Design Considerations for High Power Spacecraft Electrical Systems

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Outline

• Space Power Challenge
• Background
• Trends is Space Power Requirements
• Future Space Systems
• Challenges and Driving Requirements
• Modular Power Systems
• Advanced Power Technologies
• Conclusions
• Credits
Space Power Grand Challenge

• **Needs: Abundant, Reliable and Affordable Power**
  – NASA’s future missions of science and human exploration require abundant, reliable and affordable energy generation, storage and distribution.
  – Power needs grow exponentially as we look at extending human presence beyond near earth.

• **Problem: Today’s space power systems limit our ability to conduct human exploration beyond LEO.**
  – Current spacecraft power systems key driving requirements become even more critical as we look at meeting growing power needs.
Background: Elements of a Power System

- Power Generation
  - Solar Arrays
  - Brayton Rotating Unit
  - Stirling Radioisotope
- Energy Storage
  - Fuel Cells
- Charge/Discharge Regulator
  - Batteries
  - Flywheel
  - PMAD
- Power System Control
  - Power Distribution
- Load Converters
  - Load Leveling
- Electric Propulsion
- Communications
  - Instruments
  - Actuators
  - www.nasa.gov
Background: Types of Space Power Systems

Technology used for a power system depends on power level and mission duration.
Traditional Space Power Systems

- Power Level ≤ 15kW
- PMAD Distribution Voltage ≤ 120V
- Custom systems created from one-of-a-kind components.
- Limited or no growth potential.
- Require extensive infrastructure for verification and operation.
- Limited or no autonomous operation.
International Space Station EPS

- **Power Source**
  - Largest ever space solar array
  - 8 solar array wings on space station (2 per PV module)
  - Nominal electrical power output ~ 30 kW per PV wing BOL for ~ 240 kW total power

- **Energy Storage**
  - 24 NiH2 Batteries NiH2
  - Nominal storage capacity is ~4 kW-hr

- **Power Distribution**
  - Power Level 75 kW
  - 8 power channels
  - Distribution Voltage
    - 116-170 V primary
    - 120 V secondary
Trends in Space Power Systems

1960 1980 2000 2020

Mercury
Gemini
Apollo
STS – Space Shuttle
Skylab
International Space Station
Manned Exploration Beyond LEO

Power Requirements
Autonomous Operation
Reliability
DDT&E Cost
Operations and Logistics Cost
Potential Future Missions & Applications

- SEP Propulsion Stage
- Deep Space Habitats
- Space Outposts
- Multi-mission Space Exploration Vehicle
- Advanced Cryo Propulsion Stage
Challenges for Space Power Systems

- Environment
  - Radiation
  - Thermal
- Cost
- Wide Range of Spacecraft Configurations
  - Unique Requirements promotes “one of a kind” design.
- Long Term Operation with minimal human intervention
  - Health Monitoring
  - Power Management

- Space Power System Design Drivers:
  - Efficiency/Power density
  - Safety/Reliability
  - Radiation Hardness
  - Thermal requirements
  - Autonomous operation
  - Mass/Volume
  - DDT&E cost
  - Operations cost
Given these challenges

What should be our focus…
Modular Power System Concept

- Develop a set of modular power components that can be mixed and matched to meet “unique” requirements for different applications
  - Reduces DDT&E cost through design reuse
  - Reduces logistics cost across missions through reduction of vehicle unique components.
- “Monolithic” EPS functional units are replaced by collections of common “smart modules”.
- The power system can be “modularized” at various levels.
  - Module Level
    - Uses common devices with master-less intelligent controllers to create “smart modules” to build EPS functional units (converters, switchgear, batteries, etc.).
  - System Level
    - Integrate “smart modules” into sub-systems (power generation, storage, and distribution).
Modular PMAD - Hardware

Description
• Reusable building block(s) that can be configured in series and parallel arrangements for power management and distribution.

Key Issues to Address
• Mechanical packaging and interconnects.
• Low mass – complexity – parasitic.
• Control/configuration for multi-function, series, and/or parallel operation.

Key Benefits
• Reduced DDT&E and logistics costs.
• Enables high voltage/high power conversion and conditioning
Modular PMAD - Controls
Intelligent Control Systems

Description
• Replaces a traditional, hierarchical control system with peer-to-peer cooperating elements with each power module for enhanced operational effectiveness.

Key Issues to Address
• Embedded controls in power elements.
• Collaborative agents in components for active power quality and stability control.
• Sensor web and distributed networks for health monitoring.
• Fault isolation and reconfiguration at the lowest levels.
• Reliable inter-module communication

Benefits
• Enhanced safety and reliability.
• Facilitates “plug & play” growth and system enhancement.
• Reduces cost of system verification and logistics.
Description
• AC or DC high voltage, > 300V, delivery of large power, >100kW, from source to load

Key Issues to Address
• Insulation stress.
• High current/power connectors.
• Corona management in certain environments.
• High current switching and fault control.
• Radiation tolerance.

Key Benefits
• High voltage distribution reduces cable mass and ohmic losses.
• Minimizes power conversion which maximizes efficiency.
PMAD - Advanced Components

Description
• Components that can withstand the harsh environments, wide temperature variations, and high radiation of deep space.

Key Issues to Address
• Development of Silicon Carbide and Gallium Nitrate semiconductors.
• High current/high energy density capacitors.
• Low loss magnetic materials that can withstand high temperatures.

Key Benefits
• Facilitates high voltage switching.
• Increased radiation tolerance.
• Ruggedness improves safety and reliability.
• Lower mass/higher energy density.
• Increased operating temperature range.
Power Generation: High Efficiency & Low Mass Photo-voltaic

State of Practice

- Current Systems: Crystalline Si Cells; Triple Junction GaAs Solar Cells;
- Efficiency: Si Cells: 15%; MJ Cells: 31%
- Specific power: 50 to 100 W/kg
- Array stowage volume: 5 to 15 kW/m³

Advanced Solar Arrays

- 4-5 Junction Solar Cells; Quantum Dot Solar Cells; Thin-Film Solar Cells
- Efficiency > 50%
- Specific Power > 500 W/kg
- Array stowage volume > 100 kW/m³

- InGaP
- GaAs
- Ge

- 4 & 5 Junction Solar Cells
- Nano Solar Cells
- Thin Film Solar Cells

Si

GaInP
GaAs
Ge

AM0 SOLAR SPECTRUM 
\( P_{in} = 1367 \text{W/m}^2 \)

Low Eg Material (1.05eV)

GaAs (1.42 eV)

InGaAlP (2.0 eV)

Substrate

4 & 5 Junction Solar Cells

Nano Solar Cells

Thin Film Solar Cells

AM0 Theoretical
3-Junctions 39%
4-Junctions 42%

GaAs

Ge

Si

Rigid Panel

MGS

Phoenix

www.nasa.gov
Power Generation: Low Mass Solar Arrays

State of Practice
- Semi-rigid Deployment Mechanism
- Alpha and Beta Joints With Slip Rings or Roll Rings
- Truss Structure To Add Additional Solar Array Blankets
- Centralized Momentum Control

Advanced Solar Arrays
- Rigid Light Weight Deployment and Restowage Mechanism
- Lower Mass Pointing Mechanism Allowing Power and Thermal Transfer
- Integrated/Controlled Truss Structure With Distributed Momentum Control
Energy Storage: Batteries

State of the Art
- Ni-H2: 30 Wh/kg at the cell level life > 10 years – ISS Application
- Li-Ion: 100 Wh/kg at the cell level life > 5 years

Advanced Batteries
- Li-ion: 160 - 200 Wh/kg at the cell level for > 2000 cycles -- Rover / Lander application
- Li-ion: 270 Wh/Kg at the cell level for > 100 cycles – EVA applications
## Energy Storage
### Li-Ion vs. NiH2 Batteries

<table>
<thead>
<tr>
<th>Cell Characteristics</th>
<th>ISS NiH2</th>
<th>140Ah Li ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>81 AH</td>
<td>134-144 A</td>
</tr>
<tr>
<td>Energy density</td>
<td>~65 wh/kg</td>
<td>~150 wh/kg</td>
</tr>
<tr>
<td>Discharge voltage</td>
<td>1.25 V</td>
<td>&gt; 3.6 V</td>
</tr>
<tr>
<td>Self discharge rate</td>
<td>~7% per day (20°C)</td>
<td>&lt; 0.05% per day</td>
</tr>
<tr>
<td>Cycle life in LEO (20%-30%DOD)*</td>
<td>~ 10 years (60,000-75,000 cycles) @ 20%-30% DOD</td>
<td>~ 10 years (58,000 cycles) @ 20%-25% DOD</td>
</tr>
<tr>
<td>Spec Cycle life</td>
<td>6.5 years @ 35%</td>
<td>10 years @ ISS power levels</td>
</tr>
<tr>
<td>Storage life</td>
<td>4 years</td>
<td>6 years</td>
</tr>
<tr>
<td>Overcharge</td>
<td>Tolerant</td>
<td>Controlled by 2 FT design</td>
</tr>
<tr>
<td>Total Energy Storage (Important for contingency operations)</td>
<td>8 kW-hr (Two ORUs combined)</td>
<td>15 kW-hr (One ORU)</td>
</tr>
<tr>
<td>Battery Weight</td>
<td>744 lbs (Two ORUs)</td>
<td>415 lbs (One ORU)</td>
</tr>
</tbody>
</table>

Replacement of two NiH2 ORUs with one Li-ion ORU
Half the logistics flights
Fewer EVAs to replace batteries
Conclusions

• As human space exploration power needs increase, high power / high voltage systems will be required for future missions

• Power system technology development is critical for the future of human space exploration

• Spectrum of technology development will be needed to meet the increasing power needs of future manned missions
Credits

• Robert Scheidegger – NASA GRC
• James Soeder – NASA GRC
• Raymond Beach – NASA GRC
• Walter Santiago – NASA GRC
• Tom Kerslake – NASA GRC
• Penni Dalton – NASA GRC
• Jameka Humphrey – NASA GRC (SGT inc.)
• Azam Arastu – Boeing Space & Intelligence Systems