Space Power Architectures for NASA Missions: The Applicability and Benefits of Advanced Power and Electric Propulsion

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The relative importance of electrical power systems as compared with other spacecraft bus systems is examined. The quantified benefits of advanced space power architectures for NASA Earth Science, Space Science, and Human Exploration and Development of Space (HEDS) missions is then presented. Advanced space power technologies highlighted include high specific power solar arrays, regenerative fuel cells, Stirling radioisotope power sources, flywheel energy storage and attitude control, lithium ion polymer energy storage and advanced power management and distribution.
GRC Systems Assessment Team

List of contributors:

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- Jeff Hojnicki   Power Management & Distribution
- Tom Kerslake   Photovoltaic Arrays
- Lee Mason      Stirling Radioisotope Power
- Paul Schmitz   Flywheel Energy Storage & A/C
- Dale Stalnaker Lithium-polymer Energy Storage
Relative Importance of Power

The Power system is typically 20% to 30% of Spacecraft Dry Mass.

- Pie Chart shows the average mass breakdown by system for 24 spacecraft.
- Data from "Space Mission Analysis and Design", Wertz & Larson, 3rd Ed., Appendix A.

- Power is a relatively heavy *mission critical* system required by every other system (except Structures).

- Relative to spacecraft dry mass, the return on investment from advanced power system technology can be greater than any other spacecraft system for a wide variety of missions!
Aerospace Power Systems

Typical Power Subsystem Mass Breakdown by Function

- Power Management & Distribution 35%
- Power Generation 33%
- Energy Storage 34%

Power generation - required for every mission; advanced technology can be mission enabling.

Energy Storage - when required, improvements in this subsystem typically result in the largest systems-level mass reductions.

PMAD - improvements benefit ALL missions, especially large high power missions with significant power conversion requirements.

Investments in advanced technology for each power subsystem will benefit the widest variety of missions!
Solar Arrays in Space

1ST Space Solar Array: Vanguard 1 (1958)
- 6 body-mounted solar cell panels
- 18 single crystal 2 x 0.5 cm 10% eff. Silicon cells/panel
- 1 Watt Total Power
- 6 years life

Most Efficient Solar Arrays:
* Deep Space 1 (1998)
  - 24% multi-junction GaInP<sub>2</sub>/GaAs/Ge solar cells
  - 7x refractor concentrator array (SCARLET)
  - 2.5 kW Total Power, 44 W/kg
* Galaxy XI - Hughes 702 (1999)
  - Two-junction GaAs/Ge solar cells
  - 2x trough concentrator array
  - 10 kW Total Power, 70 W/kg

Largest Solar Arrays - International Space Station (2000)
- 30 kW Solar Array (34 x 12 m) with 32,800 solar cells
- Single crystal 8 x 8 cm 15% efficient Silicon solar cells
- Eight Arrays when complete - 240 kW Total Power Generation
- 15 year life in LEO
PV Array Technology Thrusts

- High $\eta$ Cells on Rigid Planar Arrays
  - Lo-Med. Power LEO & Hi-Power GEO
  - ISS Arrays
  - 28 W/kg (PF = 0.70)

- High $\eta$ Cells on Flexible Planar or Inflatable Arrays
  - Enables Nanosats & Large Sats & ISS
  - Smallest Array Area

- Thin-Film Cell Arrays
  - Enables Large SEP & SSP
  - Lowest Mass & Cost

Note: Specific Power (W/kg & W/m²) reference lines assume a 0.85 cell packing factor.
Near Term Thin-Film Application
Europa Orbiter

- Multi-Year Transfer & End-Game
- 20 kW (1-AU) Solar Electric Propulsion
- Extremely High Radiation Environment at Europa
- **Very Low Mass UltraFlex™ Wing**
  - Thin Film PV on 1-mil Stainless Steel reduces Wing Specific Mass (kg/m²) 3x (compared with crystalline cells)
- Thin Film PV Issues:
  - Full scale array designs
  - Demonstrate Rad Tolerance
  - Demonstrate LILT Performance
Far Term Thin-Film Application
Humans to Mars

- Multi-Year LEO-ETO-LEO Ops

- High Power (800 kW) Electric Propulsion
  - Array Span of 100+ m

- Rendezvous & Chemical Burn to Mars

- High Radiation Environment

- Power System Launch Mass is the Driver
  - High-Efficiency (17%) Thin-Film PV on Thin Polymer Substrate Enables Mission
Stirling Radioisotope Power System

Solar System Exploration Missions
- Mars Landers, Rovers, and Drills
- Europa Orbiter/Lander, Io Volcanic Explorer
- Saturn Ring Explorer, Titan Organic Explorer
- Neptune Orbiter with Triton Flyby
- Venus Lander - Combined Power & Cooling
- Outer Planets/Solar Probe Missions

Stirling Attributes
- Scalable Power Output: 100W to 10kW+
- Low System Mass
  - 5 W/kg (SOA, Lo Power) to 10 W/kg (Adv, Hi Power)
- High Efficiency to Minimize Pu-238
- Continuous, Long Life Power Output
- Minimal Sensitivity to Operating Environment
- Universal Power Converter
  - Solar, Isotope, Reactor Heat Sources

DOE SRPS System Concept

GPHS Modules per 100 Watts (EOM)
Regenerative Fuel Cell (RFC) Types

Unitized

Power

H₂ Tank

O₂ Tank

Power

Unitized Stack

Pump

H₂O Tank

Separate Fuel Cell and Electrolyzer

Power

H₂ Tank

O₂ Tank

Power

Unitized Stack

Pump

H₂O Tank

Active

Passive

H₂O Tank

H₂O Tank

H₂O Tank

H₂O Tank
Benefits of RFC Systems

- High Specific Energy
  - Theoretical H₂/O₂ perf.: 3660 Wh/kg
  - Target performance: > 400 Wh/kg
  - Perf. improves as discharge time increases
- Long Cycle Life of fuel cell & electrolyzer

Benefits of Passive RFC Systems

- Higher Specific Energy
  - reduction in ancillary mass (potentially)
  - lower parasitic power losses
- Round trip efficiency
  - about the same or better than active systems
- Reduced Complexity
  - potentially more reliable, longer life, lower cost
Flywheel Systems Level Benefits

Energy Storage Only:
- Very high usable Specific Energy
  - Saves mass
- Higher Efficiency
  - Saves power
- Long Life - 15 years in LEO
  - Less maintenance
  - Fewer replacements
- Less Volume than NiH$_2$ Batteries
  - Saves space
- Known State-of-Charge

Integrated Power & Attitude Control (IPACS)
- All of the energy storage benefits, plus...
- Combined Functions - less total hardware

Mission Applicability:
- LEO Spacecraft
- LEO Space Stations
- Peak Power
- Load Leveling
- Large Momentum Control
PMAD System Benefits for a MARS SEP Mission

Advanced high voltage/high power converters & high temperature electronics in the Power Distribution Unit (PDU) & Power Processing Units (PPUs) of a Solar Electric Propulsion system.

- Eliminate Array Regulator Unit (ARU) & active TCS for PDU
- Add advanced converter to PPU

Potential mass savings
- 1858 kg (42%) of PMAD
- 14% of total EPS mass

Complexity/cost savings
- No ARUs
- No active TCS

Reliability improved
- No TCS failure mode

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Eliminate

Active TCS

PV Array

ARU

RBIs (Typ)

N Array Sections

Li ion Battery

PDU

TE Loads

Hall PPU

Add Adv. Converters

M PPU Channels

500-V Voltage

28-V or 120-V Voltage
Applications for Advanced Batteries at NASA

Planetary Rovers

Astronaut Equipment

Planetary Lander

GEO Spacecraft

Planetary Orbiters

LEO Spacecraft
Benefits of Lithium-ion Energy Storage


**Baseline:**
GaAs Solar Arrays (19% Eff. Cells, 40 W/kg)
NiCd Batteries (38 Whr/kg, 78% RT Eff.)

S/C Total dry mass = 1340 kg.
(All values are given in kg.)

14% MORE Payload using Advanced Lithium-Polymer Batteries

Li-poly Batteries (200 Whr/kg, 90% RT Eff.)

20% MORE Payload using Advanced Lithium-Polymer Batteries, 4-Junction Solar Arrays, and Advanced PMAD Technology.

Adv. EPS:
4-J Arrays (35% Eff. Cells, 100 W/kg)
Li-poly Batteries (200 Whr/kg, 90% RT Eff.)
Synergistic Benefits of Power & Electric Propulsion
Space Science: Pluto Flyby

Stirling Radioisotope Power & Ion Electric Propulsion

- No launch window constraints, direct, fast trajectories
- Stirling Converter Reduces required number of Pu GPHS bricks

Doubles Payload Power & Mass at Flyby

All Cases:
Atlas IIIb/Star48V
2009 Launch
2020 flyby
Synergistic Benefits of Power & Electric Propulsion
Earth Science: LEO LIDAR Mission

LIDAR Mission & Spacecraft Highlights
- Measure atmospheric wind profiles from 0 to 20 km altitude using a high power laser instrument (LIDAR).
- 5 year life goal, 3 year minimum life
- 450 km, 97° inclination sun sync orbit
- Fixed arrays (instrument pointing req.)
- No propulsion system required
- 875 W payload, 155 W bus
- 1065 kg baseline spacecraft mass

Baseline
Battery: 64 AH NiH₂ IPV (27 Wh/kg)
Array: 16 m² GaAs (15%) (30 W/kg)

Advanced Power
Battery: 59 AH Li (80 Wh/kg)
Array: 10 m² 3j GaAs (24%) (90 W/kg)

Benefits
✓ 24% more payload
✓ Active altitude control
✓ Extended mission life

Advanced Power & Propulsion
Battery: 44 AH Li (80 Wh/kg)
Array: 5.6 m² 3j GaAs (24%)(90 W/kg)
Prop: Solar Electric Hall Thruster

Multi-junction Array Li Battery
350 kg Initial Payload Mass

Additional 74 kg Payload Mass (21% Increase)

Multi-junction Array Li Battery Hall Thrusters

Additional 83 kg Payload Mass
Over baseline (24% Increase)
61% Reduction in Power System Mass
The Relative Importance of Power & Propulsion

Improvements in Power & Solar Electric Propulsion (SEP) will have the *most significant impact* on Launch Mass

Neptune Orbiter Spacecraft
126 kg Dry Mass

- **Structure**: 39%
- **Power**: 16%
- **Instruments**: 13%
- **All other subsystems combined**: 32%

Neptune Orbiter Spacecraft
+ SEP Transfer Stage
1450 kg Launch Mass

- **S/C Wet Mass w/o Power**: 16%
- **S/C Power + SEP Stage (Wet Mass)**: 84%
**Title and Subtitle**
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**Notes**

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**Subject Terms**
Space power; Power generation; Electric propulsion; Energy storage