National Aeronautics and Space Administration

Lunar Power Hibernation for Surviving the Lunar Night

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Lunar Power Hibernation for Surviving the Lunar Night

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
- Hibernation and Dawn Operations
- Cryo-Temperature Electronics Technology
- Power Hibernation Architecture Development

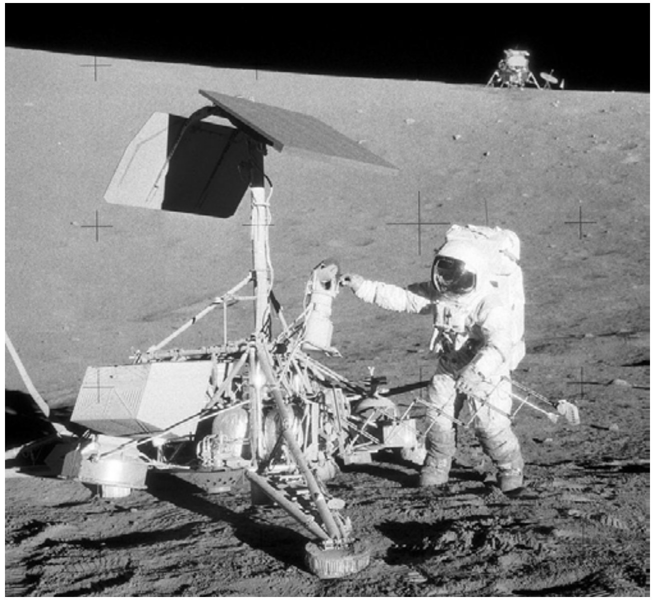
Surveyor Experience: Surviving the Lunar Night

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

- *Recent studies show that common lithium-ion cells can survive*
- *Successful Hibernation depends ability to safely restore itself at lunar dawn*

Surveyor Missions Experience (1966-1968)

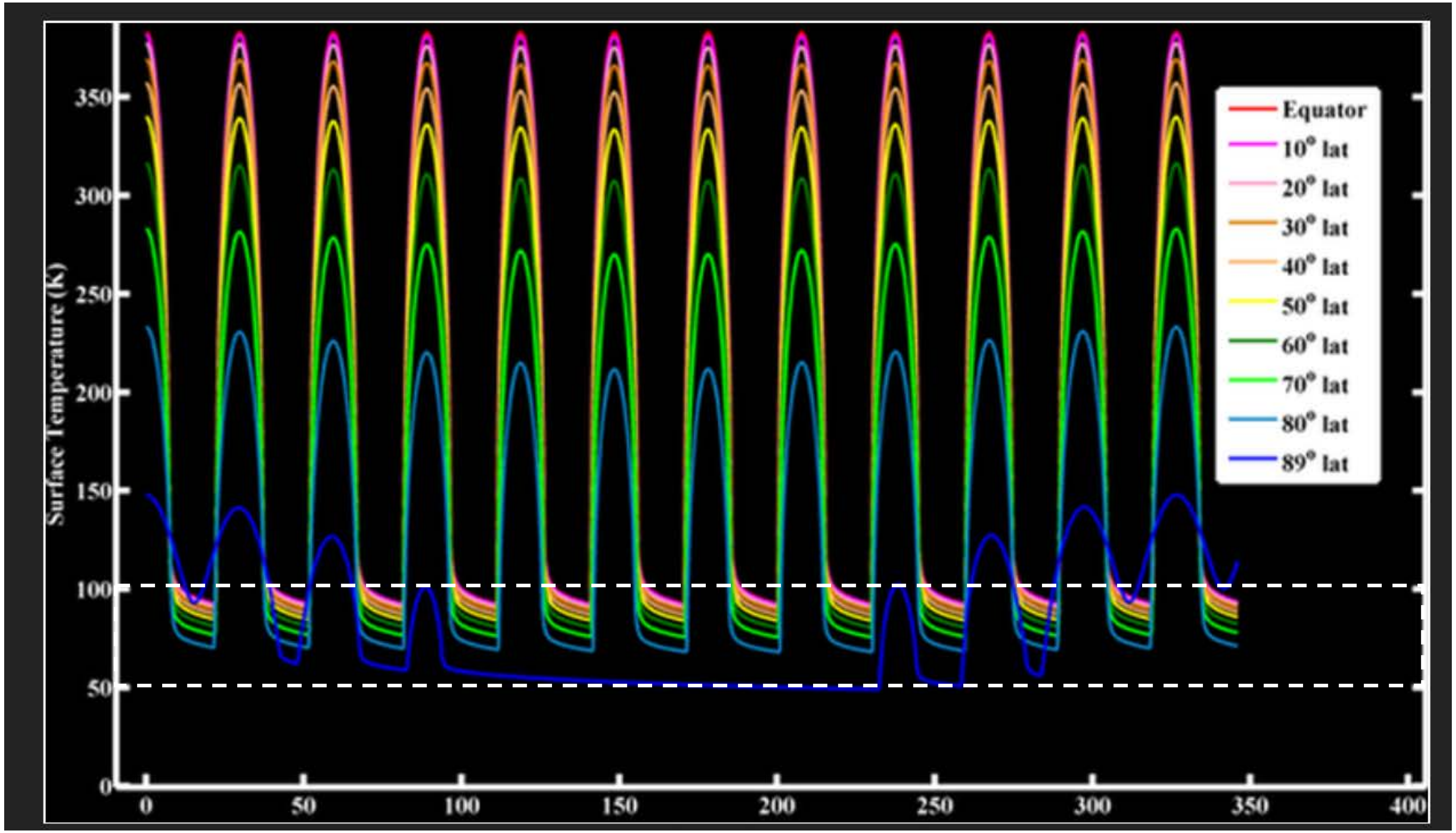
- Surveyor was not designed for Night Survival
- RTG technology still under development
- Multiple Surveyors did indeed survive the night
  - Used Silver-Zinc Batteries
  - Surveyor 1 operated fully/partially for 6 lunar cycles



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 and Illumination Environment

- Day temperatures span from below 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)
  - Polar Day Time high temps still below battery operating temperatures

Low-Cost Mission Constraints - Commercial Lunar Payload Services (CLPS)

- CLPS landers are low cost, short development cycle
  - CLPS landers are not likely to operate much beyond a single lunar daylight period
  - Hibernation is the most viable option for survival

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 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
- 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
  - Lower cost means of safely transporting Li Ion Cells.
  - Bulk shipping of Li-Ion batteries currently banded from air transport
  - Shown to prevent damage cells from going into thermal runaway

18650 Li Ion Cell Investigation at NASA Glenn

Preliminary Tests Performed at 1 Atmosphere

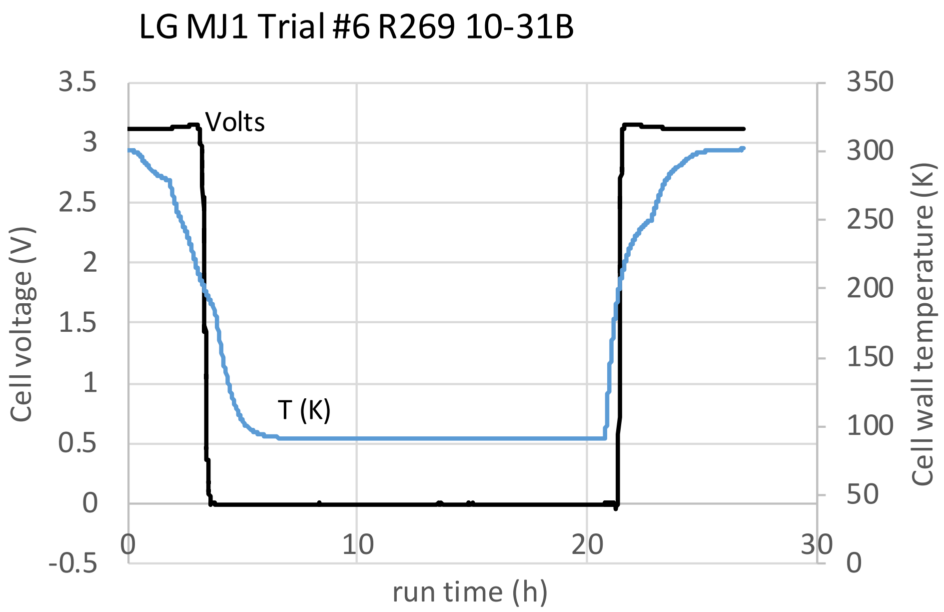
- LN_2 Vapor chilled to 80K (-193°C) (3 of 5 Survived)

2 of 5 Cells Safety Device Trips

- First cell (Current Interruption Device tripped)
- Second cell (Pressure Relief Disc vented)

Root cause of trips is not fully understood

- Cause of internal overpressure is unclear
- Normally a trip is due gas pressure from electrode and electrolyte decomposition
- Probe of the “Jelly Roll” indicated normal voltage
- Suspect Possible seal leak trapping LN_2
- Only 20 mg of trapped LN_2 would rupture the relief disc.



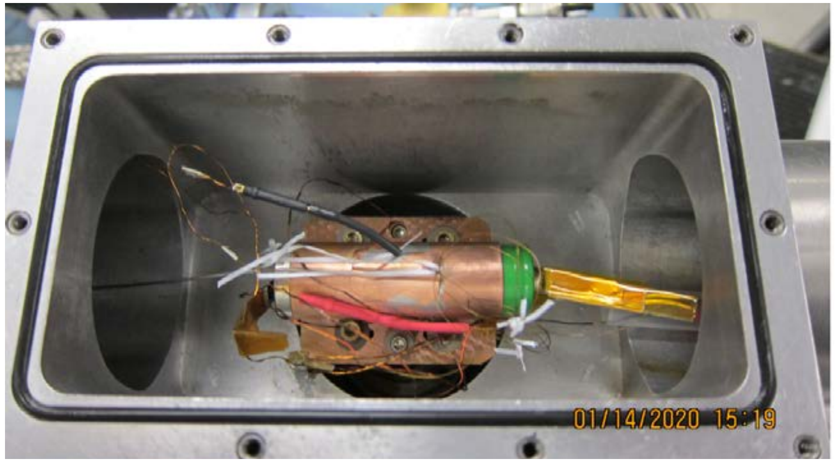
Figures Courtesy of W. Bennett NASA Glenn

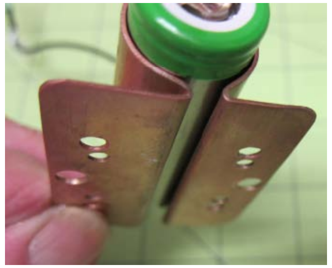
Cell Hibernation Investigation at NASA Glenn
Tested with Cryocooler in Vacuum

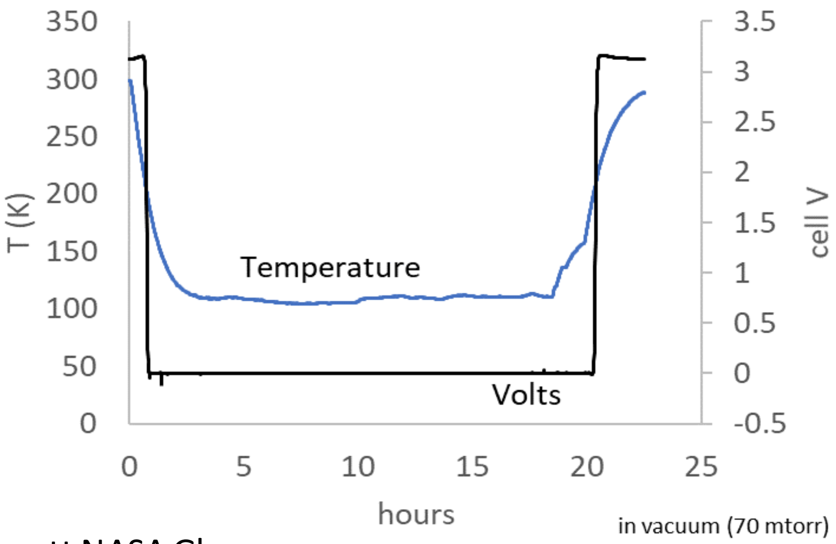
Revised Test Setup

- Improved representation of lunar environment
  - Vacuum chamber pressure at ~70 mtorr
  - Cryocooler chilled and held near 100K.
  - Eliminated pressure reversal
  - Eliminated leakage of LN_2
- Voltage dropped below 200K
- Voltage recovers when warmed above 200K
- 4 of 4 cell trials in vacuum were successful
  - *No CID Trips or Disc Ruptures*

NOTE: We need a larger set of samples from a from a NASA strategic procurement. (known good set of cells)







Photos 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 while isolated
  - Battery reconnected 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
- Avionics thermally conditioned prior to activation
- 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

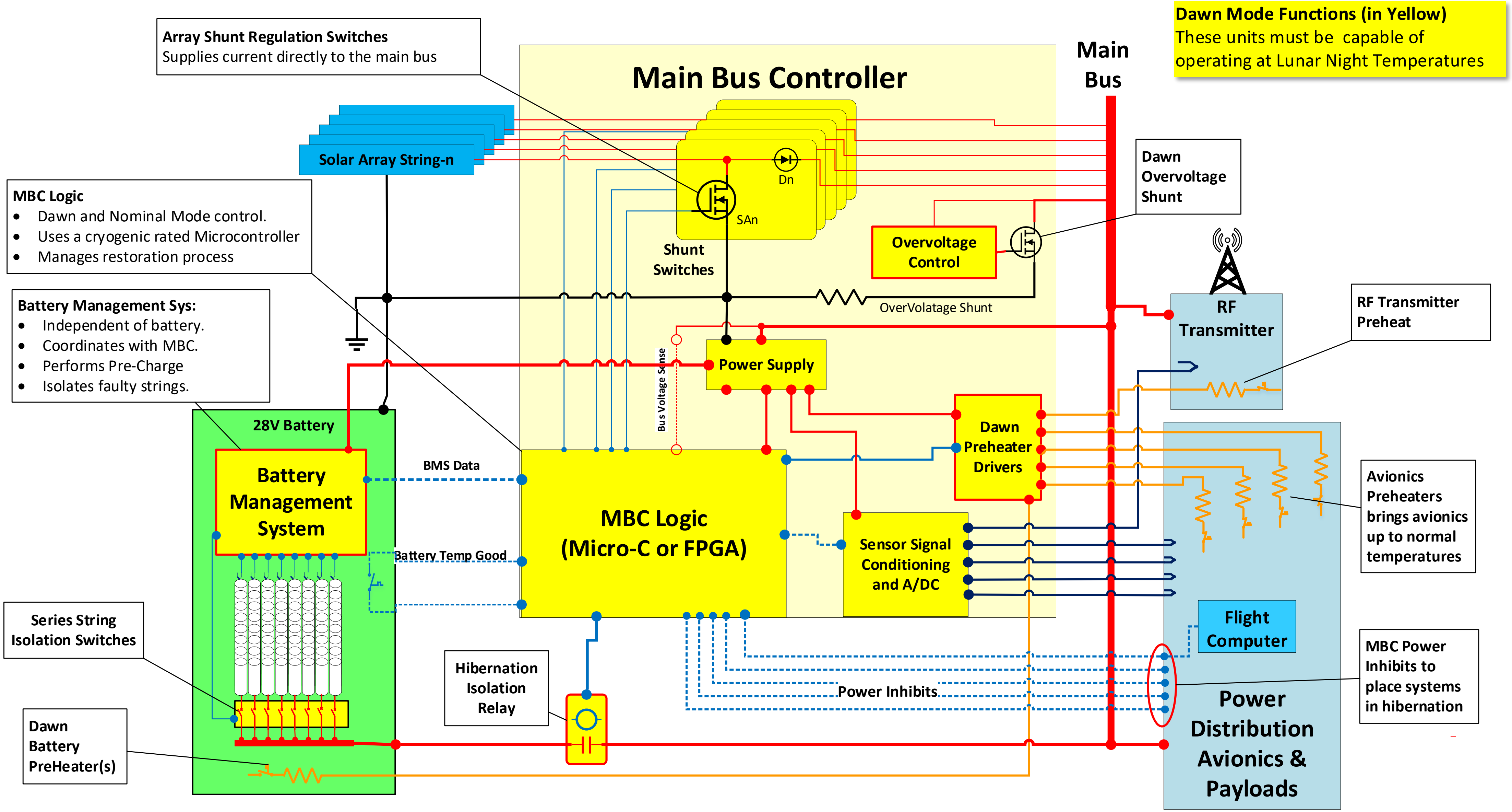
Lunar Dusk:

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 boot-up as normal

Power Hibernation Architecture



Hibernation Battery Development

Li-Ion Cell work

- NASA preliminary testing was limited to mostly one source
- ISRO tested 3 manufacturers (were not identified)
- **Future Hibernation Tests**
  - Evaluate a wider range of cell manufacturers
  - Testing of cells 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 safe cell hibernation cycle and State of Charge guidelines
- Investigate possible pre-thaw Fault Detection (*cells are safest when frozen*)

Hibernation Battery Development

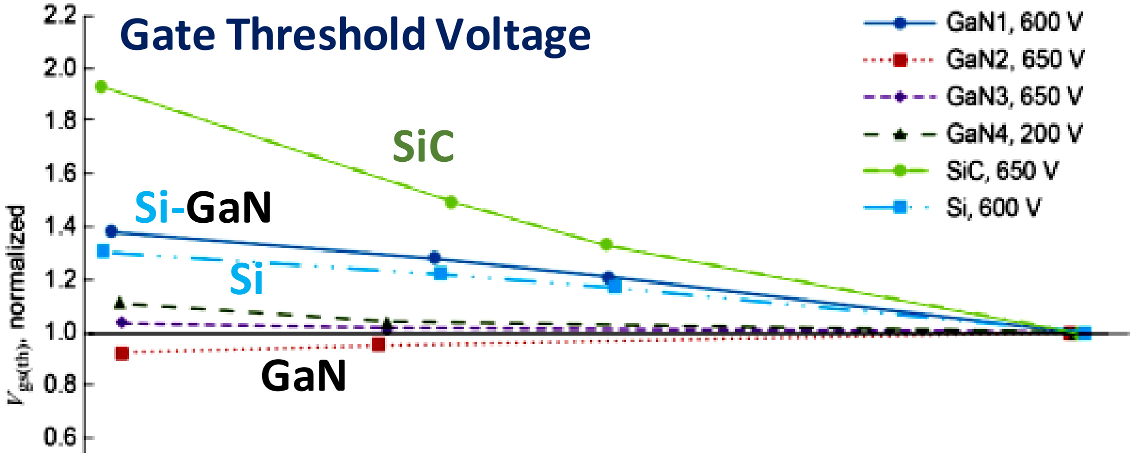
Hibernation Battery Engineering

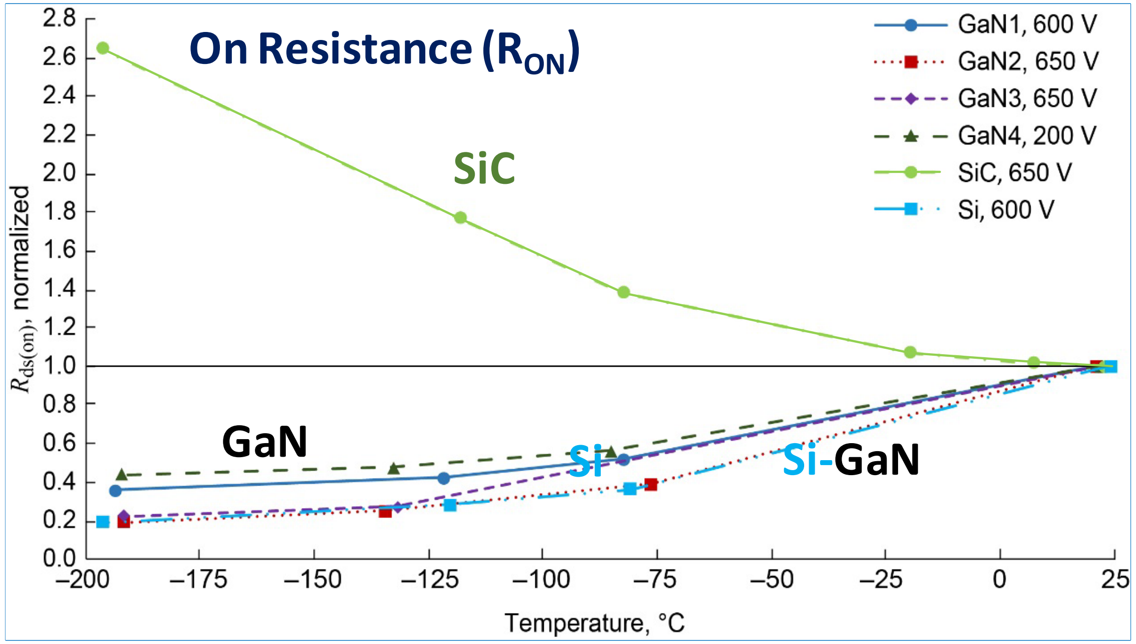
- Develop a hibernating battery design and package concept
  - Battery Thermal Model
  - Pre-heating management (temperature uniformity, uniform cell output)
- Battery Management System includes:
  - Cell Monitoring
  - Pre-Charge Control,
  - Fault Detection & Faulted String Isolation
- Battery Life Testing to demonstrate multiple lunar cycles.

Cryo-Capable Electronics Technology

Gallium-Nitride (GaN): (LN_2 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
- GaN is 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

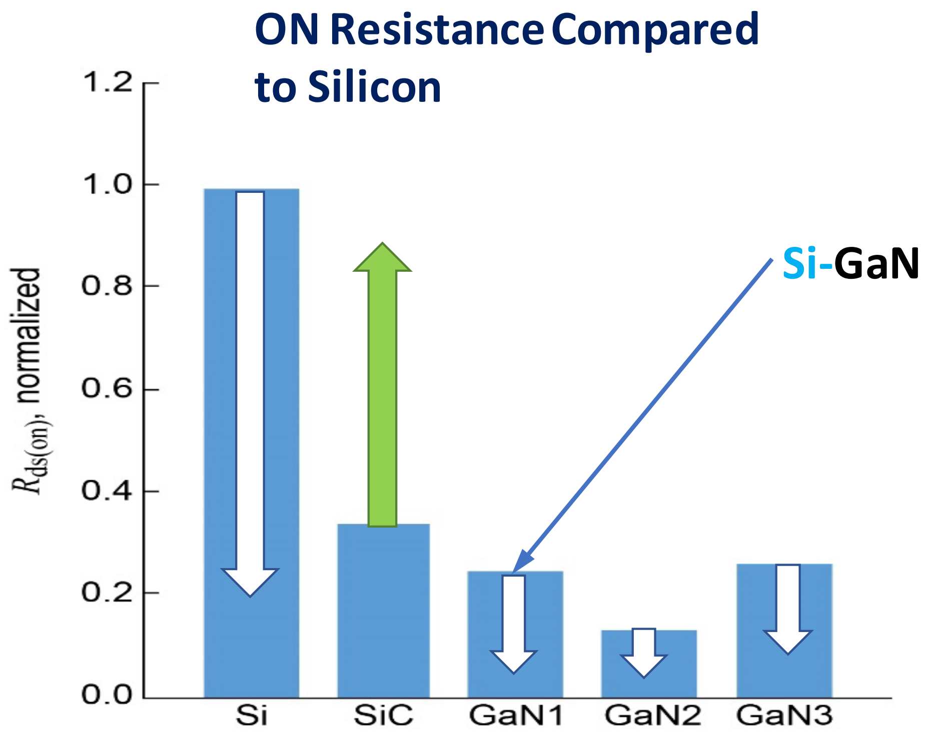
Cryo-Capable Electronics Technology

Silicon-Carbide: Poor low temp performance as an enhancement mode switch

- **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



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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 Digital and Analog 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

Lunar Power Hibernation for Surviving the Lunar Night 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 costly radioisotope heat and power sources
- Applicable to lunar robotics and lunar systems supporting human missions
- Robotics and Vehicles can operate independent pre-established infrastructure
- Restoration from Hibernation requires an Active Main Bus with *"Dawn Mode"*
    - Capable of operating in extreme cold
    - Capable of operating on solar array output alone

Lunar Power Hibernation for Surviving the Lunar Night Summary

Hibernation Enables Low Cost Missions Achieve Multi-Lunar Cycles

- 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.*

Need for collaboration with the Space Avionics Community

Hibernation depends on Avionics capable of Passively Tolerating the extreme cold.

- At a minimum avionics will need additional qualification testing.
- Certain components are typically replaced when designing for low temperature. (Electrolytic capacitors)
- NASA extreme environments group has succeeded in modifying COTS circuits for cryogenic operations.
- Conventional FRP circuit board material is remarkably tolerant.
- Minimize Thermal Gradients
- Minimize Cycles
- Minimize Rate of Change: Lunar environment changes slowly (few degrees/hour)

Acknowledgements

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