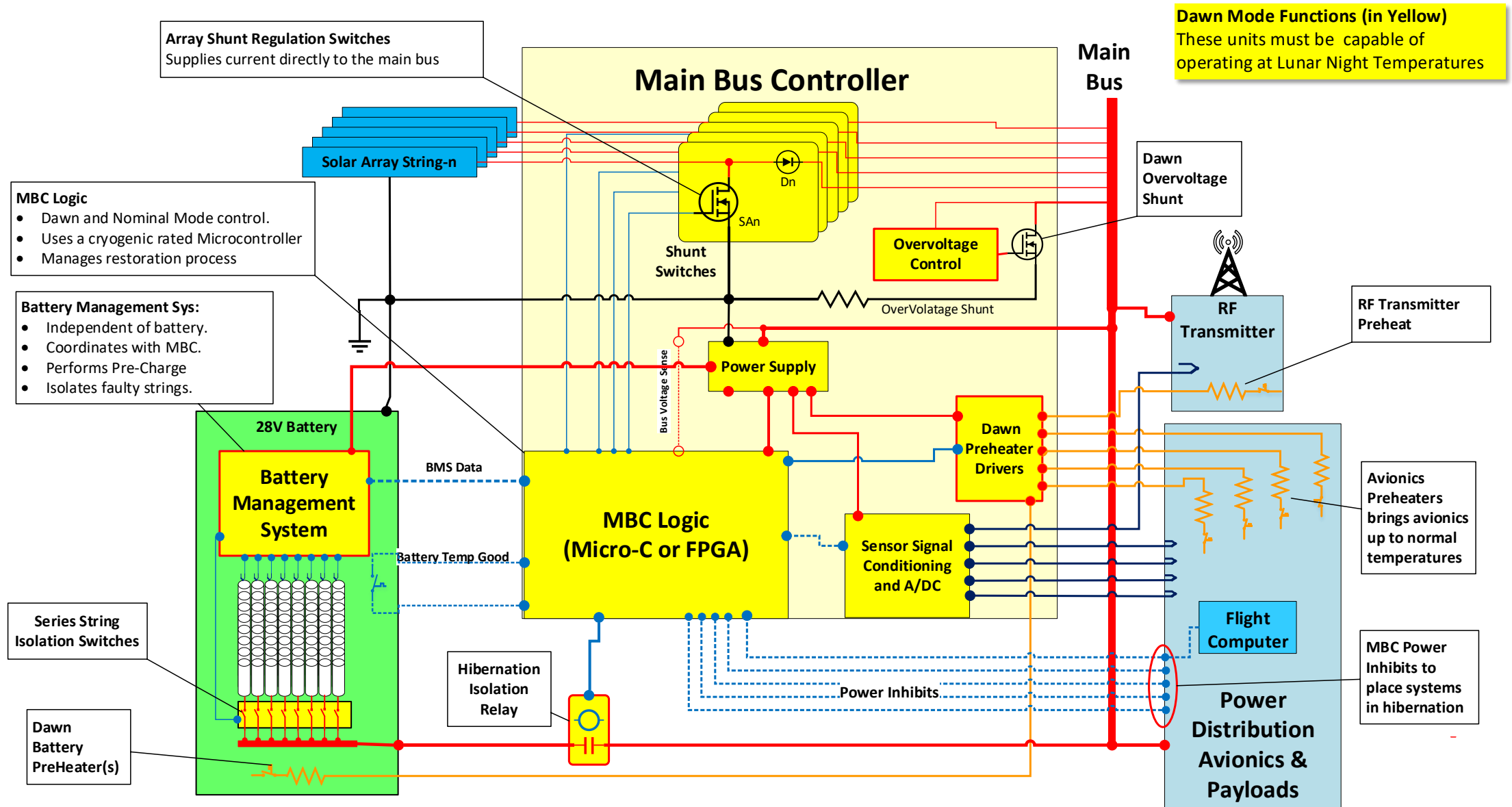
Lunar Dusk:

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

Lunar Dawn: (first illumination, coldest temperature)

- Solar Array output triggers a “**Dawn Mode**” within the **Main Bus Controller** (MBC)
- MBC is composed of electronics designed to operate in extreme cold temperature
- MBC in Dawn Mode operates on Solar Array power alone (*Battery still Isolated*)
- MBC manages thermal conditioning (Pre-Heaters) for battery and avionics
- Battery Management System (powered by MBC, also operates in extreme cold)
 - Monitor battery temperatures and voltages during Dawn Pre-heat
 - At normal temperature BMS pre-charges battery to match main bus voltage
 - If a string fault is detected the BMS isolates the faulted string
- MBC Closes Isolation Relay: Reconnects Battery to Main Bus- **Dawn Mode Complete!**
 - MBC clears “Power Inhibits” allowing system to boots-up as normal

Power Hibernation Architecture



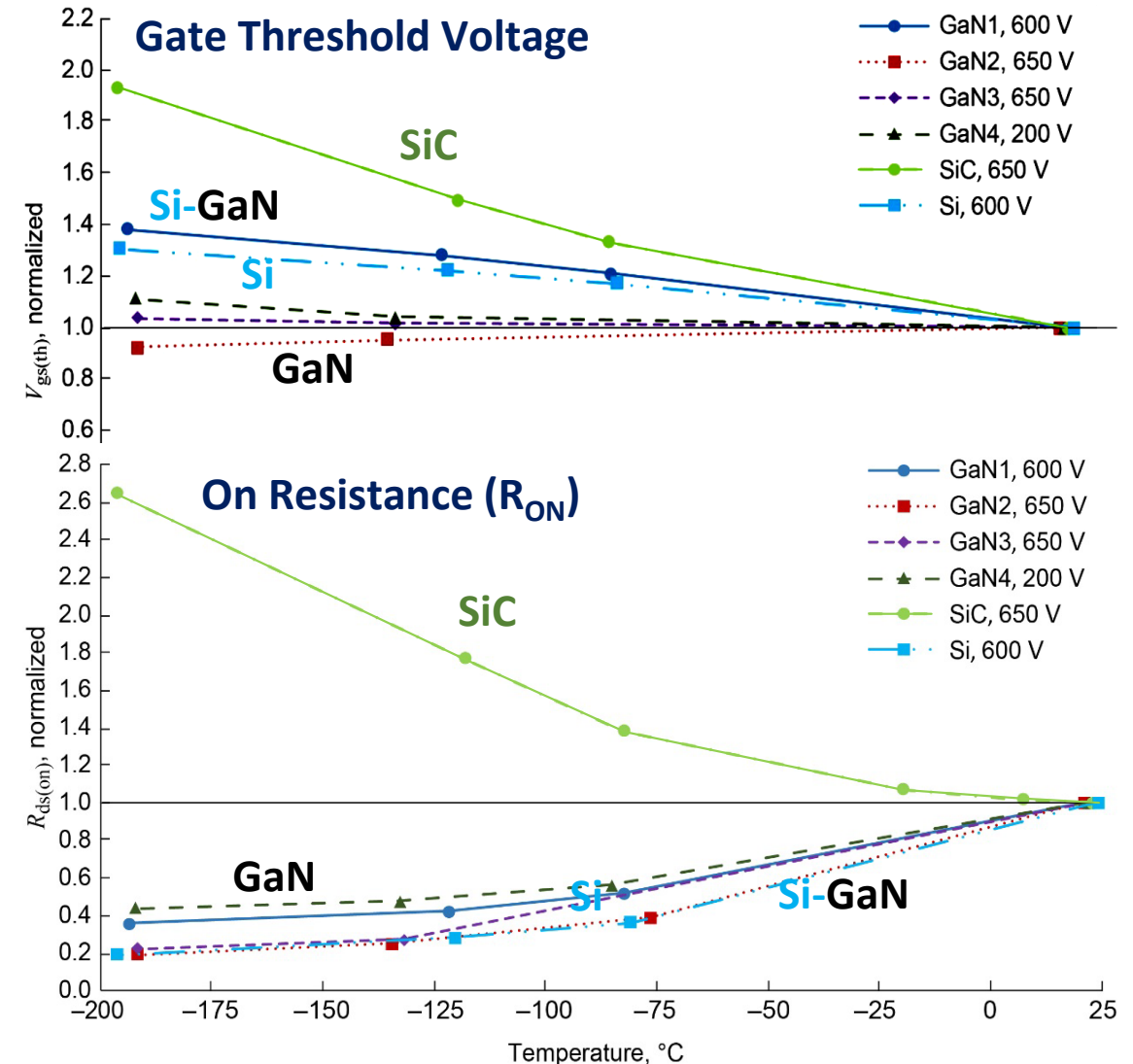
Cryo-Temp Electronics Technology



Gallium-Nitride (GaN): (LN₂ testing)

- GaN suited for low temp operations
- Tests indicate good low temp performance
 - GaN innately more efficient than Silicon
 - Gate Threshold Voltage: Stable to -196C
 - ON Resistance: Improves at low temps
- GaN used in Space Power and RF Comm
- More Radiation Tolerant than Si or SiC
- **Si-GaN Switch** (GaN with Silicon front end)
 - Overcomes Gate Over-Voltage sensitivity
 - Simplifies device driver design

Figures Courtesy of Marcelo Gonzalez NASA Glenn



Cryo-Temp Electronics Technology

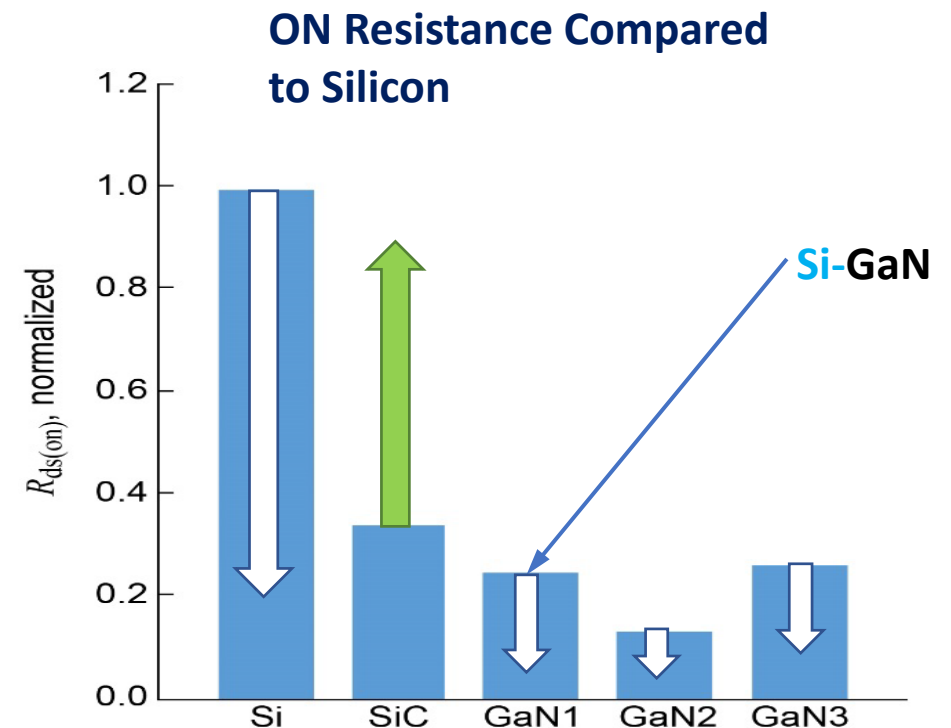


Silicon-Carbide: Poor low temp performance

- SiC Performance degrades in extreme cold
- SiC is subject to “Carrier Freeze-Out”
 - Threshold Voltage climbs
 - On-Resistance $R_{ds(on)}$ climbs

Silicon Devices:

- Silicon still dominates non-power applications
 - Wide availability and low cost
 - Huge *Body of Knowledge*
 - Will require temperature compensation
- Very Large Scale Integrated Circuits (VLSIC)
 - Micro-Controllers or FPGAs
 - SiC and GaN not available in VLSIC



Figures Courtesy of Marcelo Gonzalez NASA Glenn

Power Hibernation Architecture Development



Hibernation Battery Development

- Fully characterize electrochemistry through the hibernation thermal cycle.
- Thermal Management (uniformity temperature, uniform cell output)
- Battery Management System (cell monitoring, isolating faulty strings, pre-charge control)

Cryo Temperature Electronic Device Studies

- Gallium-Nitride, Silicon-GaN power switching evaluation
- Cryo-Temperature device evaluations (Controllers and Instrumentation)

Main Bus Controller: Dawn Mode Electronics

- PV Array Management Approach (Sequential Switching or Shunt)
- Approach to Stabilizing the main bus while battery is disconnected
- Pre-heater Power Regulation

Power Hibernation Architecture Summary



Hibernation Enables Low Cost Missions Achieve Multi-Lunar Cycles

- 18650 Li-Ion cells demonstrated a night survival capability.
- “Passive Hibernation” minimizes changes to existing hardware.
- Reduced dependency on scarce radioisotope heat and power sources.
- Robotics and Vehicles operate independent pre-established infrastructure
- Restoration requires an Active Main Bus with “*Dawn Mode*”
 - Capable of operating in extreme cold
 - Capable of operating on Array output alone
- 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.*

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