National Aeronautics and Space Administration

Power Hibernation: Surviving the Extreme Cold Lunar Environment

Presented to the
Lunar Surface Innovation Consortium

Jan 11, 2022

Richard C. Oeftering
NASA Glenn Research Center
Cleveland, Ohio 44135
richard.c.oeftering@nasa.gov

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.

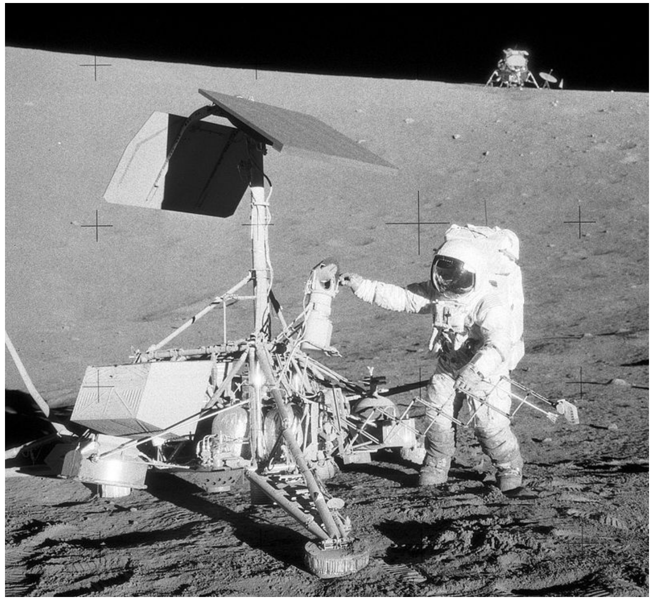
Power Hibernation: Surviving the Extreme Cold Lunar Environment

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)

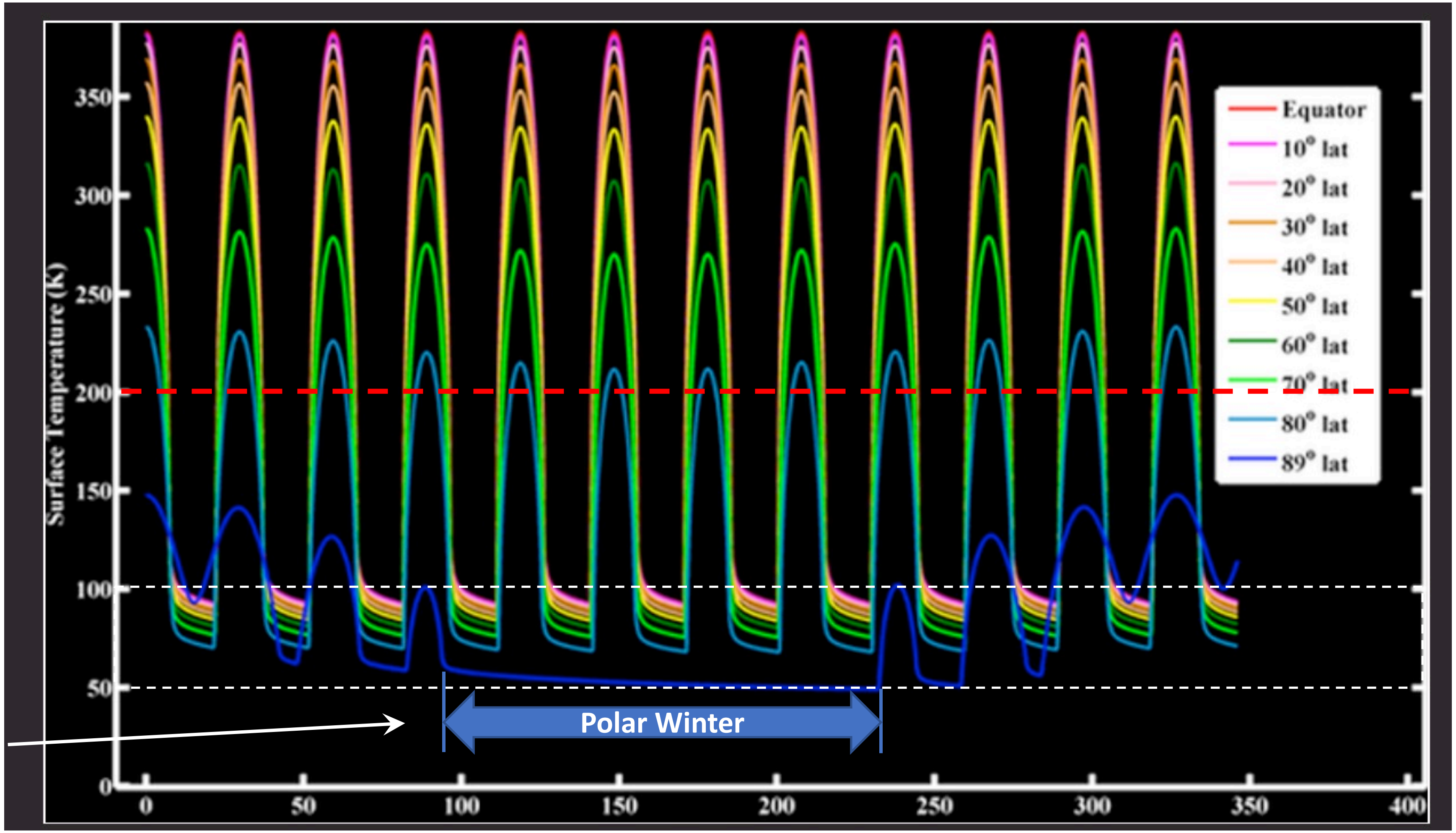
- Surveyor was not designed for Night Survival
- RTG technology still under development
- Multiple Surveyors did indeed survive the night
  - Used Silver-Zinc Batteries
  - Most Surveyor missions partially survived beyond one lunar cycle.



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.



Polar Winter 4 ½ months

<- Li-Ion Battery Approx. Freeze Temperature

< --- 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 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

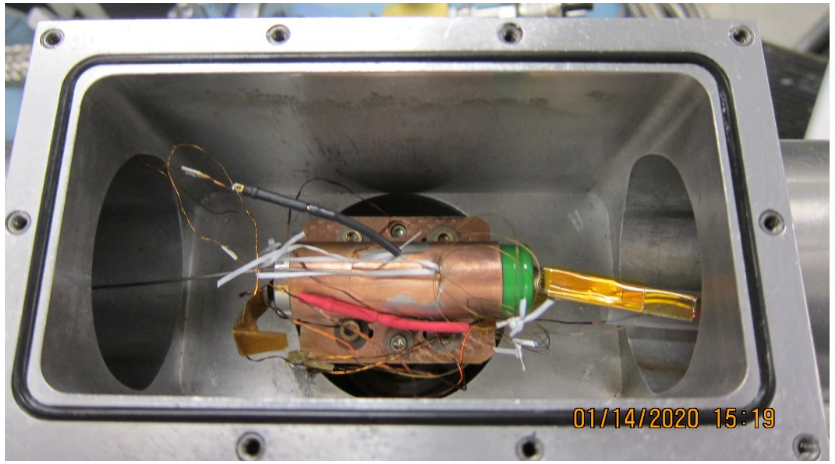
Cell Hibernation Investigation at NASA Glenn

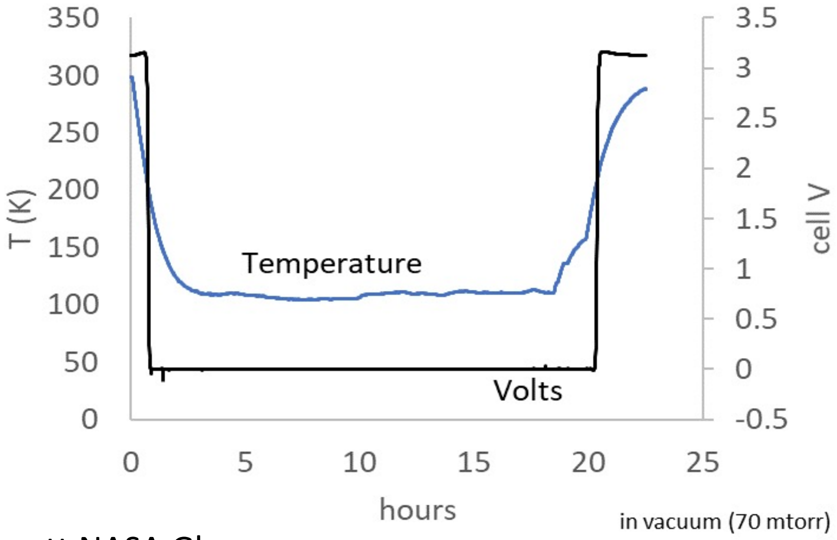
Preliminary Tests Performed at 1 Atmosphere

- Chilled to 80K (-193°C) (3 of 5 Survived)
- Strongly suspect seal leak and trapped LN_2
- 20 mg trapped LN_2 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 LN_2 Intrusion
- Voltage dropped to zero below 200K
- Voltage recovers when warmed above 200K
- 4 of 4 cell trials in vacuum were successful





Photos courtesy of W. Bennett NASA Glenn

Hibernation and Dawn Operations

Power Hibernation:

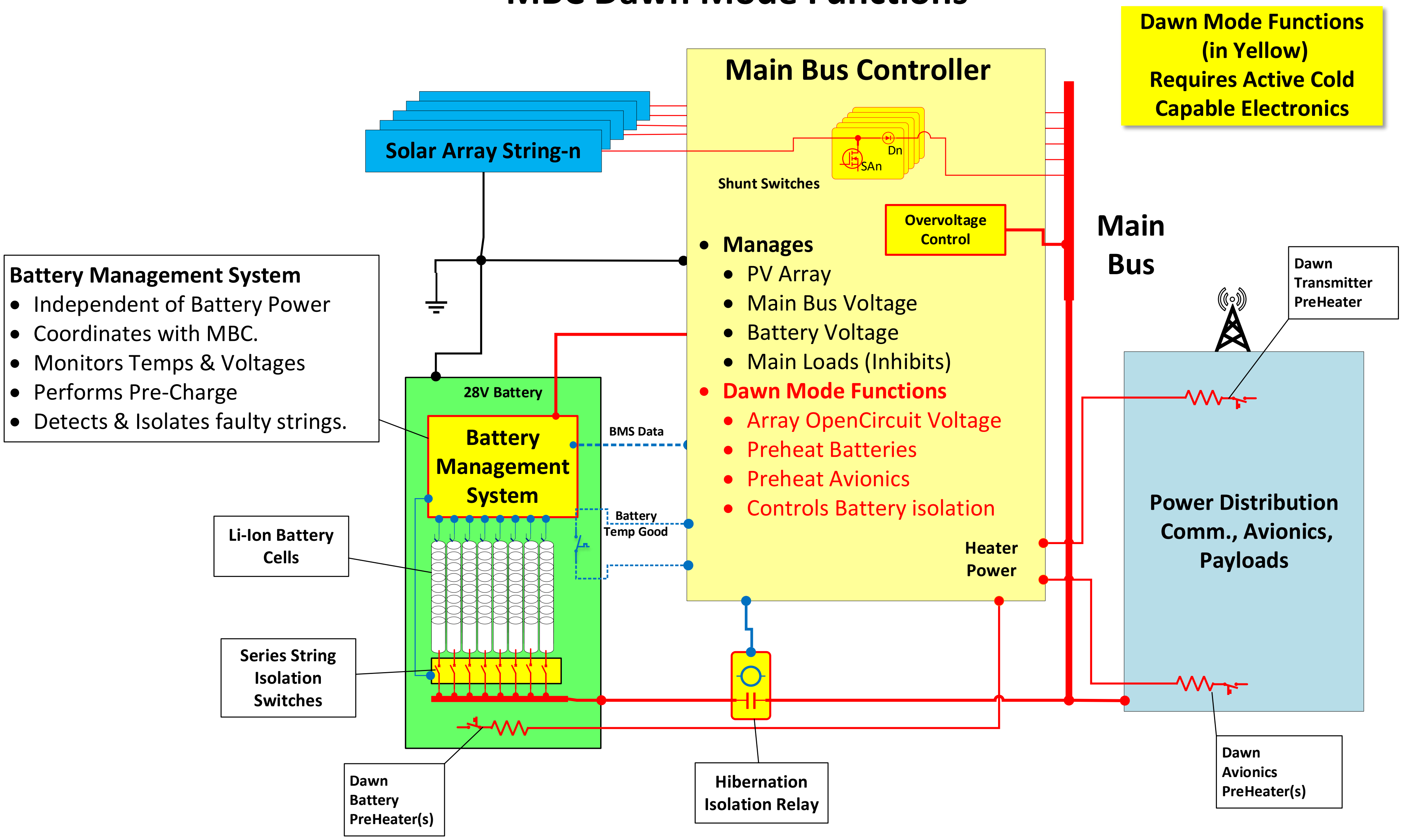
Point Arrays toward Dawn, Shut-Down Loads, Isolate Battery, Wait for Dawn

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
- <u>Battery Management System</u> (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- ***<u>Dawn Mode Complete!</u>***
- 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

<u>Cryo-Capable:</u> 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.
  - **<u>Ideally,</u>** 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 LN_2

Silicon (Si)

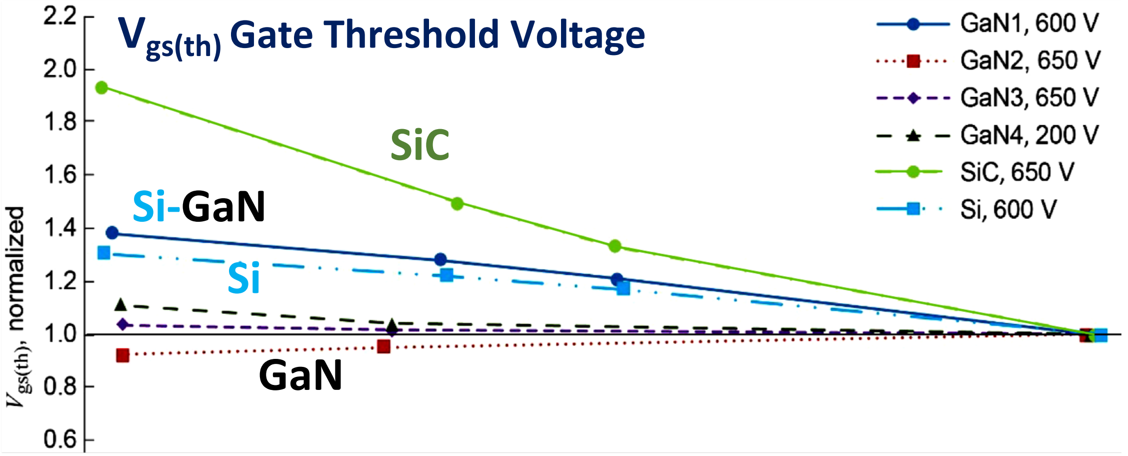
- Sensitivity to temperature
- On-Resistance $R_{ds(ON)}$ improves at low temps

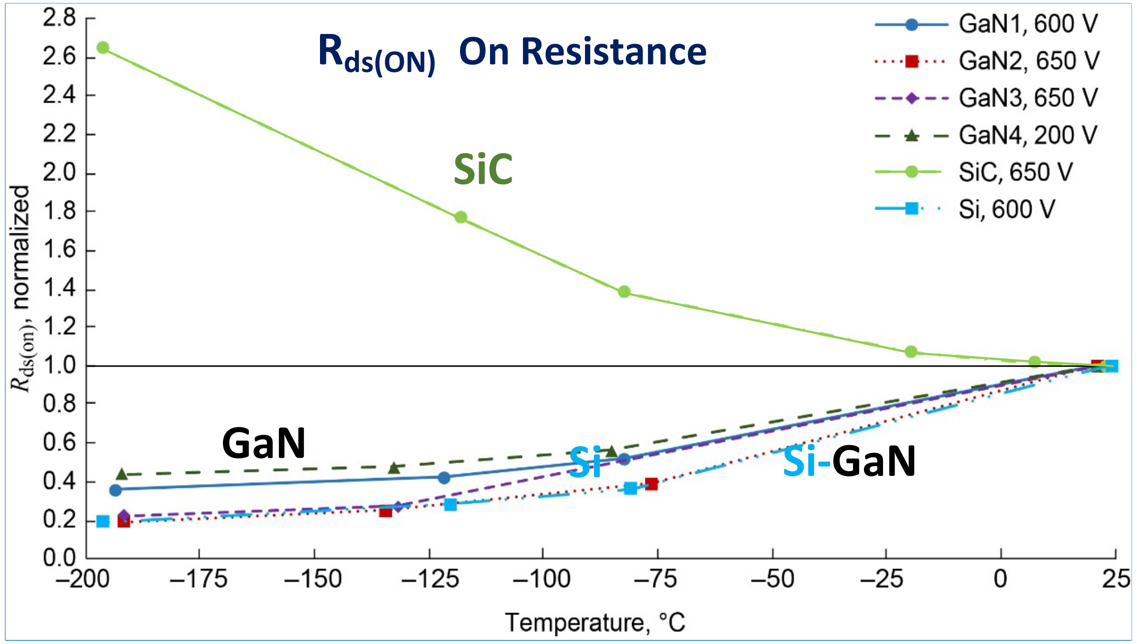
Silicon-Carbide (SiC)

- 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



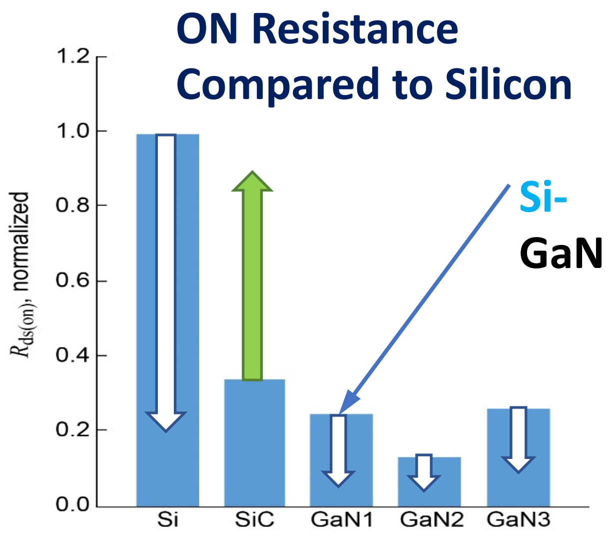


Figures Courtesy of Marcelo Gonzalez NASA Glenn

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

Acknowledgements

William Bennett LEX/Photovoltaic and Electrochemical Systems Branch
Frederick Vankeuls LEX/Photovoltaic and Electrochemical Systems Branch
Ahmad Hammoud LME/Environmental Effects and Coatings Branch
Marcelo Gonzalez LEM/Power Management and Distribution Branch
Nicholas Uguccini LEP/Power Architecture and Analysis Branch
Lucia Tian LEP/Power Architecture and Analysis Branch

Contact:

Richard C. Oeftering
Power Architecture and Analysis Branch,
NASA Glenn Research Center,
Cleveland, Ohio 44135

richard.c.oeftering@nasa.gov

References

- NASA TM 33-432 *Surveyor Batteries: Final Engineering Report*, A.J. Moses, W.M. Hetherton, D. Weinberger, Hughs Aircraft Co., A.A. Uchiyama, R.S. Bogner, W.L. Long, Jet Propulsion Laboratory, (1970)
- *Surveyor Final Engineering Report, Vol II System Design*, SSD 88027, Hughes Aircraft Co., (1968)
- LRO DIVINER Lunar Radiometer Experiment, https://www.diviner.ucla.edu/science
- K. Nandini, K. Usha, M.S. Srinivasan, M. Pramod, P. Satyanarayana, M. Sankaran, Indian Space Research Organization; Satellite Centre, "*Study on survivability of 18650 Lithium-ion cells at cryogenic temperatures*", J of Energy Storage 17 (2018) 409-416
- S. Muthusamy, Indian Space Research Organization, "*Design framework of a configurable electrical power system for lunar rover", (2017),* https://www.researchgate.net/publication/321408524
- NASA/TP-2018-219973, M. C. Gonzalez, L. W. Kohlman, and A. J. Trunek, *Cryogenic Parametric Characterization of Gallium Nitride Switches,* Glenn Research Center, Cleveland, Ohio, (2018)
- Thomas R.B. Grandjean, Jakobus Groenewald, Andrew McGordon, James Marco, Energy and Electrical Systems, WMG, University of Warwick, Coventry, CV4 7AL, UK, "*Cycle life of lithium ion batteries after flash cryogenic freezing*", Journal of Energy Storage 24 (2019) 100804