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

David J. Hoffman
Glenn Research Center, Cleveland, Ohio

July 2001

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SPACE POWER ARCHITECTURES FOR NASA MISSIONS: THE APPLICABILITY AND BENEFITS OF ADVANCED POWER AND ELECTRIC PROPULSION

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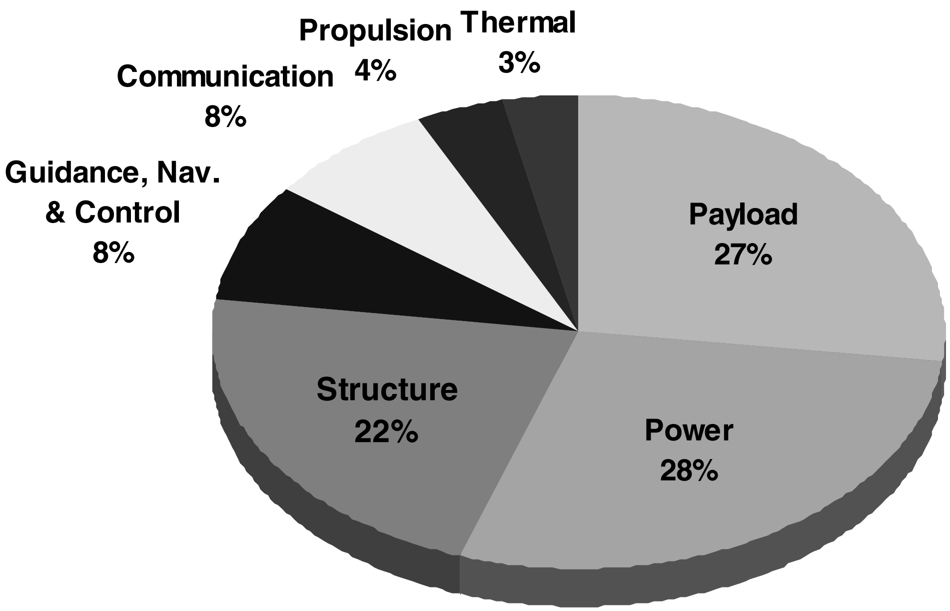
The relative importance of electrical power systems as compared with other spacecraft bus systems is examined. The quantified benefits of advanced space power architectures for NASA Earth Science, Space Science, and Human Exploration and Development of Space (HEDS) missions is then presented. Advanced 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:**

– Clint Ensworth	Regenerative Fuel Cells
– 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.**

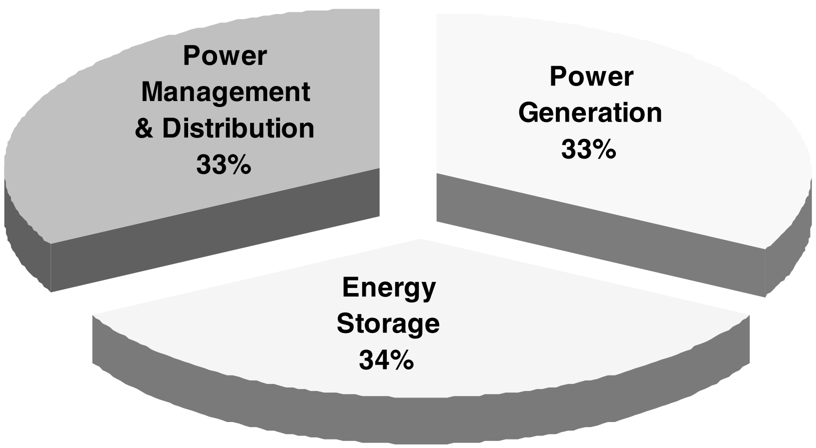
– **Data from "Space Mission Analysis and Design", Wertz & Larson, 3rd Ed., Appendix A.**

➢ **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



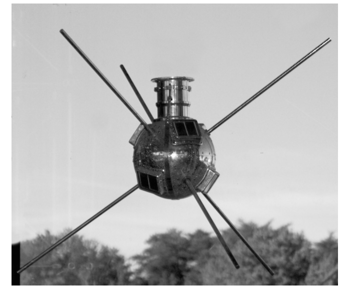
Power generation - required for every mission; advanced technology can be mission enabling.

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.

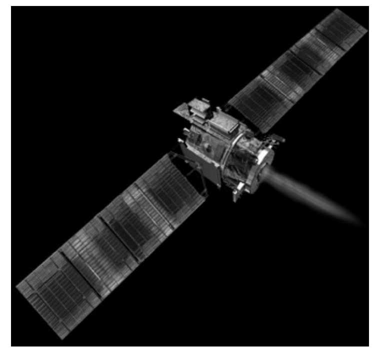
Investments in advanced technology for each power subsystem will benefit the widest variety of missions!

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



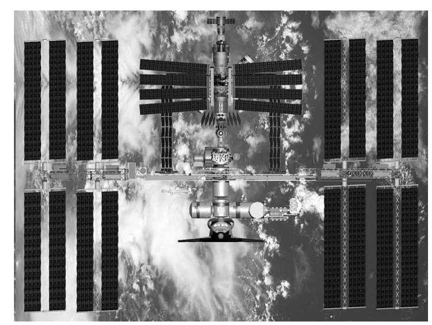
Most Efficient Solar Arrays:

*** Deep Space 1 (1998)**

- 24% multi-junction $GaInP_2$/GaAs/Ge solar cells
- 7x refractor concentrator array (SCARLET)
- 2.5 kW Total Power, 44 W/kg

*** Galaxy XI - Hughes 702 (1999)**

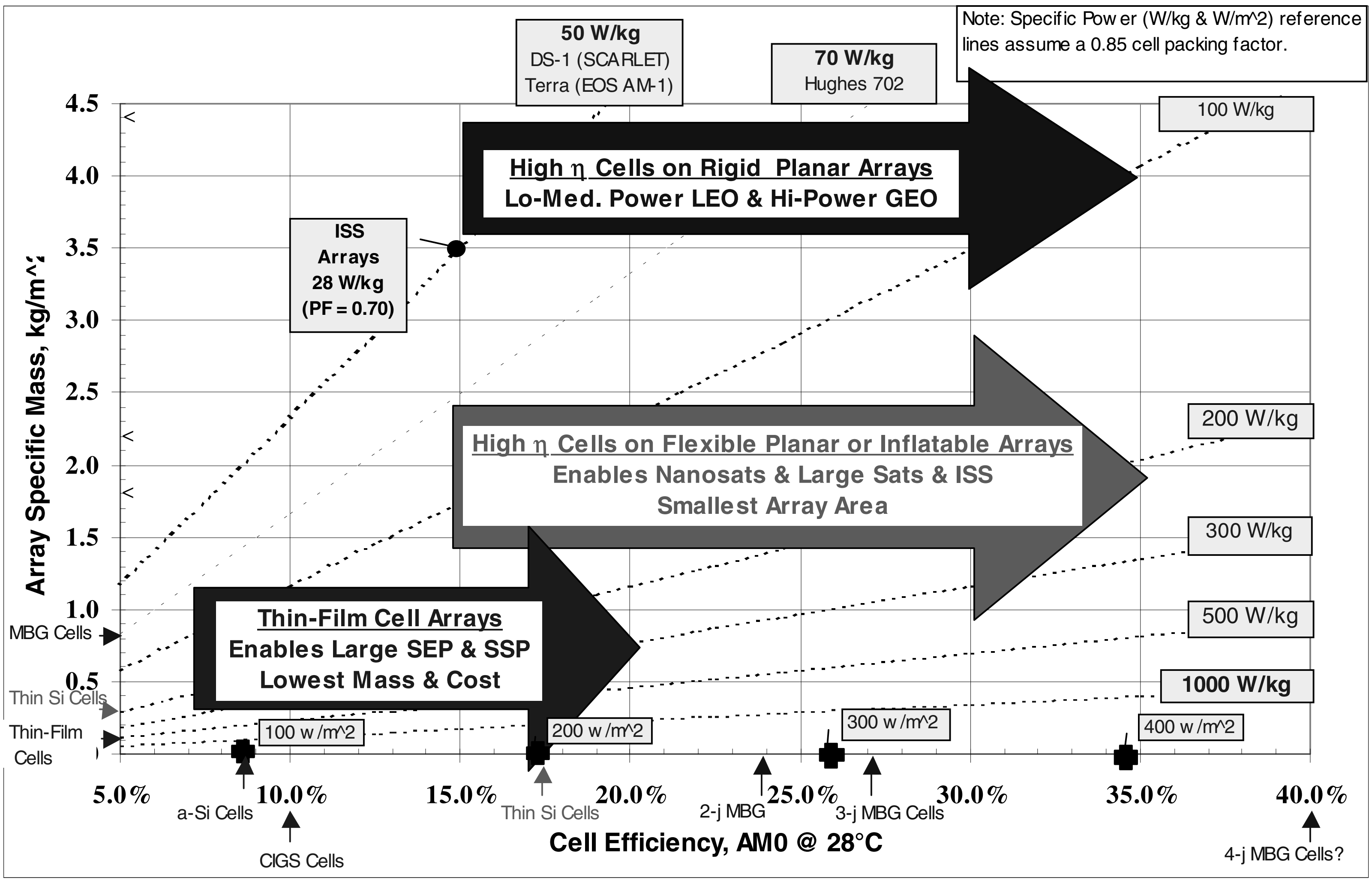
- Two-junction GaAs/Ge solar cells
- 2x trough concentrator array
- 10 kW Total Power, 70 W/kg



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



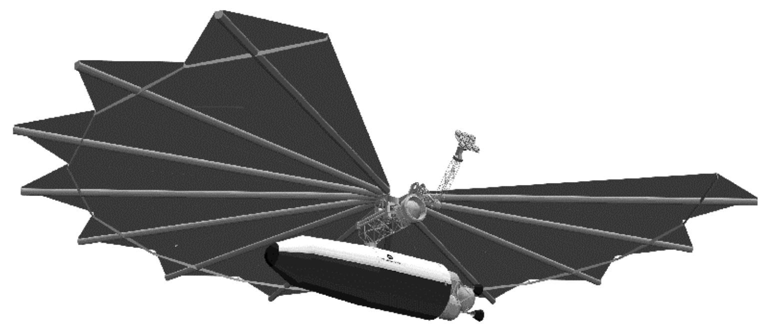
Near Term Thin-Film Application
Europa Orbiter

- **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/m^2) 3x (compared with crystalline cells)**
- **Thin Film PV Issues:**
  - **Full scale array designs**
  - **Demonstrate Rad Tolerance**
  - **Demonstrate LILT Performance**

AEC Able UltraFlex™ Wings
On the Mars 2001 Lander

Far Term Thin-Film Application Humans to Mars

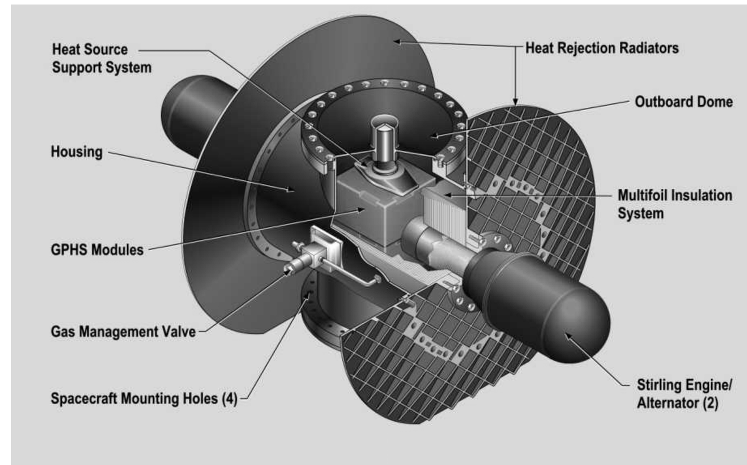
- Multi-Year LEO-ETO-LEO Ops
- High Power (800 kW) Electric Propulsion
  - Array Span of 100+ m
- Rendezvous & Chemical Burn to Mars
- High Radiation Environment
- Power System Launch Mass is the Driver
  - ✓ High-Efficiency (17%) Thin-Film PV on Thin Polymer Substrate ***<u>Enables</u>*** Mission



Stirling Radioisotope Power System

Solar System Exploration Missions

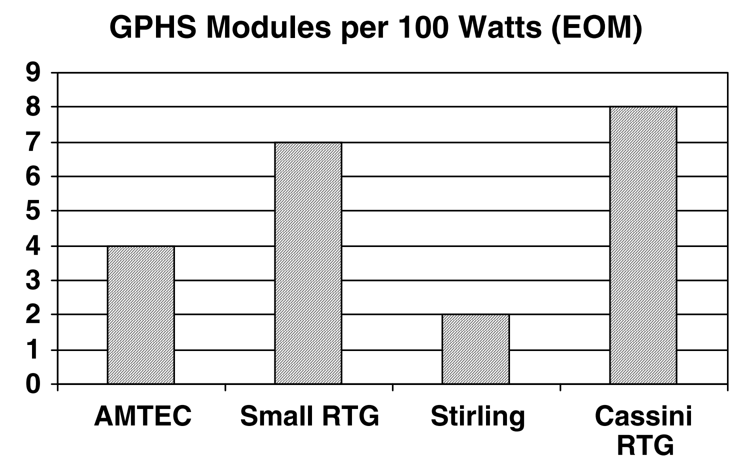
- Mars Landers, Rovers, and Drills
- Europa Orbiter/Lander, Io Volcanic Explorer
- Saturn Ring Explorer, Titan Organic Explorer
- Neptune Orbiter with Triton Flyby
- Venus Lander - Combined Power & Cooling
- Outer Planets/Solar Probe Missions



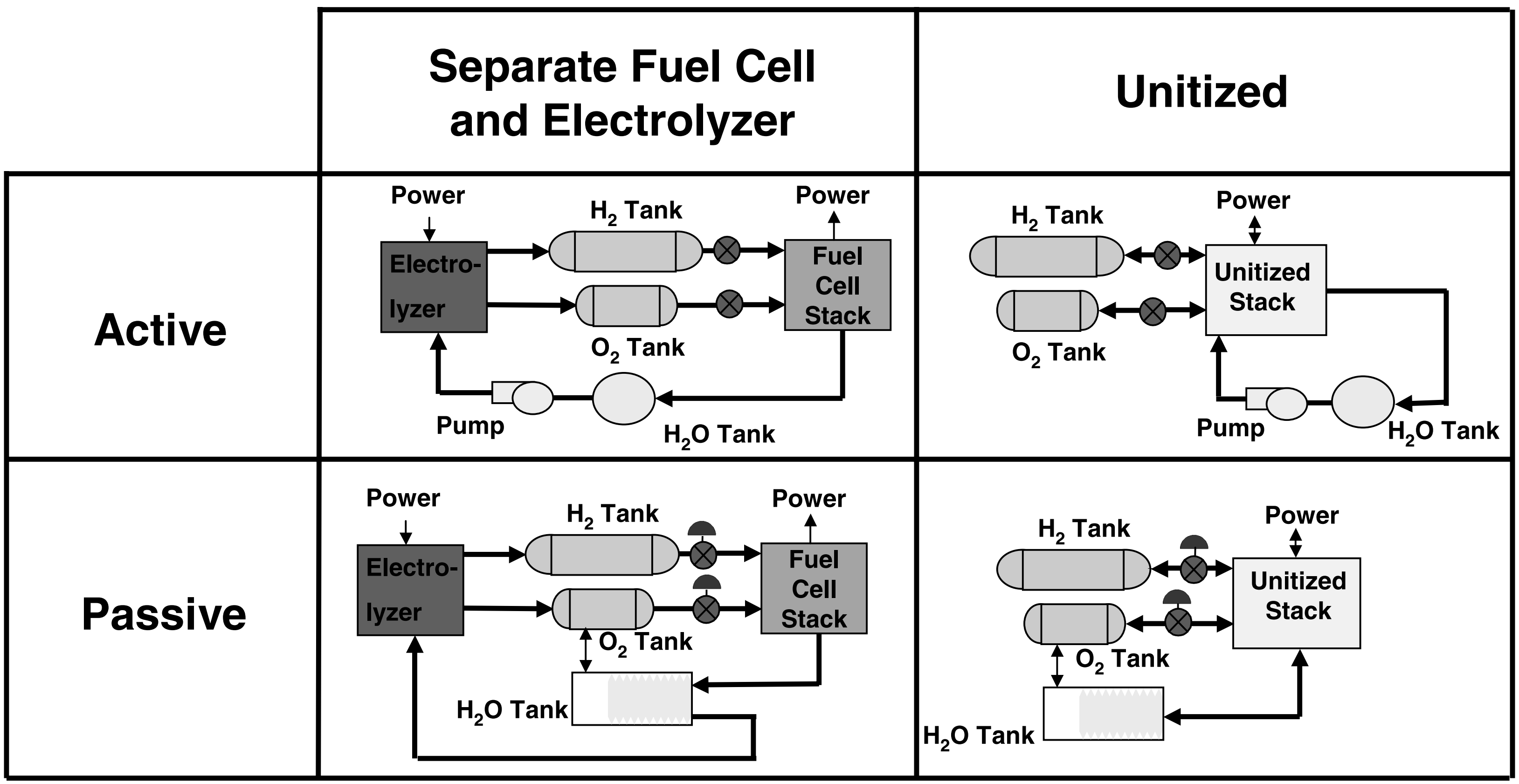
DOE SRPS System Concept

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



Regenerative Fuel Cell (RFC) Types



Benefits of RFC Systems

Benefits of RFC Systems

- **High Specific Energy**
  - Theoretical H_2/O_2 perf.: 3660 Wh/kg
  - Target performance: > 400 Wh/kg
  - Perf. improves as discharge time increases
- **Long Cycle Life of fuel cell & electrolyzer**

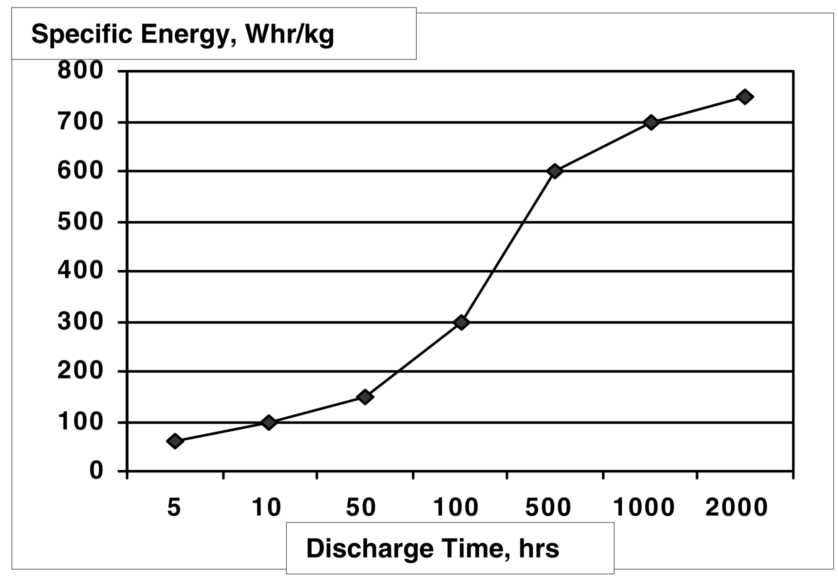
Benefits of Passive RFC Systems

- **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

RFC Mission Applicability

- Un-piloted Aerial Vehicle
- Ultra Long Duration Balloon
- Stratospheric Satellites
- LEO Energy Storage
- Mars Surface Power
- Mars/Lunar Rover
- Lunar Surface Power

Dryden Flight Research Center EC99-45285-6 Photographed NOV1999
The prototype of the Helios solar-electric high-altitude flying wing lands on the lakebed near Dryden. NASA Dryden/Tom Tschida



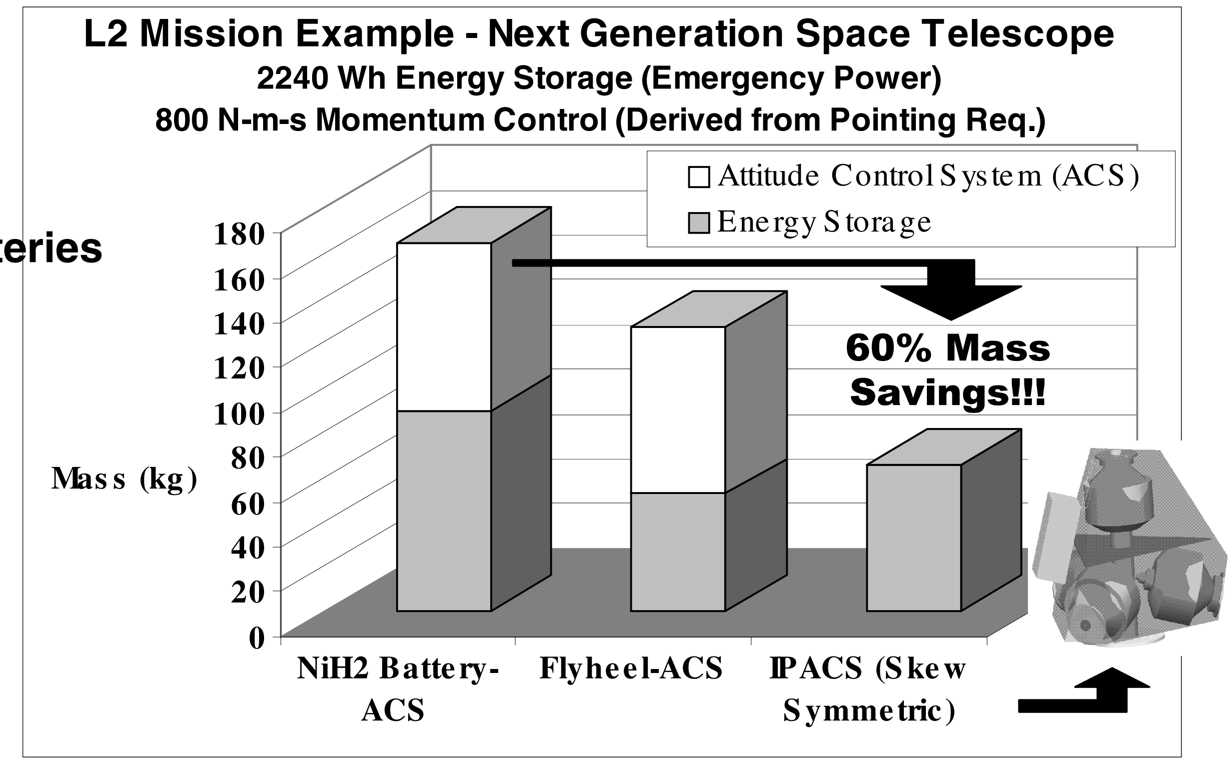
Flywheel Systems Level Benefits

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)

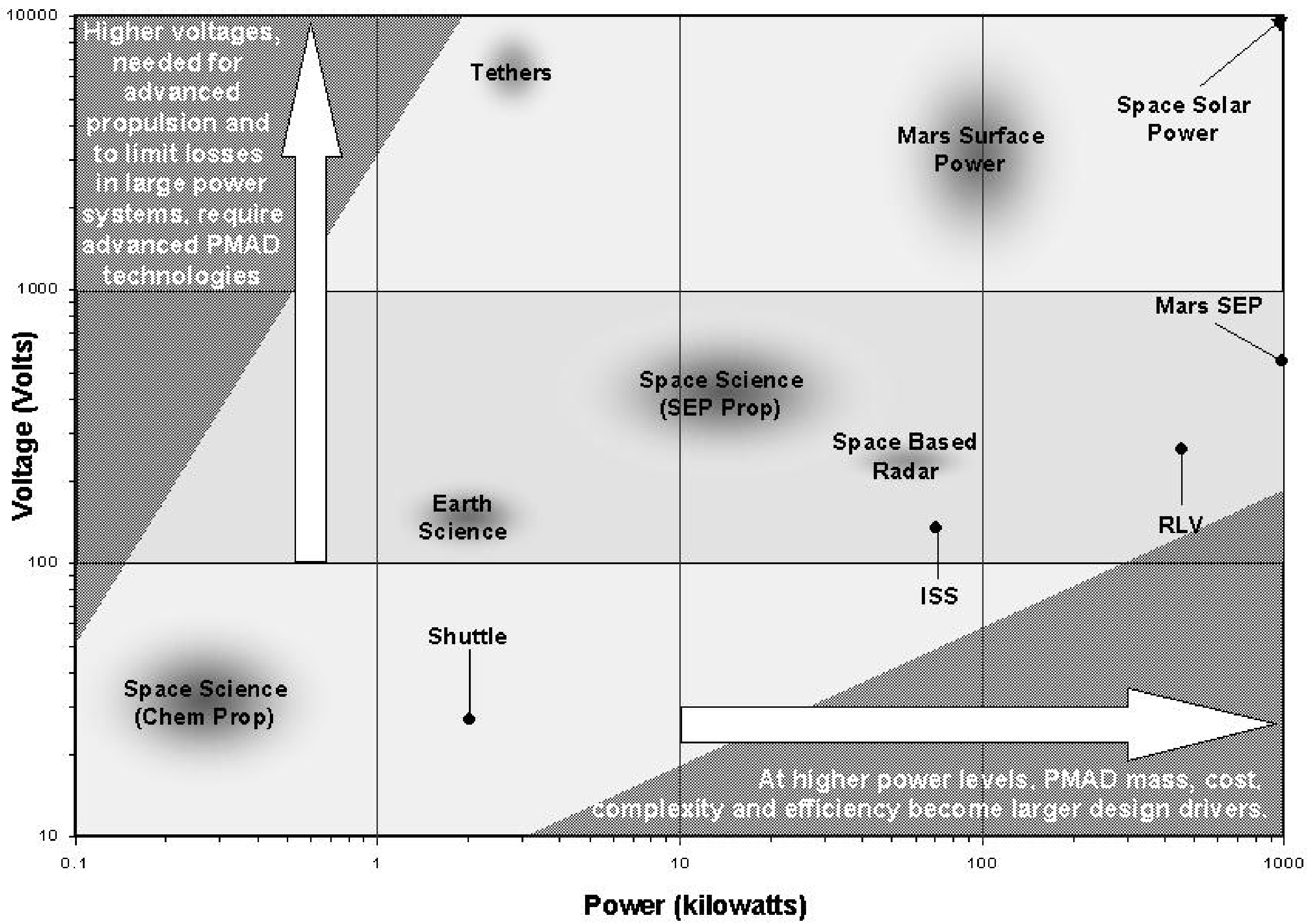
- All of the energy storage benefits, ***plus***…
- Combined Functions - less total hardware



Mission Applicability:

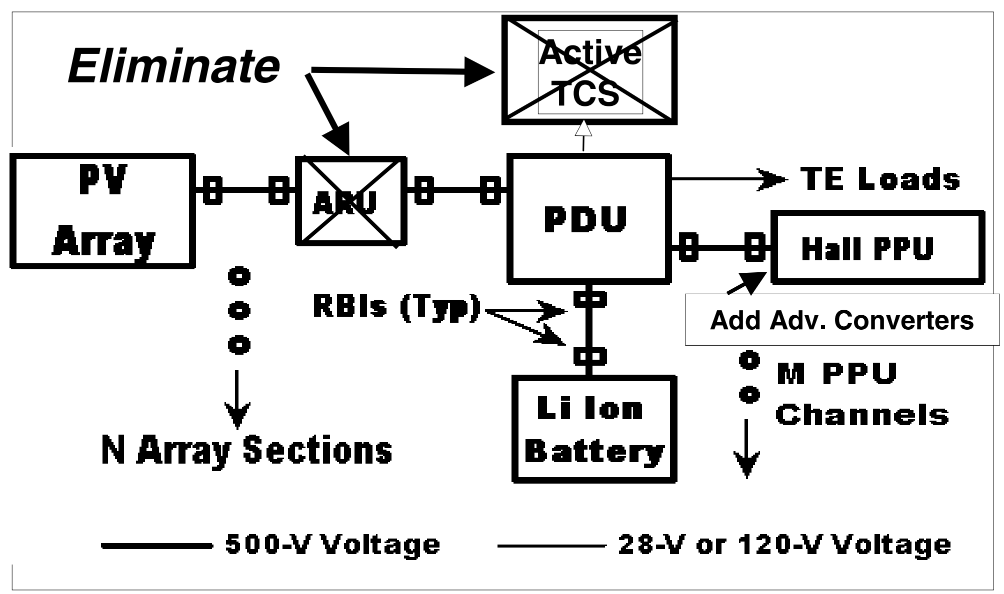
- LEO Spacecraft
- LEO Space Stations
- Peak Power
- Load Leveling
- Large Momentum Control

Power Management & Distribution



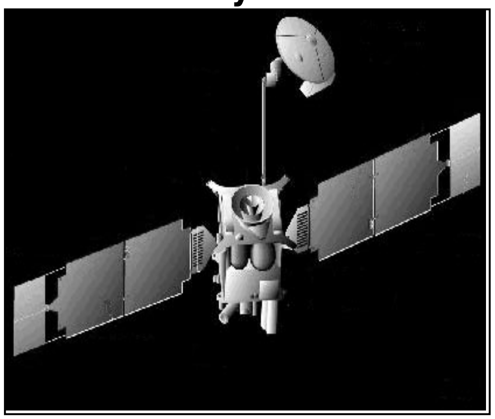
PMAD System Benefits for a MARS SEP Mission

- **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**

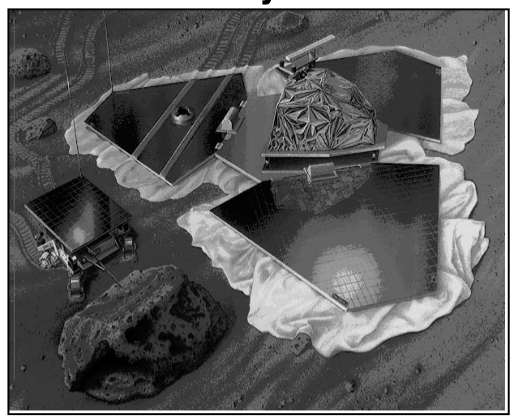


Applications for Advanced Batteries at NASA

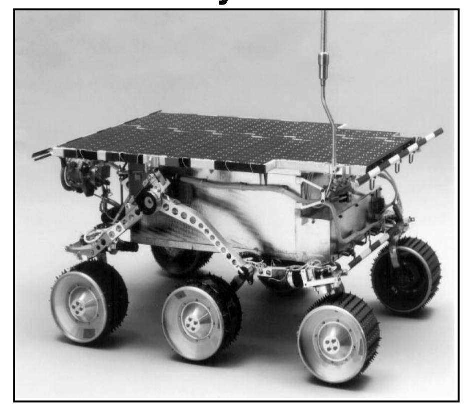
Planetary Orbiters



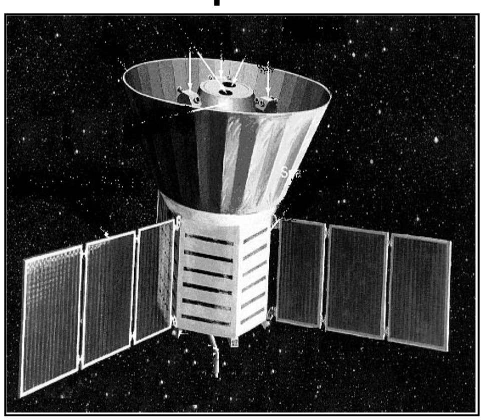
Planetary Lander



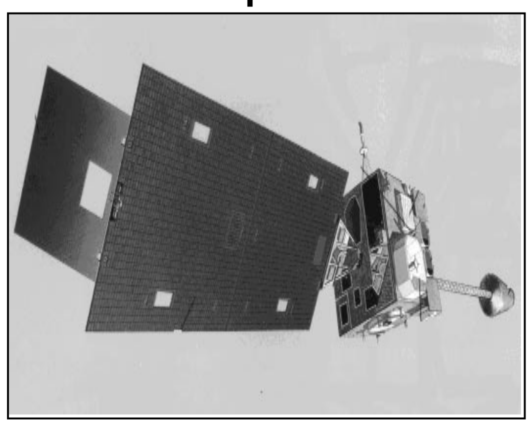
Planetary Rovers



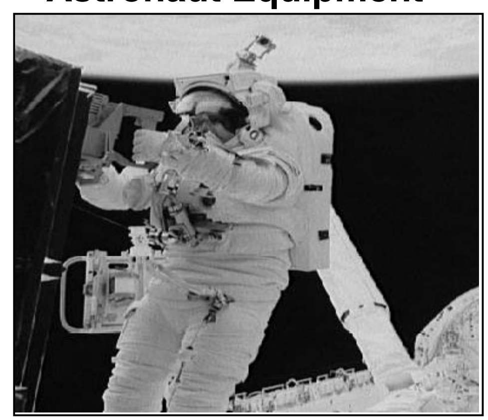
LEO Spacecraft



GEO Spacecraft



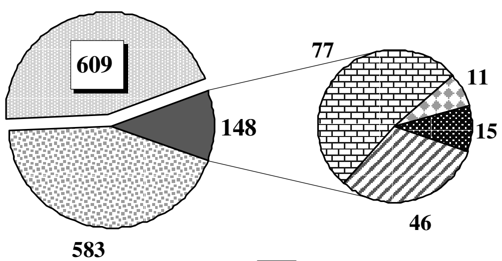
Astronaut Equipment



Benefits of Lithium-Ion Energy Storage

Example Mass Benefits of Adv. Power Generation & Energy Storage Technology as Applied to Far Ultraviolet Spectroscopic Explorer (FUSE) Spacecraft

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

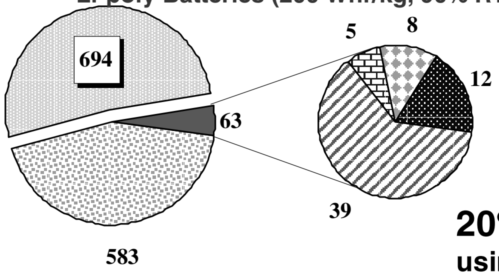


S/C Total dry mass = 1340 kg.
(All values are given in kg.)

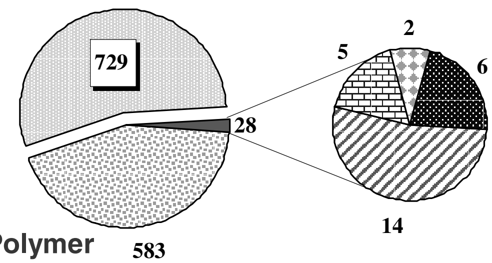
Legend:
- Array & Drive
- Energy Storage
- Thermal Control
- Electronics
- Bal. of Platform
- Payload

14% MORE Payload using Advanced Lithium-Polymer Batteries

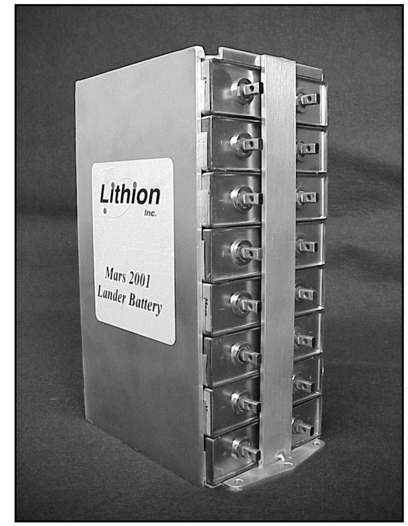
Li-poly Batteries (200 Whr/kg, 90% RT Eff.)



Adv. EPS:
4-J Arrays (35% Eff. Cells, 100 W/kg)
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.



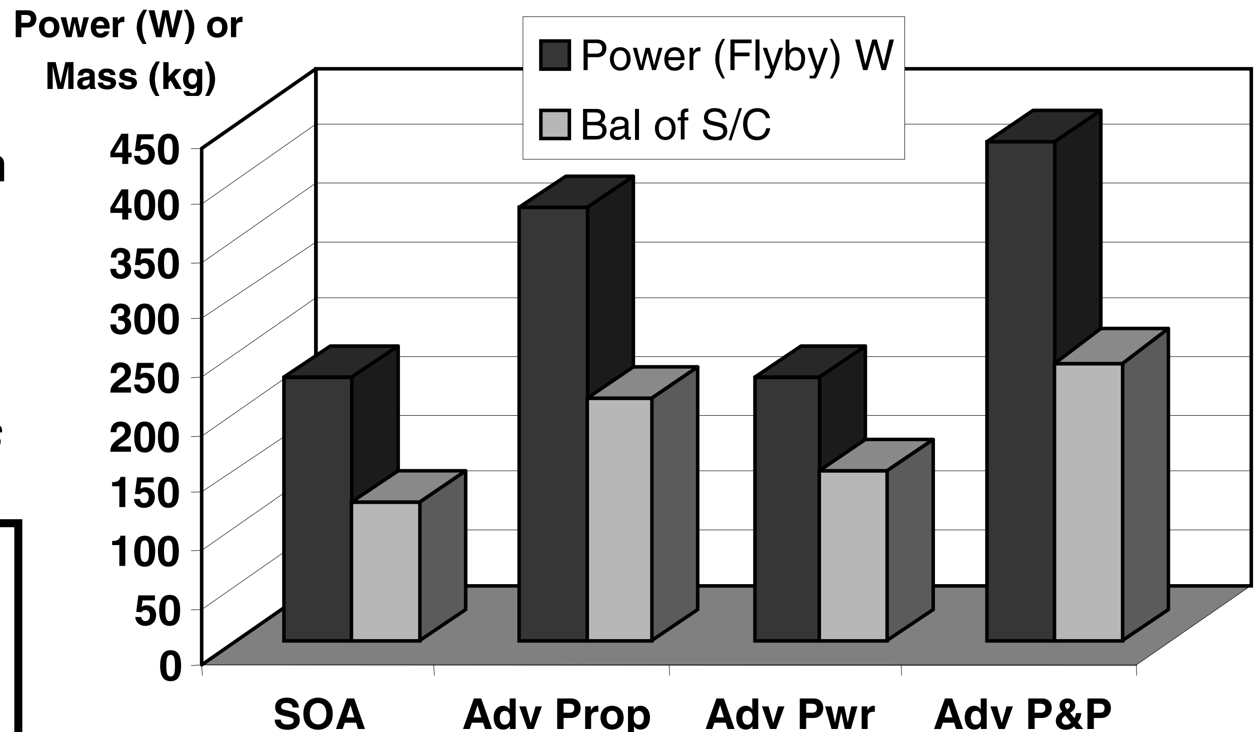
Synergistic Benefits of Power & Electric Propulsion
Space Science: Pluto Flyby

Stirling Radioisotope Power & Ion Electric Propulsion

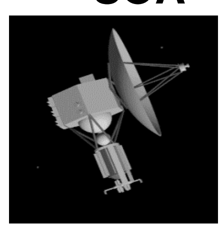
- *No launch window constraints, direct, fast trajectories*
- *Stirling Converter Reduces required number of Pu GPHS bricks*

Doubles Payload Power & Mass at Flyby

All Cases:
Atlas IIIb//Star48V
2009 Launch
2020 flyby

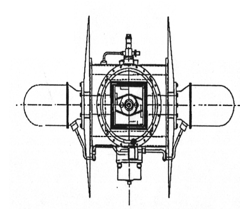


Electric Propulsion and Stirling Radioisotope Converters



Direct RTG

Electric Prop- 8cm Ion thrusters



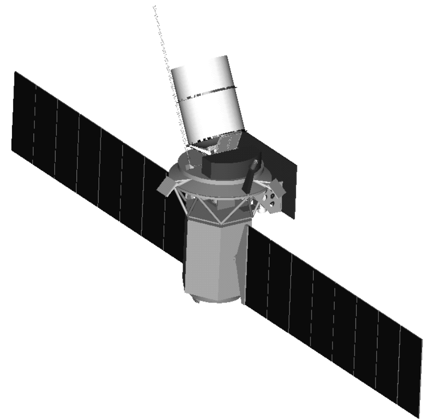
Radioisotope with Stirling Converters

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

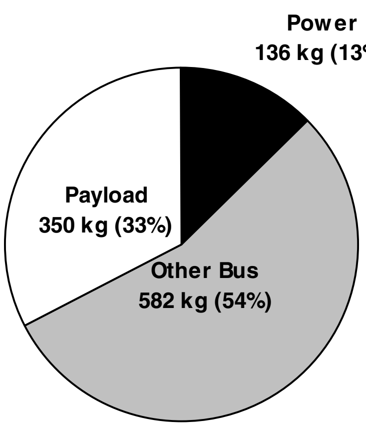


Benefits

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

Baseline

Battery: 64 AH NiH_2 IPV (27 Wh/kg)
Array: 16 m^2 GaAs (15%) (30 W/kg)

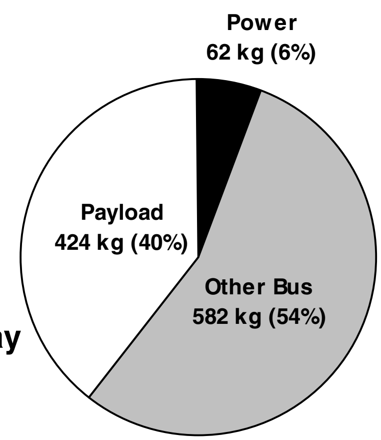


350 kg Initial Payload Mass

Multi-junction Array
Li Battery

Advanced Power

Battery: 59 AH Li (80 Wh/kg)
Array: 10 m^2 3j GaAs (24%) (90 W/kg)

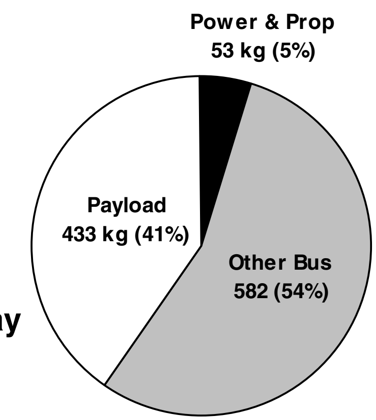


Additional 74 kg Payload Mass
(21% Increase)

Multi-junction Array
Li Battery
Hall Thrusters

Advanced Power & Propulsion

Battery: 44 AH Li (80 Wh/kg)
Array: 5.6 m^2 3j GaAs (24%)(90 W/kg)
Prop: Solar Electric Hall Thruster

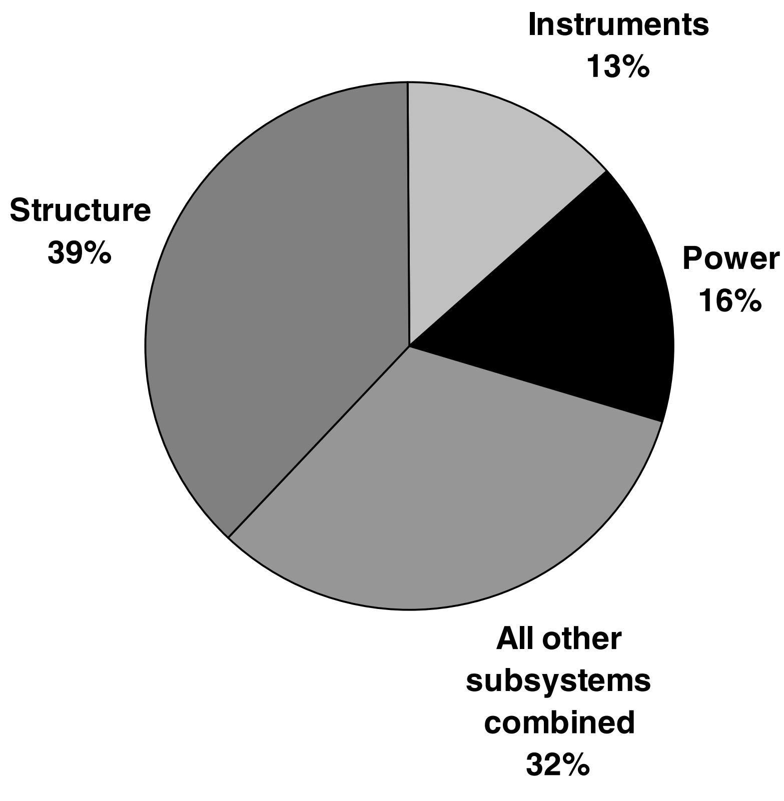


Additional 83 kg Payload Mass
Over baseline (24% Increase)
61% Reduction in Power System Mass

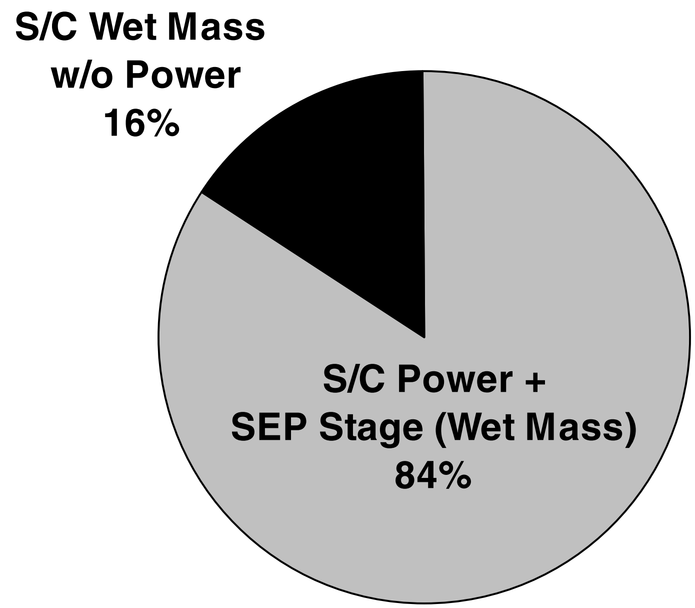
The Relative Importance of Power & Propulsion

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

Neptune Orbiter Spacecraft
126 kg Dry Mass



Neptune Orbiter Spacecraft
+ SEP Transfer Stage
1450 kg Launch Mass



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