Point-of-Load Devices for Space

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Objectives

• Evaluate the suitability of point-of-load regulators and DC/DC converters for current and future NASA missions
  – Leverage the specifications of currently available radiation hardened and commercial-off-the-shelf devices against NASA application requirements
  – Evaluate susceptibility to the radiation environment and electrical reliability

• Develop test guideline for the space radiation community
  – SEE test board design considerations
  – Impact of circuit configurations on SETs
Working Group Description

• Team
  – JPL: Philippe Adell and Greg Allen,
  – GSFC: Dakai Chen and Jack Shue (expert consultant)
  – Other contributors: Dennis Nguyen, Tien Nguyen, and Christopher Stell from JPL, A. Phan, T. Wilcox, and A. Topper from GSFC

• Collaborate with vendors for Radiation Hardened (Radhard) and commercial-off-the-shelf (COTS) devices:

• Reliability
  – Evaluate electrical performance over extreme operation range including temperature
  – Develop multi-stage power distribution architecture with currently available POL devices
  – Perform stress test to validate POL performance over a long period of time

• Radiation
  – Perform radiation testing: heavy-ion, pulsed-laser, protons, and/or Co-60
  – Identify failure/degradation modes
  – Determine radiation testing challenges and develop proper test techniques
  – Develop test guideline
# Devices Under Study

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Manufacturer</th>
<th>Assurance level</th>
<th>Device type</th>
<th>Input Voltage</th>
<th>Output Voltage</th>
<th>Output Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSK5820-2.5RH</td>
<td>MS Kennedy</td>
<td>Radhard</td>
<td>Low-voltage-drop-out (LVDO)</td>
<td>2.9 to 6.5 V</td>
<td>2.5 V</td>
<td>3 A</td>
</tr>
<tr>
<td>MSK5900RH</td>
<td>MS Kennedy</td>
<td>Radhard</td>
<td>LVDO</td>
<td>2.9 to 7.5 V</td>
<td>Vdo = 0.3 V</td>
<td>4 A</td>
</tr>
<tr>
<td>MSK5810RH</td>
<td>MS Kennedy</td>
<td>Radhard</td>
<td>LVDO</td>
<td>2 - 7.5 V</td>
<td>Adjustable down to 1.5 V</td>
<td>5 A</td>
</tr>
<tr>
<td>IRUH330</td>
<td>International Rectifier</td>
<td>Radhard</td>
<td>LVDO</td>
<td>5 V</td>
<td>Adj down to 0.7 V</td>
<td>3 A</td>
</tr>
<tr>
<td>TPS7A4901</td>
<td>Texas Instruments</td>
<td>COTS</td>
<td>LVDO</td>
<td>3 to 36 V</td>
<td>1.2 V</td>
<td>0.15 A</td>
</tr>
<tr>
<td>TPS79133</td>
<td>Texas Instruments</td>
<td>COTS</td>
<td>LVDO</td>
<td>-3 to 6 V</td>
<td>3.3 V</td>
<td>0.1 A</td>
</tr>
<tr>
<td>ISL70001SRH</td>
<td>Intersil</td>
<td>Radhard</td>
<td>Buck regulator</td>
<td>3V to 5.5V</td>
<td>Adjustable down to 0.8 V</td>
<td>6 A</td>
</tr>
<tr>
<td>MSK5059RH</td>
<td>MS Kennedy</td>
<td>Radhard</td>
<td>Buck regulator</td>
<td>16 V</td>
<td>Adjustable down to 1.8 V</td>
<td>4.5 A</td>
</tr>
<tr>
<td>PE9915X</td>
<td>Peregrine</td>
<td>Radhard</td>
<td>Buck regulator</td>
<td>5 V</td>
<td>3.3 V and 1.8 V</td>
<td>10 A (3.3 V)</td>
</tr>
<tr>
<td>MFP0507S</td>
<td>Interpoint</td>
<td>Radhard</td>
<td>DC/DC converter</td>
<td>6 V</td>
<td>3.3 V and 0.8 V</td>
<td>7 A (3.3 V) 5 A (0.8 V)</td>
</tr>
<tr>
<td>SBB503R3S</td>
<td>International Rectifier</td>
<td>Radhard</td>
<td>DC/DC converter</td>
<td>4.5 to 5.5 V</td>
<td>3.3 V</td>
<td>9.1 A</td>
</tr>
<tr>
<td>SA50-28</td>
<td>Microsemi</td>
<td>Rad hard</td>
<td>DC/DC converter</td>
<td>28 V</td>
<td>5 V</td>
<td>10 A</td>
</tr>
</tbody>
</table>

- Devices evaluated since 2011 for reliability and radiation performance
- Planning radiation testing and reliability studies for newly released and in-development devices from TI, Aeroflex and 3D-plus
Motivation

- As demand for high-speed, on-board digital processing ICs spacecraft increases, point-of-load (POL) regulator becomes a prominent design issue for power systems.

- Shrinking process nodes have resulted in core rails dropping to values close to 1.0 V and with relatively high output current.

- This drastically reduces design margins to standard switching converters or regulators that power digital ICs.
Power System Architecture

- Current practices use large COTS hybrid power conversion modules and custom circuitry to meet minimum design principles and requirements for spacecraft applications.

- Architecture with POL converters use two stages system distribution scheme incorporating the necessary features for FP, FT, OVP, UVL, sequencing and improves efficiency from $\eta < 50\%$ to $\eta > 80\%$.

Typically POL development focuses:
1) FP, FT, OVP and Sequencing;
2) Efficient POL conversion and 3) Immunity to Single event transient.
Presented by Dakai Chen at the NASA Electronic Parts and Packaging Program (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center in Greenbelt, MD, June 11-13, 2012 and published on nepp.nasa.gov.

**POL Types**

- **Integrated devices**
  - Linear regulator
  - Non-isolated DC-DC

- **Hybrid switching converters**
  - Isolated (magnetic) or non-isolated
  - High efficiency
  - Can step-up (boost), step-down (buck)

- **Hybrid Linear regulators**
  - Low efficiency
  - Can only step down
  - Fast transient response

**Switch + Control**

1. capacitor
2. chip resistor
3. thick film resistor
4. magnetic device
5. discrete
6. ICs in die form
7. ceramic substrate
8. package

**Power Bipolar**

Packaging and layout is a critical component of POL designs for reliability
Reliability

- In FY2011, assessment of available POL regulators was carried out to determine use conditions that had acceptable performance.
  - Among the tests performed were efficiency, turn-on, load transient response, synch., at different temperatures.
  - Several potential problem areas were identified, mainly at low temperature.
  - In addition, two stages system implementation preliminary assessment was conducted for performance comparison between manufacturers.

- In FY2012, the objective is to develop a matrix of performance by implementing a power distribution architecture by using available POLs in combination with the most common isolated converters used in NASA programs.
Objectives

- Perform standard measurements on state of the art commercial POL regulators as they become available
- Continue investigating the limits of operation for the different POLs at low and high temperature
- Perform a matrix of performance comparison when POLs operating in two stages system architecture
Two stages modular board implementation

- **First stage**
  - Two flights isolated DC-DC converters 28 V to 5 V
  - M3G2805RS from International Rectifier
  - SMTR285R5S from Interpoint
  - Adaptable to other isolated converters

- **Second stage**
  - Various POL listed in Table I
  - Eval boards
  - Linear regulators
  - Hybrid POL

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Board Description

Characteristics

- Input Voltages/Currents
- Output Voltages/Currents
- Efficiency Measurements
- Dynamic load measurements
- FFT measurements
- Line regulation
- Load regulation
- EMI filter option
  - various filtering LC, RL
  - Exercise systems with R, L, C
  - Adaptable for SET testings
  - Close to real applications
Parameter “h”

Intersil ISL7001  

Crane MFP0507

End-to-end efficiency plot with the combination of IR MG32805SR + ISL7001 or MFP0507S. Conditions: 28 V input, 5 V intermediate voltage, and 0.8, 1.2 or 3.3 V output vs load (0-6 A).

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Step Load Change

- $\text{SMTR285R5S + SBB503R3S}$

- $1\text{A} – 7\text{A}$ step-to-load change @ $V_{\text{out}} = 3.3\text{ V}$
Plans

- Matrix of performance for POLs operating in two stage architecture with isolated converters used in NASA programs
  - Use a variety of common 28 V isolated converters
    - Interpoint (in-house), International rectifier (in-house) and VPT
  - Develop a modular characterization board to test and compare POL performances in a power distribution architecture
    - Impact of ESR
    - Input capacitance
    - Load regulation
    - Line regulation
    - Exercise system with various variable
    - Adaptable to SET characterization
  - Report of issues of stability and limits of performance
- Continue evaluate emerging POL design
  - Likely will be Texas Instrument, Aeroflex and 3Dplus
- Stress test for to evaluate performance for flight-like application
Radiation Susceptibility

- Radiation can cause various degradation and failure modes in POL devices which may impact system level performance
  - Total Ionizing Dose and Displacement Damage
  - Single Event Transient (SET)
    - Localized ion strike on a sensitive node resulting in voltage/current spikes
    - SETs can propagate through multiple stages of the power architecture and cause catastrophic failure to a Microprocessor/FPGA
  - Functional Interrupt (i.e. output dropout)
    - Self-recoverable or requiring power cycle
  - Destructive Event
    - Single Event Latchup, Single Event Burnout, and Single Event Gate Rupture
Radiation-induced Output Dropout

**MSK5059RH Radhard buck regulator from MSK**

- Tested at TAMU cyclotron facility with 15 MeV/amu cocktail heavy-ions
- Testing challenges:
  - Design/fabricate SET test board to suppress output ripple oscillation and provide proper heat dissipation
  - Output dropped at \( \text{LET}_{\text{eff}} = 124 \text{ MeV} \cdot \text{cm}^2/\text{mg} \)
  - Thermal shutdown?
  - Single event latchup?

- 400 nm high speed bipolar process, hybrid design
- Tested with \( V_{\text{in}} = 7 \text{ V} \), \( V_{\text{out}} = 3.3 \text{ V} \), \( I_{\text{out}} = \) up to 1.5 A

**Investigate what caused the output dropout**

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Dropout from PN Junction Capacitor

**MSK5059RH Radhard buck regulator from MSK**

- Tested with pulsed-laser at the Naval Research Laboratory (NRL)
- Observed dropout for strikes on the junction capacitor overlaying the C-B of NPN that controls the reference voltage
  - Dependent on laser pulse frequency
- Laser energy threshold 55 to 110 pJ, correspond to ~165 to 330 MeV·cm²/mg
  - Similar $\text{LET}_{\text{th}}$ as events from heavy-ion test
- Not a concern for most missions due to the high energy threshold

*Laser testing identified sensitive component causing dropout*
Dropout from Soft-Start Upset

Radhard DC/DC Converter from XX

- $V_{in} = 28\text{V}$, $V_{out} = 5\text{V}$, $I_{out} = 10\text{A}$ continuous
- Tested at Lawrence Berkeley National Laboratory with 16 MeV/amu cocktail heavy-ions in vacuum
- Testing challenges:
  - Vacuum chamber introduced noise
  - Surface mount technology with ICs on front and backside of PCB
Dropout from Soft-Start Upset

Radhard DC/DC Converter from XX

- Observed output dropouts lasting 110 ms
- Single Event Upsets in the PWM initiated soft-start
  - Supervisory circuitry shuts off device for 100 ms when output drops below 4 V
- Features designed for device reliability can drastically influence the SEE response
- Test findings prompted redesign
SET Characterization

MSK5058RH Buck Regulator from M.S. Kennedy

- Heavy-ion irradiation at LBNL with 10 MeV/amu heavy-ions in vacuum
- Pulsed-laser testing performed at NRL and JPL
- Testing challenges
  - Vacuum environment
  - Heat dissipation: needed to shut off device following high current modes (case temperature < 55°C)
  - Long cables introduce high resistive drops for high output loads
  - Facility (vacuum chamber) introduced noise ~ 600 mVpp

- Hybrid design, RH3480 die from Linear Technology, BIPC150 1.5 µm bipolar process
- \( V_{in} = 3.6 \text{ to } 36 \text{ V, } V_{out} = 0.79 \text{ to } 20 \text{ V, } \) Maximum 2A continuous output load
SET Characterization

**MSK5058RH Buck Regulator from M.S. Kennedy**

- No destructive event or functional interrupt (dropout) up to LET = 83 MeV·cm²/mg
- Mission error rate can be calculated from cross section
- Determine the significance of SET (amplitude and duration)
- SET magnitude and cross section dependent on output current load
SET Characterization

**MSK5058RH Buck Regulator from M.S. Kennedy**

- Pulsed-laser testing identified sensitive locations
- SETs most significant from the voltage reference PNP
  - Dropouts occur for very high energies (220 pJ): not a realistic concern for space
Investigation of Circuit Configurations

• JPL lead effort to investigate the effects of circuit configurations and device operating conditions on SET characteristics
  – Output capacitor selection (ESR values)
  – Output loading type (resistive vs. electronic load)
  – Device operating conditions (Input voltage and output load)

• Provide test recommendations and insights to the space radiation community
Spice Modeling

- Simulated ion strike on a sensitive transistor in the amplifier
- ESR value of the output capacitor influences the SET peak amplitude and settling time
- Improper capacitor selection can cause significant oscillation and induce prolong instability (100 µs)
Laser-induced SETs – ESR Impact

MSK5920RH Radhard Low Voltage Dropout Regulator (LVDO) from MSK

- \( V_{\text{in}} = 2.9 \) to \( 6.5 \) V, \( V_{\text{out}} = 1.5 \) V, \( I_{\text{out}} = 5 \) A
- Tested with pulsed-Laser at JPL
- Evaluated different output capacitors with various ESR values
- Manufacturer recommended ESR values:
  - Less than 180 m\( \Omega \) for many applications
  - Less than 57 m\( \Omega \) for most stringent applications
- SET magnitude increases with increasing capacitor ESR
  - Similar response has been observed for MSK5900
  - Effect worse at low load current

Laser energy 55 pJ, output 1.5 V, Vin 5 V, 50 mA
Impact of Device Test Conditions

MSK5058RH Buck Regulator from M.S. Kennedy

SET response varies with input voltage, load conditions and load types
Conclusion

- The various process technologies and distinct design architectures of modern POL devices lead to a variety of distinct radiation responses
  - Different mechanisms can trigger functional interrupts (output dropouts)
  - SET characteristics depend on device operating conditions and circuit configurations
    - Pulsed-laser a good tool for SET evaluation
- Identified SEE testing challenges and determined solutions which will aid in developing test guideline for space radiation community