Low Temperature Electronics for Space and Terrestrial Applications

Richard L. Patterson  
NASA Glenn Research Center  
MS 309-2  
Cleveland, OH 44135  
Richard.L.Patterson@grc.nasa.gov

Ahmad Hammoud  
QSS Group  
NASA Glenn Research Center  
Cleveland, OH 44135  
Ahmad.Hammoud@grc.nasa.gov

Scott S. Gerber  
ZIN Engineering  
NASA Glenn Research Center  
Cleveland, OH 44135  
Scott.S.Gerber@grc.nasa.gov

Malik Elbuluk  
University of Akron  
Electrical & Computer Engineering Dept.  
Akron, OH 44325  
melbuluk@uakron.edu

Eric Overton  
NASA Glenn Research Center  
MS- 301-5  
Cleveland, OH 44135  
Eric.Overton1@grc.nasa.gov

John Dickman  
NASA Glenn Research Center  
MS 302-2  
Cleveland, OH 44135  
John.Dickman@grc.nasa.gov

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
OUTLINE

1. Deep Space Temperature Requirements And Applications
2. Terrestrial Applications
3. Low Temperature Electronics at NASA GRC
4. Power Electronic Components, Circuits and Systems
5. Selected Results
**Temperature Data for Planetary Missions**

<table>
<thead>
<tr>
<th>Distance from Sun</th>
<th>Spacecraft Temperature (Sphere, Abs. = 1, Emiss. = 1, Internal Power = 0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>448 K, 175 °C</td>
</tr>
<tr>
<td>Venus</td>
<td>328 K, 55 °C</td>
</tr>
<tr>
<td>Earth</td>
<td>279 K, 6 °C</td>
</tr>
<tr>
<td>Mars</td>
<td>226 K, -47 °C</td>
</tr>
<tr>
<td>Jupiter</td>
<td>122 K, -151 °C</td>
</tr>
<tr>
<td>Saturn</td>
<td>90 K, -183 °C</td>
</tr>
<tr>
<td>Uranus</td>
<td>64 K, -209 °C</td>
</tr>
<tr>
<td>Neptune</td>
<td>51 K, -222 °C</td>
</tr>
<tr>
<td>Pluto</td>
<td>44 K, -229 °C</td>
</tr>
</tbody>
</table>
Deep Space Electronics Temperature Requirements

Requirements

- Electronics Capable of Low Temperature Operation
- High Reliability and Long Life Time
- Improved Energy Density and System Efficiency

Benefits of Low Temperature Electronics

- Survive Deep Space Hostile Cold Environments
- Eliminate Radioisotope and Conventional Heating Units
- Improve System Reliability by Simplified Thermal Management
- Reduce Overall Spacecraft Mass Resulting in Lower Launch Costs
Low Temperature Electronics Program

Goals

- Provide a technology base for the development of lightweight electronic components and systems capable of low temperature operation with long lifetimes
- Develop and characterize state-of-the-art components which operate at low temperatures
- Integrate advanced components into mission-specific low temperature circuits and systems
- Establish low temperature electronic database and transfer technology to mission groups
Space Applications of Low Temperature Electronics

- Mars 2003 Lander/Rover
- Mars Flyer
- JWST (NGST)
- Pluto Flyby
- Jupiter Probe
JAMES WEBB SPACE TELESCOPE (formerly NGST)

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
L2 Point – Location of JWST

4 June 2003
This is an illustration of the L2 point showing the distance between the L2 and the Sun, compared to the distance between Earth and the Sun.

Credits: ESA

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
Terrestrial Applications of Low Temperature Electronics

- SMES
- ICARUS
- AMANDA / ICE BURG
- Magnetic Levitation
SMES
Superconducting Magnetic Energy Storage

- An energy storage system, used by electric utilities, to stabilize voltages on power grids
- The energy storage device is about the size of a small number of 55 gallon drums
- Typical energy storage is about 1 MegaJoule
- System is mobile and about the size of a truck trailer
- Used by the Tennessee Valley Authority, PacifiCorp, Wisconsin Public Service, Scotland’s Orkney Islands, and an aluminum foundry in Austria
ICARUS

Imaging Cosmic and Rare Underground Signals

- A neutrino detector (no charge and very little mass)
- A large tank of liquid argon (-180 °C)
- Needs some electronic components to operate at (-180 °C)
- Located inside a mountain in northern Italy
ICARUS

Internal Detector view

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
Amanda and Ice Cube Neutrino Detection System

South Pole

Dark sector

Skiway

AMANDA

Dome

IceCube

Planned Location 1 km east

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
IceCube Drilling

Drill following:
- 2400 m depth
- 60 cm diameter
- Deviation from vertical is +1 m
- Drill rate 60-100 m/hr
AMANDA / ICE CUBE PHOTOMULTIPLIER SENSOR

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
AMANDA NEUTRINO DETECTION SYSTEM
Inserting One Sensor into the Melted Hole

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
Low Temperature Electronics Program

Facilities

- Three environmental chambers
  - Programmable rate for thermal cycling and long term soaking
  - Simultaneous and automated operation
  - Temp range from −193 °C to +250°C
- Ultra-low temperature environmental chamber for electronic testing to 20K
- Instrumentation to evaluate digital and analog circuits
- Computer controlled CV/IV semiconductor device characterization
- Inframetrix infrared camera system
- Multiple high voltage, HIGH current source measure units
- Two programmable precision RLC instruments
- Surface and volume resistivity chamber, film dielectric and capacitance test fixture, breakdown voltage test cell
- Passive components high-power test circuitry
Facilities

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
**Commercial Off-the-Shelf 12-Bit Serial CMOS Analog-to-Digital Converter (Rated for Operation Between –40 °C and +85 °C)**

Digital Outputs at Three Temperatures for Various Analog Inputs

<table>
<thead>
<tr>
<th>Analog Input (V)</th>
<th>Digital Output (V) @ 25 °C</th>
<th>Digital Output (V) @ -100 °C</th>
<th>Digital Output (V) @ -190 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.007</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>0.5</td>
<td>0.505</td>
<td>0.498</td>
<td>0.508</td>
</tr>
<tr>
<td>1</td>
<td>1.004</td>
<td>1.006</td>
<td>1.004</td>
</tr>
<tr>
<td>2</td>
<td>2.000</td>
<td>2.002</td>
<td>1.993</td>
</tr>
<tr>
<td>5</td>
<td>4.994</td>
<td>4.994</td>
<td>5.001</td>
</tr>
<tr>
<td>7.25</td>
<td>7.241</td>
<td>7.228</td>
<td>7.226</td>
</tr>
<tr>
<td>10</td>
<td>9.983</td>
<td>9.963</td>
<td>9.963</td>
</tr>
<tr>
<td>10.1</td>
<td>10.000</td>
<td>10.000</td>
<td>10.000</td>
</tr>
</tbody>
</table>
Low Temperature Electronics Program

Products

- **Components**
  - Magnetic Devices: Inductors & Transformers
  - Capacitors
  - Semiconductor Switches
  - Batteries
  - Transducers

- **Circuits**
  - DC/DC Converters
  - A/D Converters
  - Oscillators
  - PWM Control Circuits
  - Other ICs

- **Systems**
  - Energy Storage
  - Power Conditioning
  - Communication & Control
Normalized Output Frequency for Three Oscillators at Low Temperatures

- Temperature Compensated Low Temperature Oscillator C
- Typical Uncompensated Oscillator A
- Uncompensated Low Temperature Oscillator B

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
Output Voltage of a DC/DC Converter at Various Temperatures

- 36Vin/0.5Aout
- 36Vin/4.0Aout
- 72Vin/0.5Aout
- 72Vin/4.0Aout

Output Voltage (V)

Temperature (°C)
Output Voltage of Another DC/DC Converter At Various Low Temperatures

- 18Vin/0.5Aout
- 18Vin/2.5Aout
- 36Vin/0.5Aout
- 36Vin/2.5Aout
EXPERIMENTAL SETUP & RESULTS

COMMERCIAL DC-DC CONVERTER MODULES

- SPECIFICATIONS

<table>
<thead>
<tr>
<th>Module</th>
<th>Input Voltage (V)</th>
<th>Output Voltage (V)</th>
<th>Power (W)</th>
<th>Operating Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9 –36</td>
<td>3.3</td>
<td>10</td>
<td>-40 to 60</td>
</tr>
<tr>
<td>2</td>
<td>36-72</td>
<td>3.3</td>
<td>10</td>
<td>-40 to 85</td>
</tr>
<tr>
<td>3</td>
<td>18-36</td>
<td>3.3</td>
<td>10</td>
<td>-40 to 70</td>
</tr>
<tr>
<td>4</td>
<td>18-36</td>
<td>3.3</td>
<td>13</td>
<td>-40 to 85</td>
</tr>
<tr>
<td>5</td>
<td>9-36</td>
<td>3.3</td>
<td>10</td>
<td>-40 to 85</td>
</tr>
</tbody>
</table>

- TEST TEMPERATURE RANGE: 20°C to -190°C
- TEST PARAMETERS:
  - INPUT VOLTAGE: 9-72V
  - LOAD CURRENT: 0 – 3.0 A
- MEASURED PARAMETERS:
  - EFFICIENCY
  - OUTPUT VOLTAGE REGULATION
  - CURRENT RIPPLE CHARACTERISTICS

Glenn Research Center

Power and On-Board Propulsion Tech. Div. at Lewis Field
## EVALUATION SUMMARY OF SOME DC/DC CONVERTERS

<table>
<thead>
<tr>
<th>Converter Specifications</th>
<th>GRC Evaluations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mod #</strong></td>
<td><strong>Input Voltage (V)</strong></td>
</tr>
<tr>
<td>1</td>
<td>9 –36</td>
</tr>
<tr>
<td>2</td>
<td>36-72</td>
</tr>
<tr>
<td>3</td>
<td>18-36</td>
</tr>
<tr>
<td>4</td>
<td>18-36</td>
</tr>
<tr>
<td>5</td>
<td>9-36</td>
</tr>
</tbody>
</table>
Output Waveforms of a Pulse Width Modulation Controller  
At Room Temperature and –190 °C

Glenn Research Center  
at Lewis Field
CAPACITORS

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
## CAPACITORS (Continued)

### LEAKAGE CURRENT (nA)

<table>
<thead>
<tr>
<th>Type</th>
<th>Unaged (RT)</th>
<th>Aged (RT)</th>
<th>In LN2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene 1</td>
<td>1.80</td>
<td>1.20</td>
<td>0.02</td>
</tr>
<tr>
<td>Polypropylene 2</td>
<td>8.30</td>
<td>2.45</td>
<td>1.20</td>
</tr>
<tr>
<td>Polypropylene 3</td>
<td>9.50</td>
<td>5.00</td>
<td>0.06</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>3.20</td>
<td>2.64</td>
<td>0.14</td>
</tr>
<tr>
<td>Mica</td>
<td>7.10</td>
<td>10.80</td>
<td>0.10</td>
</tr>
<tr>
<td>Solid Tantalum</td>
<td>27.50</td>
<td>22.60</td>
<td>0.08</td>
</tr>
</tbody>
</table>
NASA Langley Laminated Flexible Printed Circuit Board

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
JAMES WEBB SPACE TELESCOPE MOTOR CONTROLLER

Control Computer → Motor Select Commands

Motor Phase Drive → Power Supply

Parallel To Serial → Serial To Parallel

Sun Shield

Room Temperature

Temperature = 40 K

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
STEPPER MOTOR CONTROLLER / SELECTOR
SEMICONDUCTORS FOR USE AT ULTRALOW TEMPERATURES

Lin Engineering Stepper Motor
Model 213-10-12 (Rated 0.3 Amps / phase)
High Side Motor Selection
Transistor Base Currents Approx 7 mA

- SGA9289 SiGe HBT, Vm=2.2V
- SGA9289 SiGE HBT, Vm=2.2V
- 2N1302 Ge npn bipolar, Vm=2.5V

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
Switching Characteristics of a MOSFET Device
At Various Temperatures Before Cycling

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
Switching Characteristics of a MOSFET Device
At Various Temperatures After Cycling

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field
CONCLUSIONS

• LOW TEMPERATURE ELECTRONICS APPLICATIONS
  ➢ DEEP SPACE MISSIONS
  ➢ SATELLITES
  ➢ CRYOGENIC INSTRUMENTATION

• CAN COMPONENTS SURVIVE?
  ➢ EXTREME TEMPERATURES
  ➢ HARSH ENVIRONMENTS

• NEED TO SATISFY :
  ➢ COMPACTNESS
  ➢ REDUCED WEIGHT
  ➢ RELIABILITY
  ➢ INCREASED EFFICIENCY
CONCLUSIONS (Continued)

- COTS COMPONENTS, DEVICES, CIRCUITS AND SYSTEMS HAVE BEEN CHARACTERIZED AT LOW TEMPERATURES
  - NEED-BASED
  - TECHNOLOGY-BASED
  - TEMPERATURE RANGE BEYOND SPECIFICATIONS (-40°C OR -55°C)

- ADVANCED COMPONENTS ARE INTEGRATED INTO MISSION-SPECIFIC LOW TEMPERATURE CIRCUITS AND SYSTEMS
  - MODIFY EXISTING
  - DEVELOP NEW TECHNOLOGIES

Glenn Research Center
Power and On-Board Propulsion Tech. Div. at Lewis Field