Overview of the Space Power Conversion and Energy Storage Technologies

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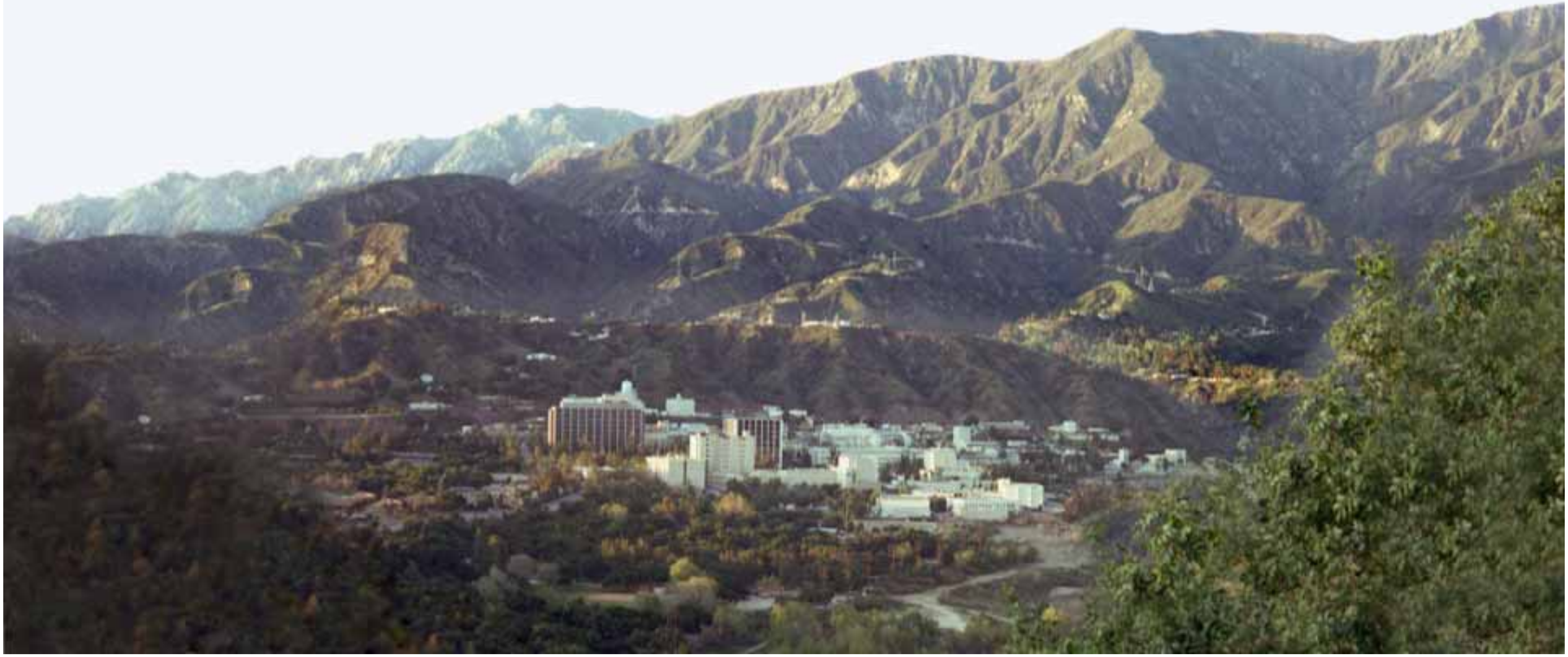


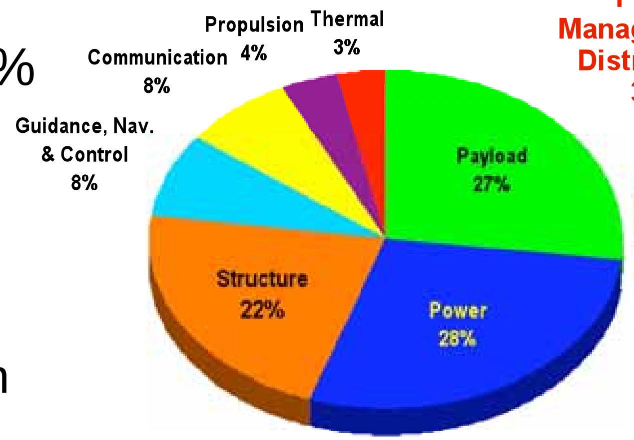
Outline

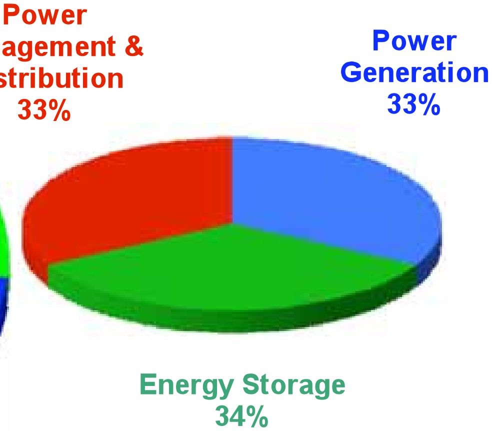
- Overview of Potential Future Missions
- Power Technology Challenges
- Radioisotope Power Source Technology
- Solar Cell and Array Technology
- Energy Storage Technology
- Summary

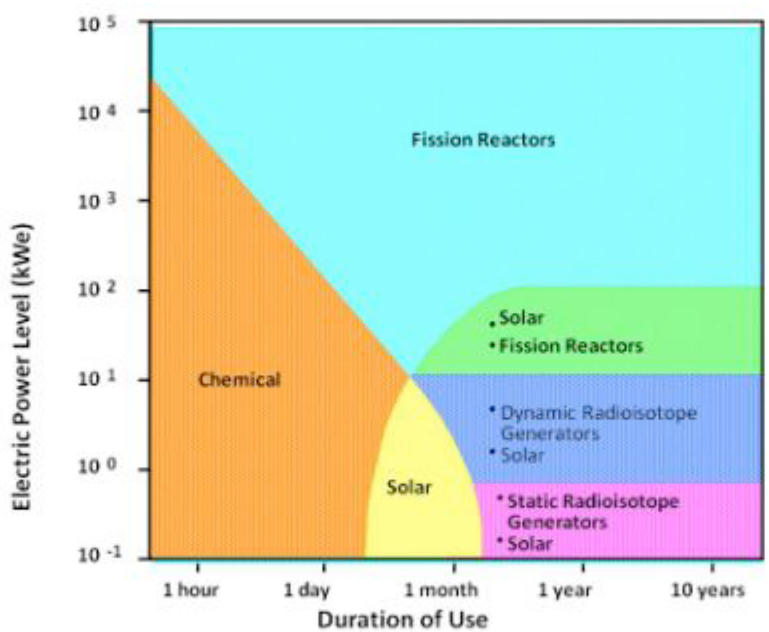
Power Technology Challenges

Space Power Technology Area Overview

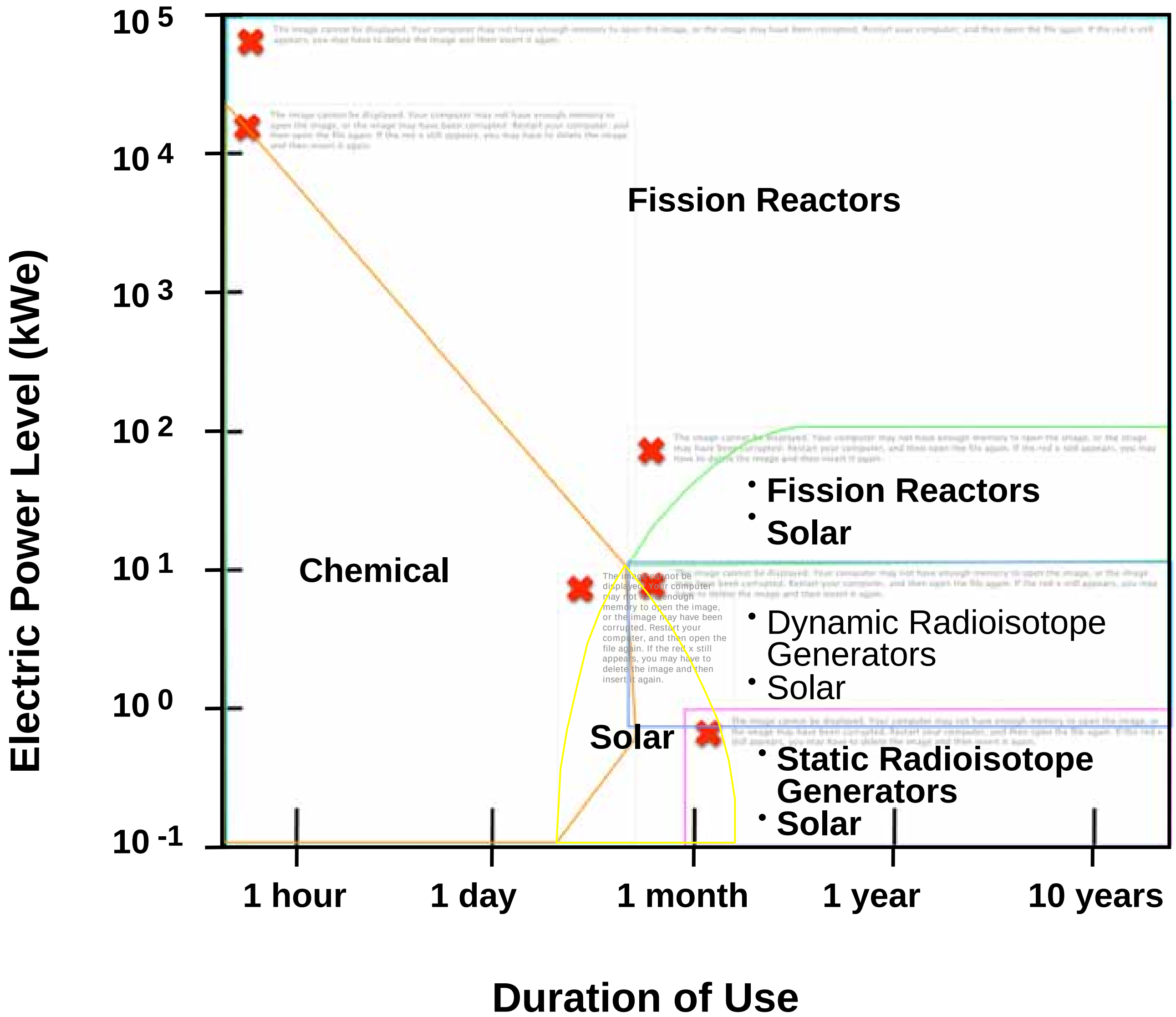
- Power system is 20-30% of spacecraft mass and costs 20% of the spacecraft budget.
- The major power subsystems are:
  - Power Generation/Conversion
  - Energy Storage
  - Power Management and Distribution
- Space missions need a variety of power solutions
  - Solar power systems
  - Nuclear power systems
  - Batteries
  - Fuel Cells
  - New Technology





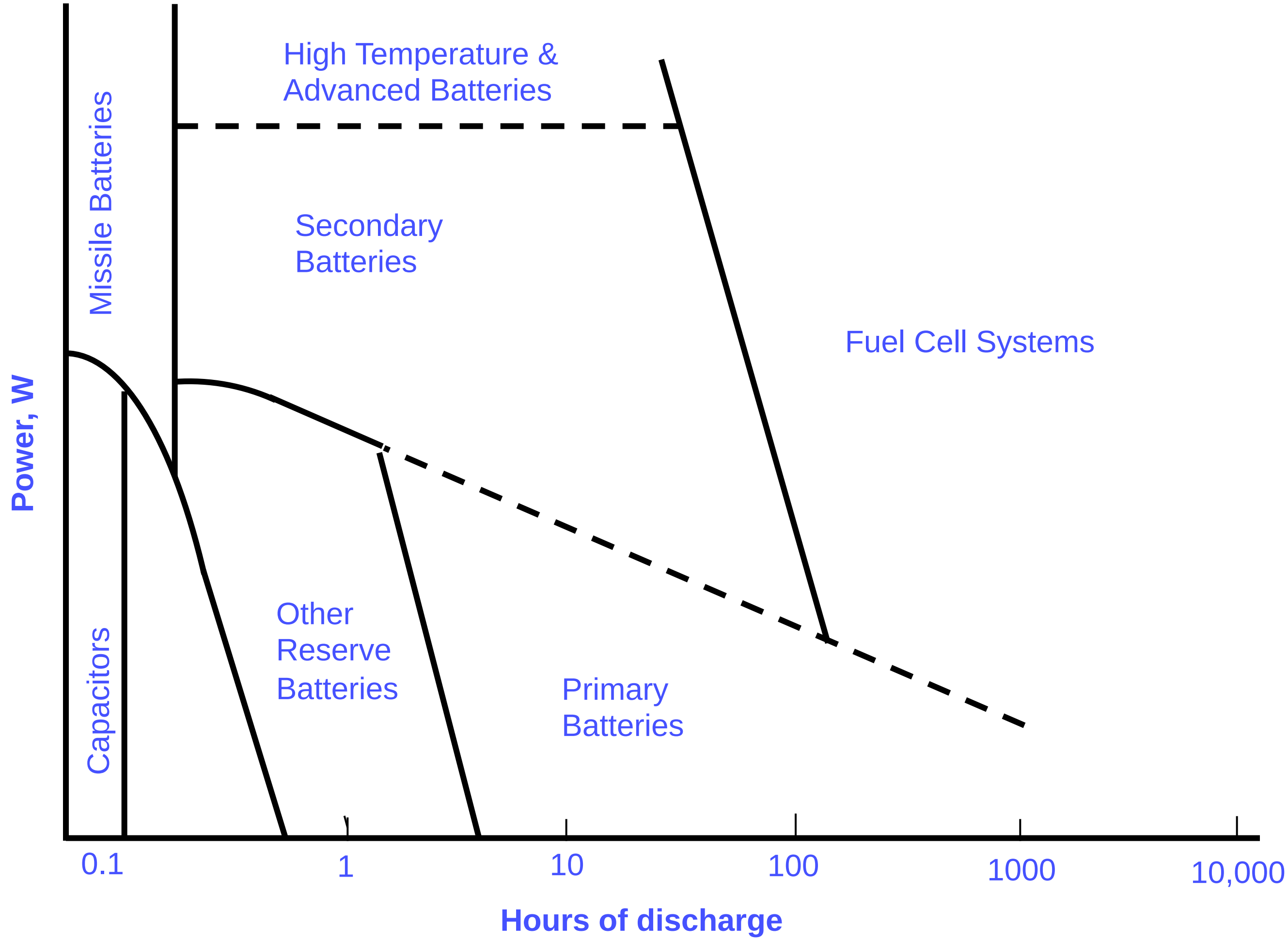


Operational Envelope of Power Conversion Technologies



Space missions need a variety of power solutions (solar cells, radioisotope power sources, nuclear reactor, batteries)

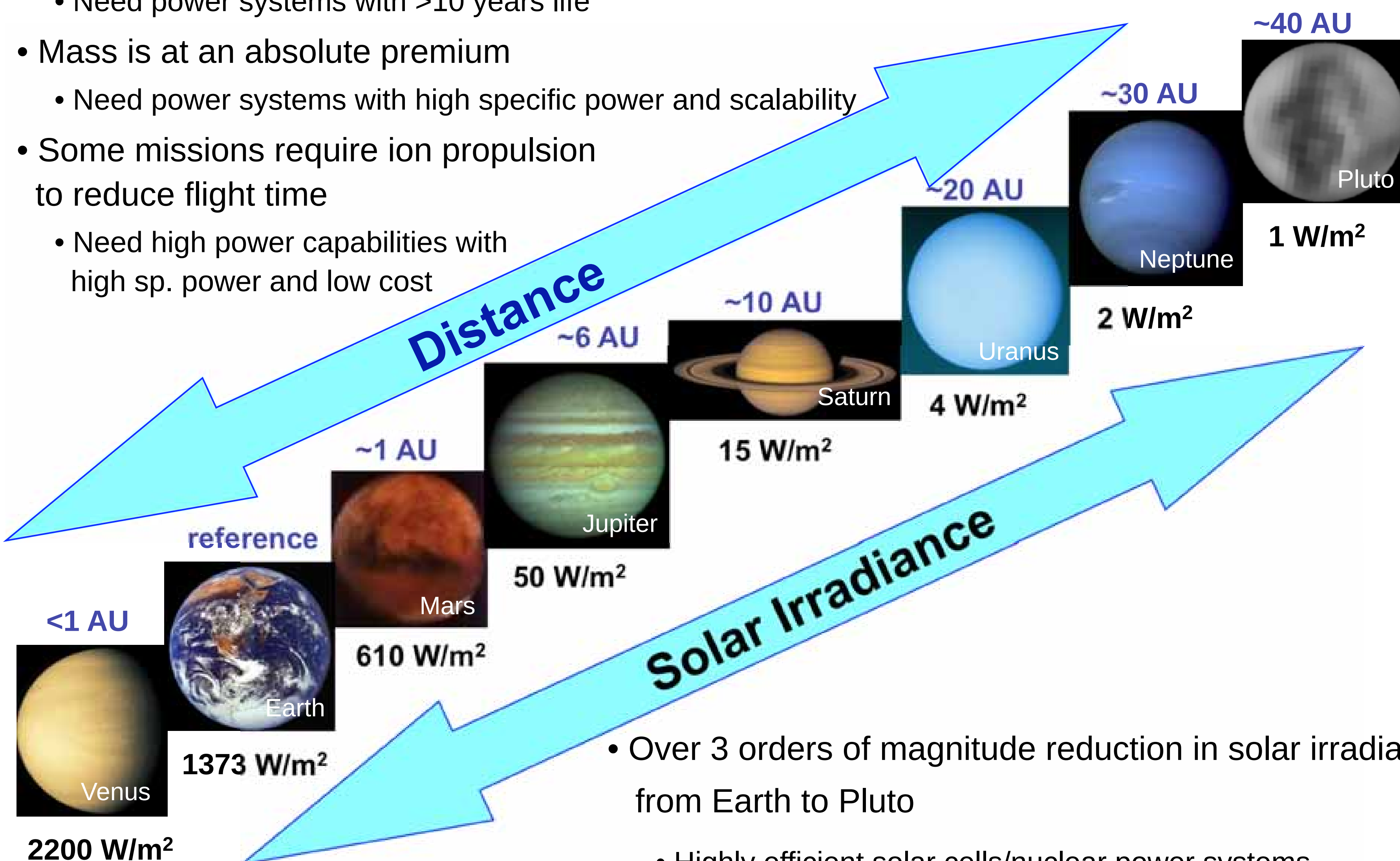
Performance Envelope of Electrochemical Power Sources



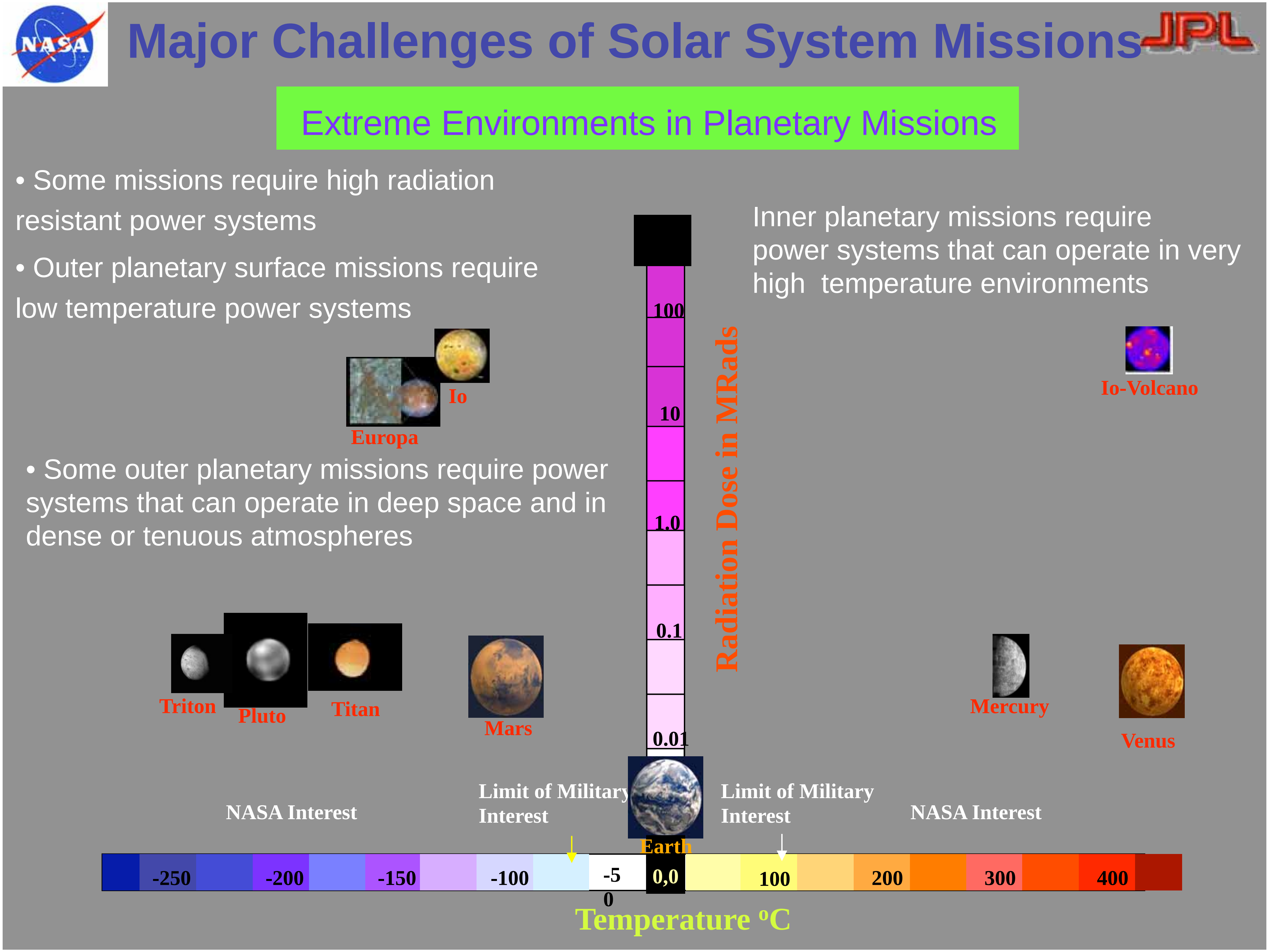
Service life dictates the choice of energy storage technology

Major Power Challenges of Solar System Missions

- Flight times are long
  - Need power systems with >10 years life
- Mass is at an absolute premium
  - Need power systems with high specific power and scalability
- Some missions require ion propulsion to reduce flight time
  - Need high power capabilities with high sp. power and low cost

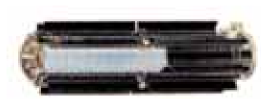


- Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
  - Highly efficient solar cells/nuclear power systems



NASA
Major Challenges of Solar System Missions
JPL
Extreme Environments in Planetary Missions
• Some missions require high radiation resistant power systems
• Outer planetary surface missions require low temperature power systems
Inner planetary missions require power systems that can operate in very high temperature environments
• Some outer planetary missions require power systems that can operate in deep space and in dense or tenuous atmospheres
Io
Europa
Io-Volcano
Radiation Dose in MRads
100
10
1.0
0.1
0.01
Triton
Pluto
Titan
Mars
Mercury
Venus
Earth
NASA Interest
Limit of Military Interest
Limit of Military Interest
NASA Interest
-250
-200
-150
-100
-5
0
0,0
100
200
300
400
Temperature ºC

SOP Technology Capabilities

Technology Element	Capability
Power System	Direct Energy Transfer Shunt Regulator/Radiator 0.5 to 20 kW, 28- 120 V dc
Power Electronics	 22- 120 V dc -55 to 75C, up to a 1Mrad > 85% converter efficiency
Radioisotope Power Sources	 GPHS RTG 4-5 W/kg 6.5 % eff
Solar Cells	 Si cells 9-15% eff , TJ Cells 24-26% Rigid Panel 30-40 W/kg Flexible Fold Out Array : 40-60 W/kg
Rechargeable Batteries	 Ni-H_2 30-100 Wh/kg >30,000 Cycles (30% DOD) >10 years -10 to 30 C

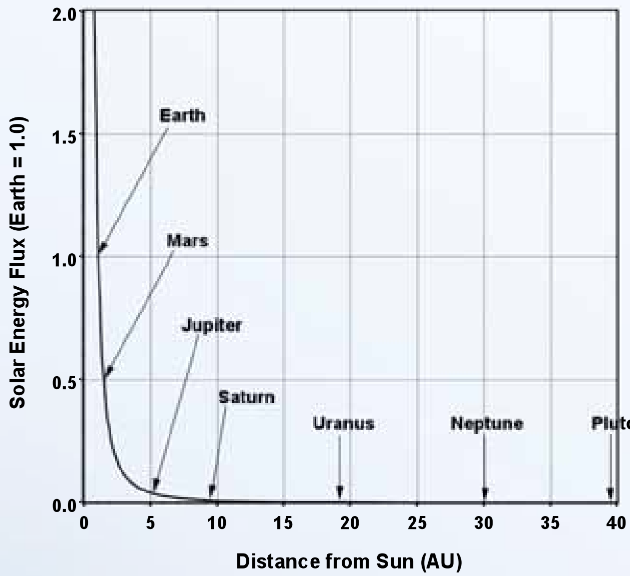
Power System Technology Challenges

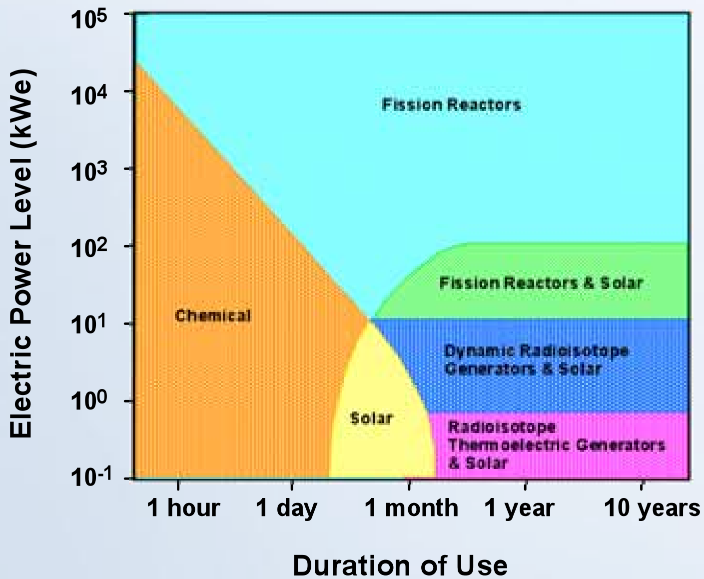
- Power systems that provide significant mass and volume savings (3-4 x SOP)
  - High specific power solar arrays (500 W/kg, 2kg/kW)
  - High specific mass nuclear power systems (>5 kg/kW)
  - High specific energy batteries (500 Wh/kg)
  - High specific power fuel cells (400 W/kg)
- Power systems with high voltage (100-1000 V) high power (100 kW- 5 MW) capabilities.
  - High Voltage & High Power Solar Arrays (1000 V; >100 kW)
  - Nuclear fission (2 kWe; 40 kWe; > 1 MWe Power Systems)
  - Aneutronic fusion power system (>50 MW)
  - High Voltage & High Power PMAD (100-1000 V; 10 kW-1 MW)
- Power systems with operational capability in extreme space environments
  - Extreme Temperatures (-100 to 450^{o}C)
  - High radiation environments (5 MRAD)
  - Dusty environments
- Power systems with long life capability (> 30 years), high reliability and safety

Radioisotope Power Systems

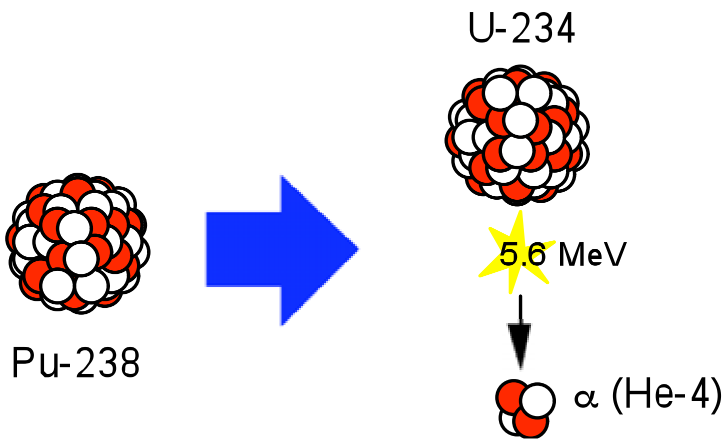
Why Radioisotope Power Systems?

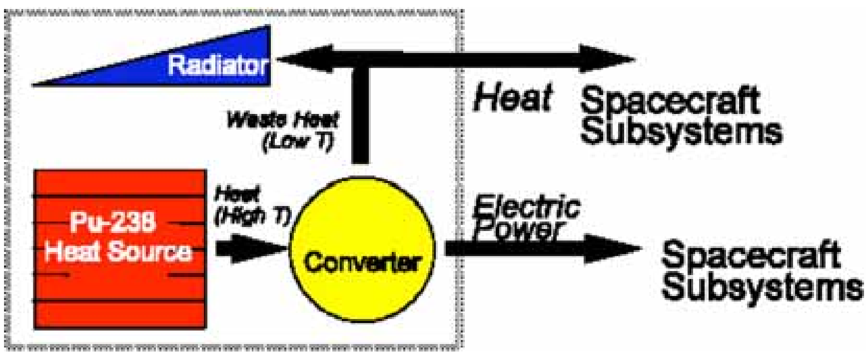
- Provide power for deep space missions where there is little or no available solar energy
- Provide power for long duration surface and subsurface exploration missions where solar power not readily or continuously available (lunar polar craters, high Martian latitudes)
- Provide power for planetary nuclear electric propulsion systems to remove dependency on gravity assists





Radioisotope Power Systems





RPS Functional Diagram

Contains:

1. Radioisotope heat source
   - General Purpose Heat Source

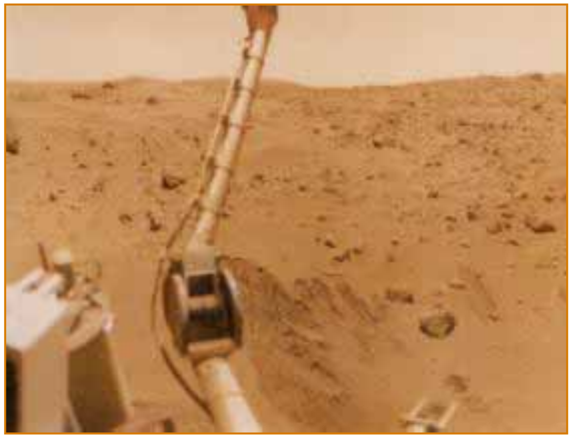
2. Power converter
   - Thermoelectric
   - Stirling
   - TPV

3. Radiator
   - Passive
   - Active

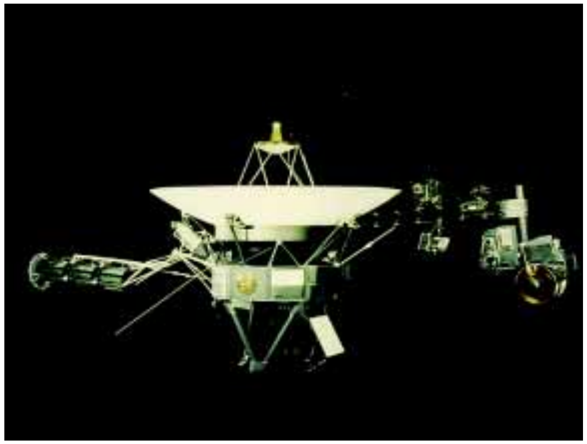
Thermal energy from a radioisotope source is converted to electrical energy

Past NASA RTG Powered Missions

Apollo

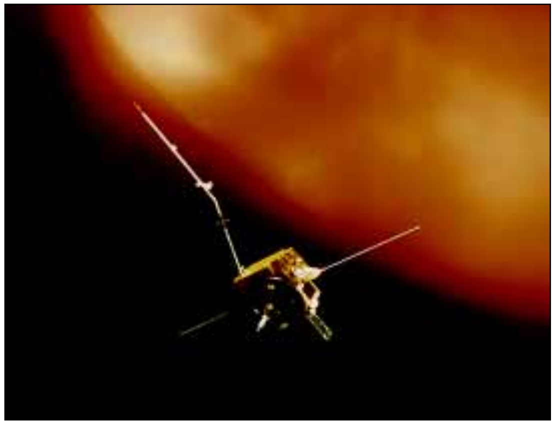


Viking



Voyager

Galileo



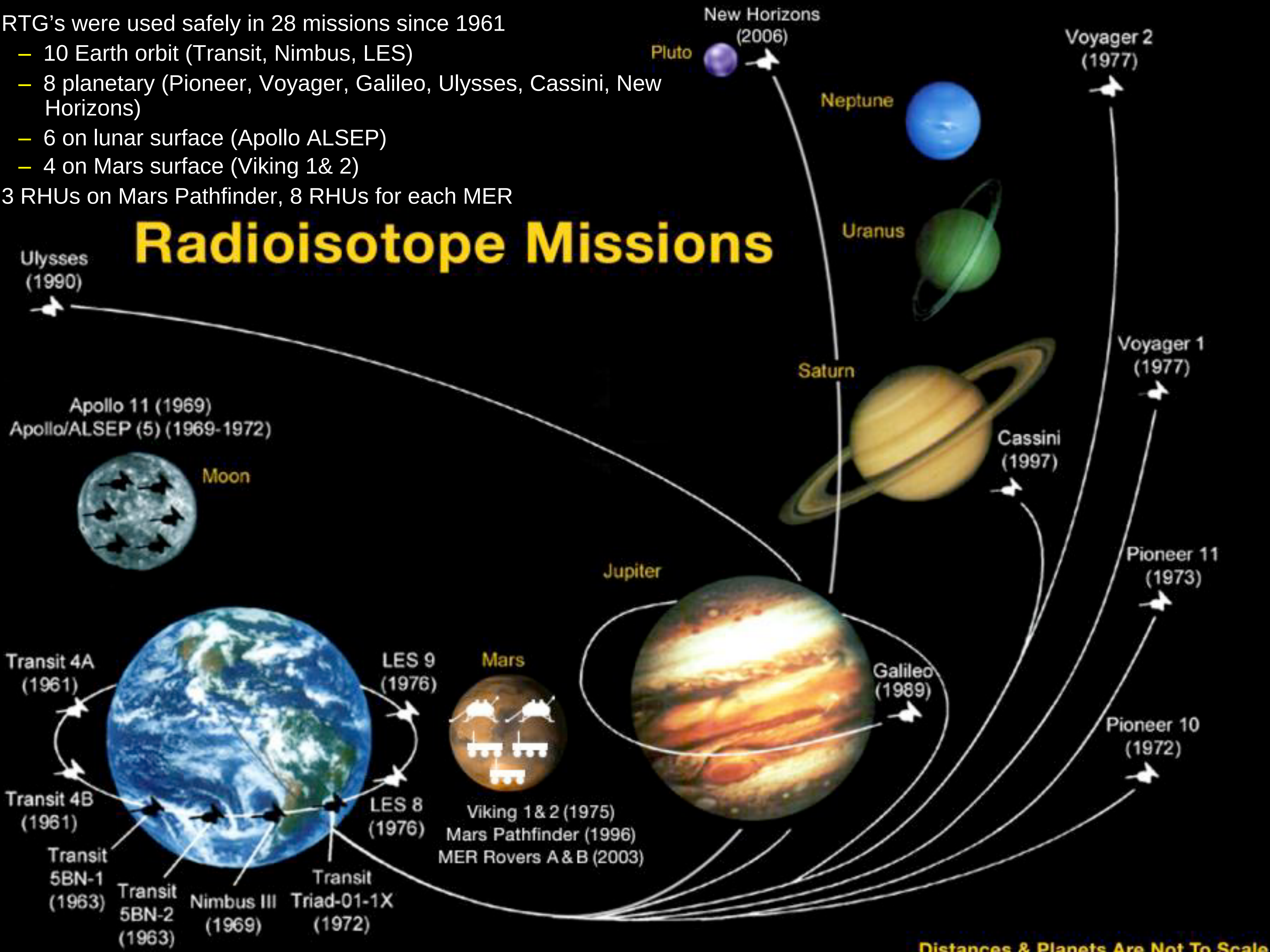
Ulysses

Cassini

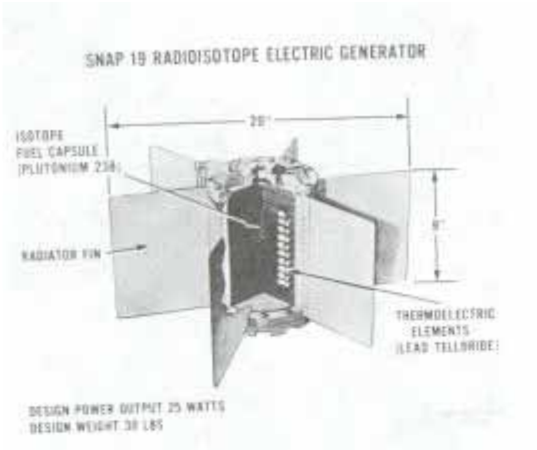
Since 1961, 46 RTGs have been used on 26 US space systems.

- RTG's were used safely in 28 missions since 1961
  - 10 Earth orbit (Transit, Nimbus, LES)
  - 8 planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
  - 6 on lunar surface (Apollo ALSEP)
  - 4 on Mars surface (Viking 1& 2)
- 3 RHUs on Mars Pathfinder, 8 RHUs for each MER

Radioisotope Missions



Radioisotope Thermoelectric Generators Used In Space Missions



SNAP-19(PbTe RTG)
(1960-70's)

40.3 Watts (BOM)
6.2 % efficiency
3 We/kg

22.86 cm (9.0 in) long
50.8 cm (20 in) dia
~13 kg (28.6 lb)
PbTe Thermoelectrics

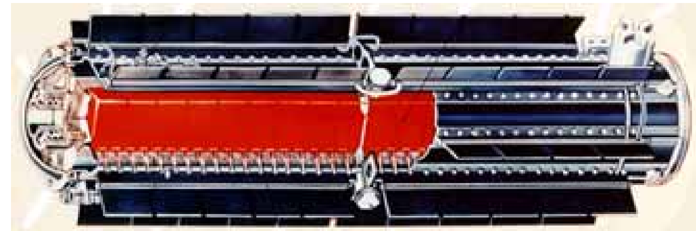
Nimbus B-1/III, Pioneer 10/11, Viking 1/2

SiGe MHW RTG
(1970's)

158 We (BOM)
6.6 % efficiency
4.2 We/kg

58.4 cm (23 in) long
39.7 cm (15.64 in) dia
38 kg (83.7lb)
SiGe Thermoelectrics

LES 8/9, Voyager 1/2



SiGe GPHS RTG
(1980-2006)

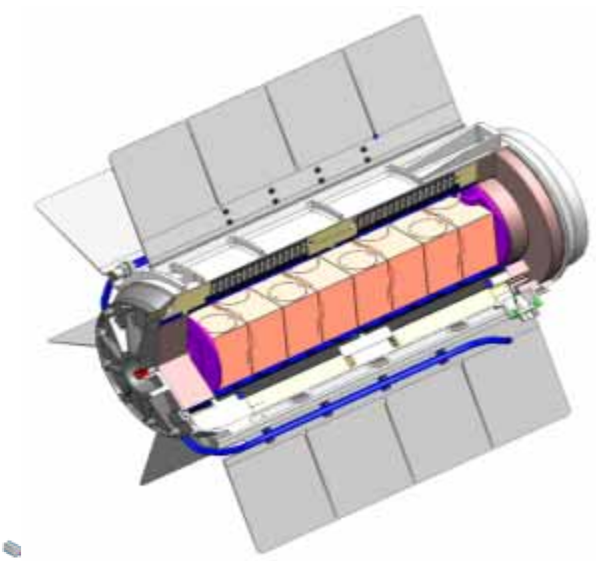
285 We (BOM)
6.8% efficiency
5.1 We/kg

114 cm (44.9 in) long
42.7cm (16.8in) dia
56 kg (123 lb)
SiGe Thermoelectrics

Galileo, Ulysses, Cassini & New Horizons

Limitations: Low Specific Power & Low Efficiency

100 We Class RPS Under Development



- Multi-Mission RTG (MMRTG)
  - Specfic Power: 2.8 We/kg
  - System efficiency: 6.3%
  - Design Life: 14 Years + Storage
  - Power BOM/14 years: 125 We/100 We
  - Environments: Deep space, Planetary
  - Under development to support 2009 first launch

- Stirling Radioisotope Generator (SRG)
  - Specific Power: ~ 6 We/kg
  - System efficiency: 30%
  - Design Life: 14 Years + Storage
  - Power BOM: 130 We
  - Environments: Deep space, Planetary
  - Under development to support 2015 first launch

The Evolution Of Radioisotope Power Systems

MHW-RTG

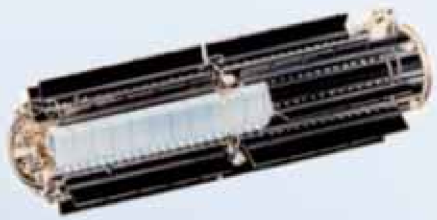
TRL 9-10

158 We
4.2W/kg
6. 6% Efficiency
> 14 Year life

- LES 8/9, Voyager 1 & 2

GPHS-RTG

TRL 9-10



283We
5.1 W/kg
6. 8% Efficiency
> 14 Year life

- Ulysses, Gallileo, Cassini, New Horizons

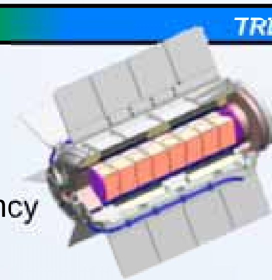
SNAP-19

TRL 9-10

40 We
3 W/kg
6. 2% Efficiency
➢14 Year life
➢Viking 1 & 2 (8/20/75)

TRL 5-6 → *TRL 7-8*

MMRTG △
125 We
2.8 W/kg
6.3% Efficiency
- MSL



TRL 1-2 → *TRL 3* → *TRL 4*

ARTG △
6-8 W/kg
8-10% efficiency

TRL 3-4 → *TRL 5*

△ **ASRG**
7 W/kg
28% efficiency

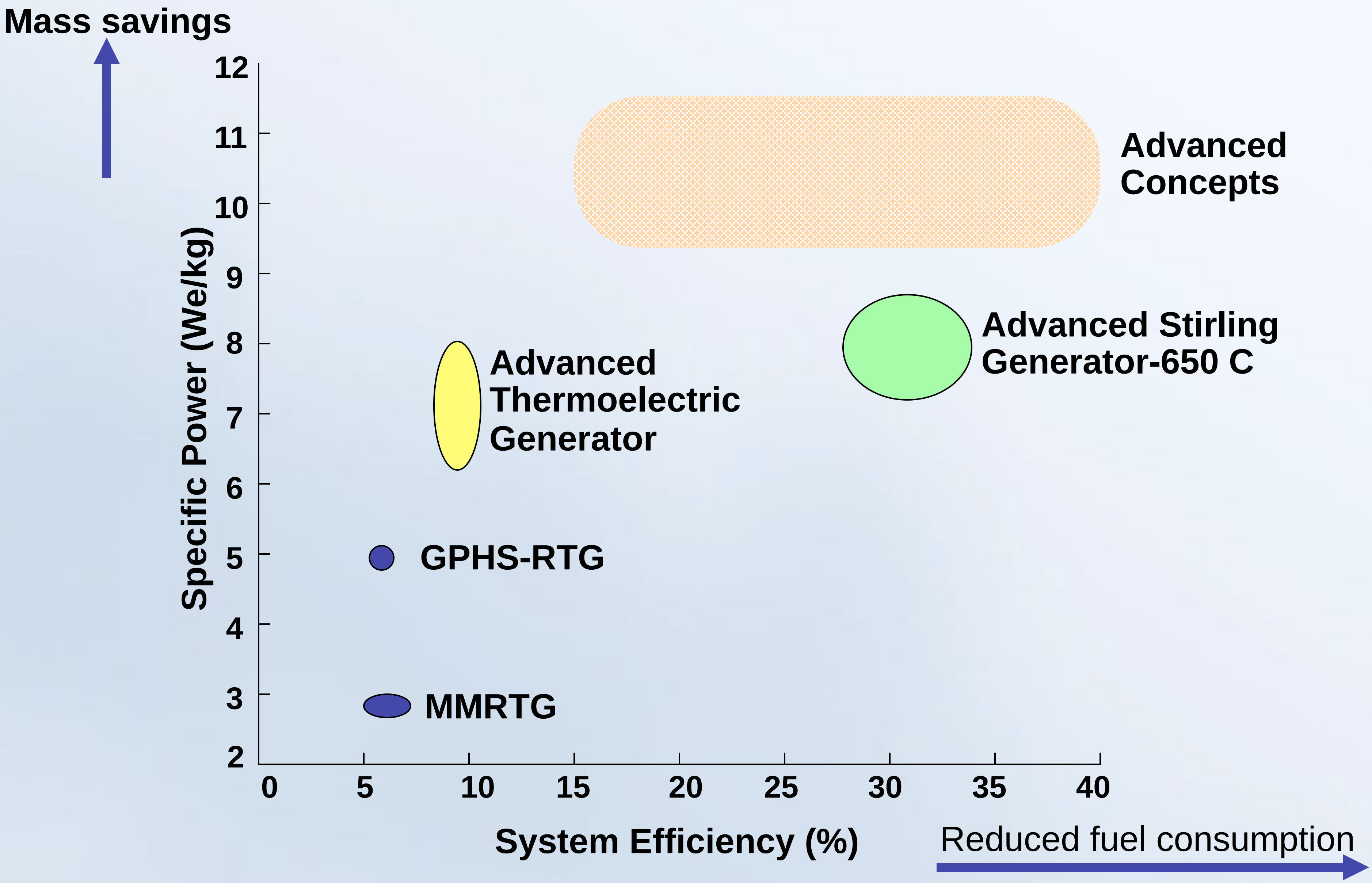
1970 | 1980 | 1990 | 2000 | 2004 | 2006 | 2007 | 2010

NOTE: Graphics not to Scale

Summary of Future Space Science Mission Needs For Radioisotope Power Systems

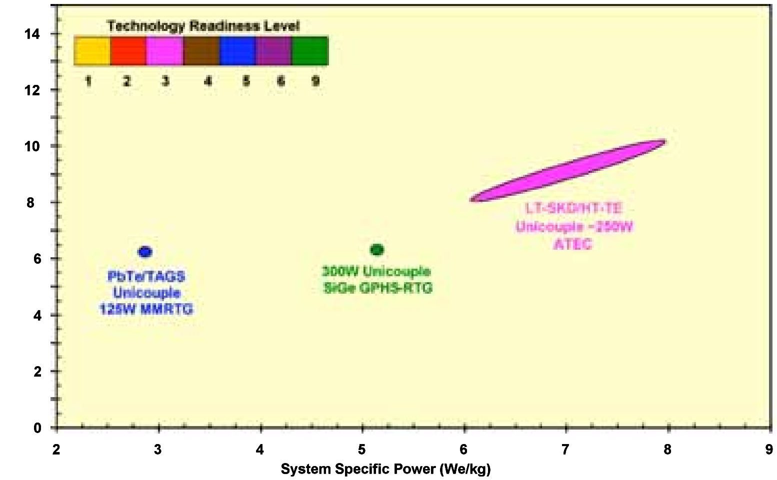
- Need 100-300 Watt Class RTG Modules
  - Future missions are smaller in size and require lower power
- Low Mass
  - High Specific Power 8-10 W/kg (2 X SOA SiGe RTGs)
- High Efficiency 13-35 % (2-4 X SOA SiGe RTG's)
  - Uses Less Radioisotope Material
- Long Life
  - 14 Years - Enable Deep Space Missions
- Low EMI & Vibration
  - Enable use of High Precision Cameras and Magnetometers
- Function in CO_2 and other planetary Atmospheres
  - Enable Long Duration Mars and other planetary surface missions (> 2 earth years)

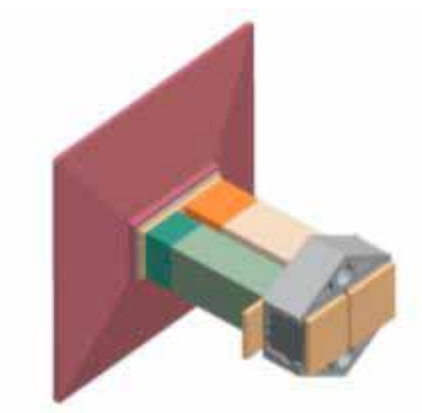
RPS Performance Ranges

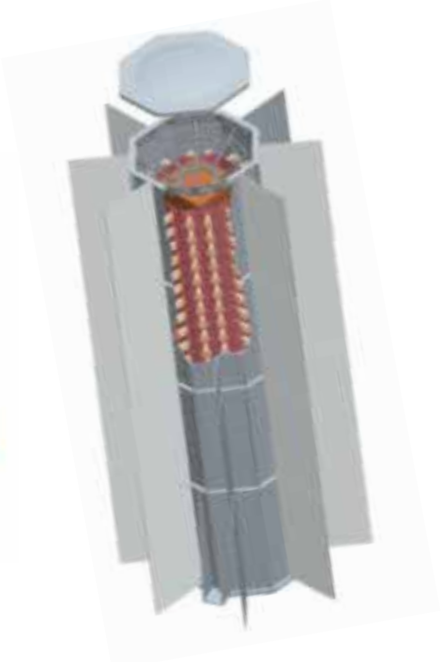


Advanced RTG

- Power: 250 We
- Specific Power: 6-8 W/kg
- Efficiency : 10%
- Employs advanced TE materials and Unicouple configuration
  - High ZT(>1.0) thermoelectric materials
    - Higher efficiency
  - Segmented couples
    - Each segment optimized for maximum performance

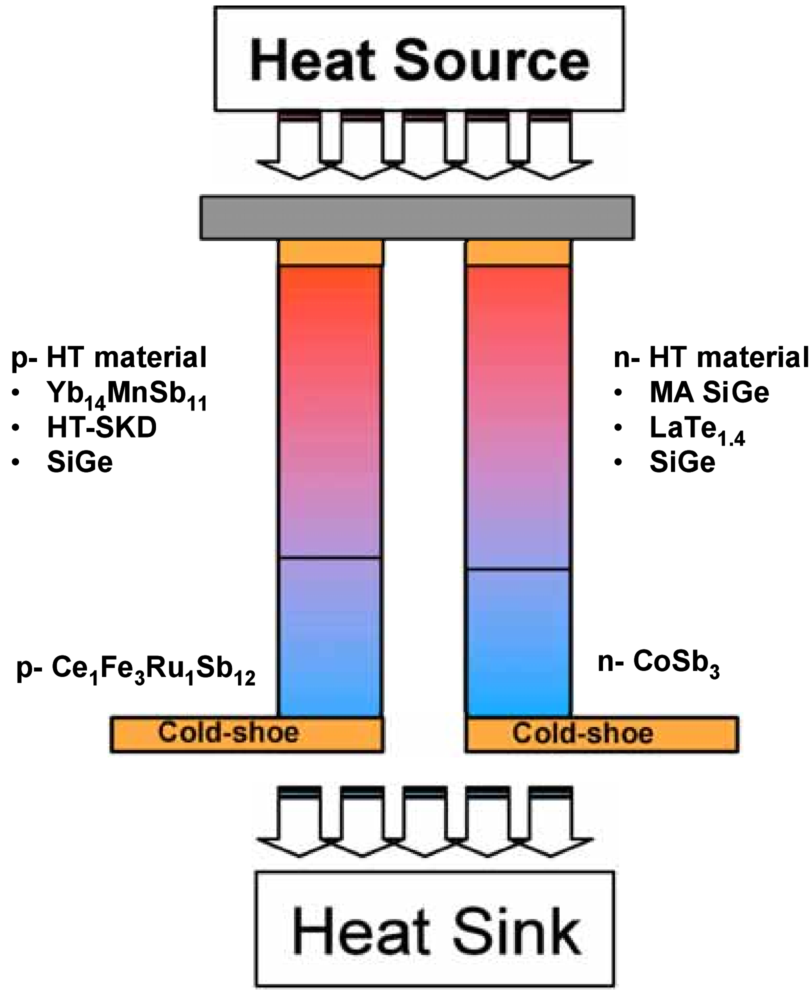






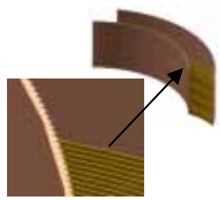
Technical Approach to Achieve High Efficiency and Long Life

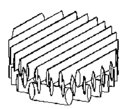
- High ZT(>1.0) thermoelectric materials
  - higher efficiency
- Segmented couples
  - each segment optimized for maximum performance
- Large Delta T: (1275 to 525 K Operation)
  - Higher efficiency
- Sublimation Control
  - Aerogel
  - Metal/metal oxide coatings



Further Advances in Stirling Engine Technology Feasible by Increasing Hot End Temperature

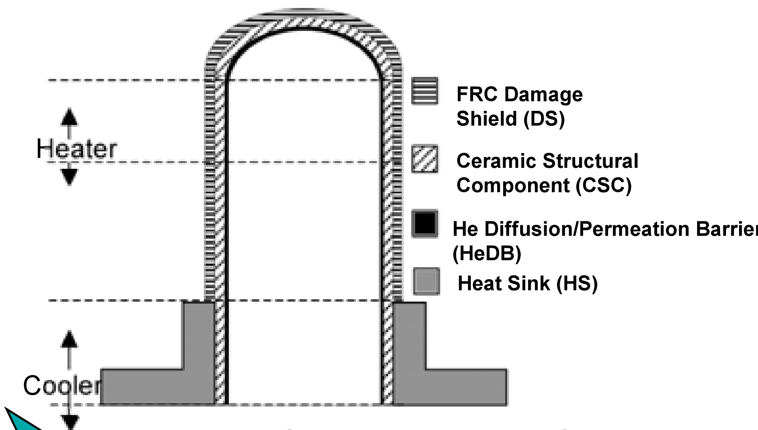
High Efficiency Regenerator


Involute Foil


Lenticular

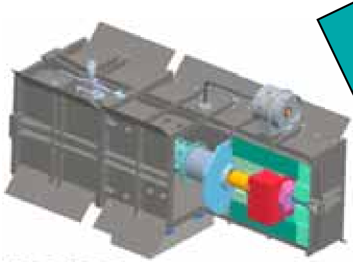

Honeycomb

Possible ceramic heater head layout



Ceramic Heater Head

850°C Heater Head Temperature

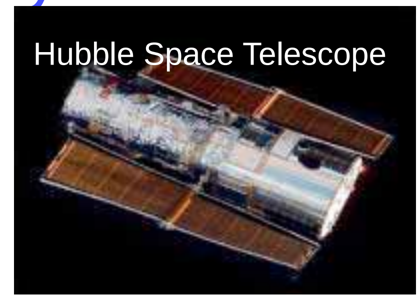

ASRG
650°C Heater Head Temperature

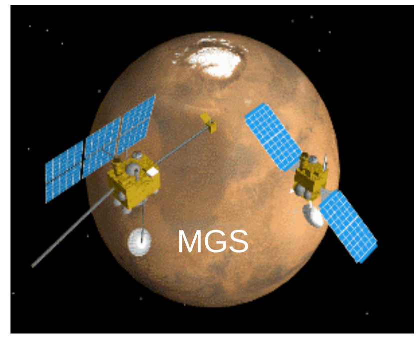

4 engines with Mar M 247 heater head fabricated by Sunpower – Pratt & Whitney Rocketdyne Team

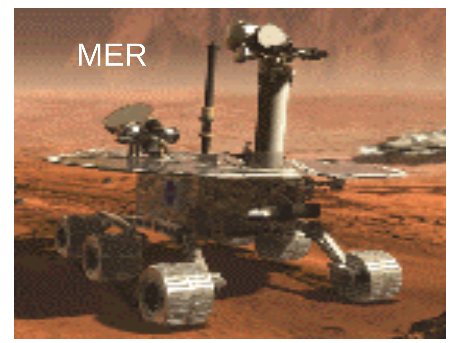
Solar Cells/Arrays

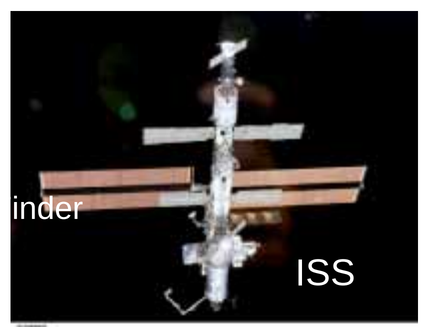
Applications of Photovoltaic Power Systems

- Used on >99% of the space missions launched to date:
  - Earth Orbital : GEO, LEO,MEO
  - Planetary Orbital/fly byes
  - Ion Propulsion Missions:DS-1
  - Mars, Jupiter, Venus, Mercury,
  - Plantary Surface: Mars, Moon
  - Human Exploration: ISS





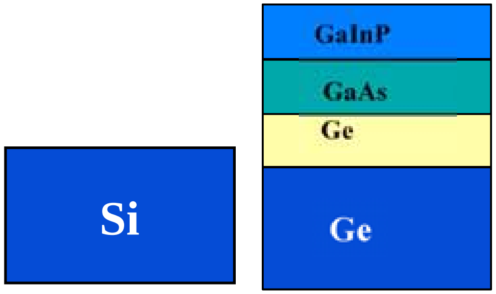




SOA Solar Cells & Arrays-Overview

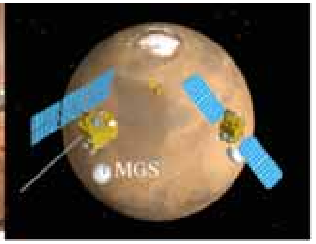
- Solar Cells
  - High efficiency Silicon and Multi Junction Solar Cells are presently being used in many space missions

Cell Type	Efficiency
High Efficiency Si Cells	16 %
Multi Junction Solar Cells	26.5%



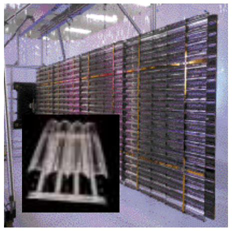
- Solar Arrays
  - Body mounted, rigid panel and flexible deployable arrays are currently being used in many spacecraft.
  - These arrays are mostly suitable for low–medium power (0.5-5 kW) applications

Body-Mounted



Rigid Panel

Array Type	Specific Power (W/kg)
Rigid Panel Array	30-40 (3 J)
Flexible Fold Out Arrays	30-50 (Si)
Concentrator Arrays	30 -60
Flexible fold out Arrays	8-100 (3 J)

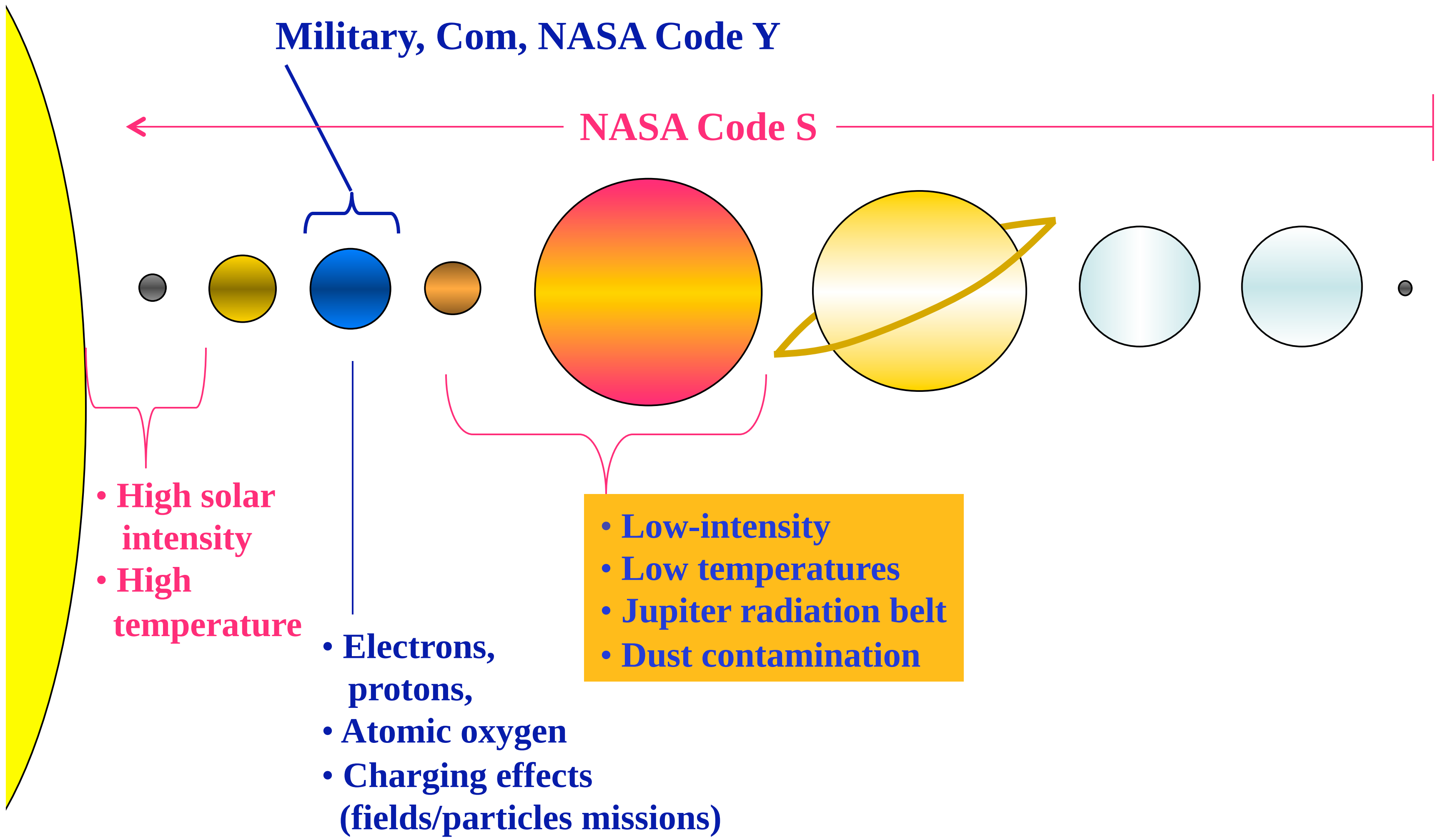


Concentrated Array

Flexible Deployable Panel

Performance of SOP Solar Cells and Arrays is Inadequate for Future Code-S Missions

Solar Array Environments for Space Science Missions



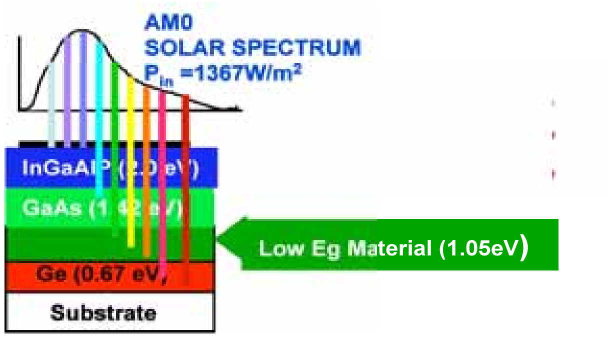
Summary of Future Space Science Mission Needs

- High Efficiency Solar Cells (> 30%)
  - Essentially all solar powered missions benefit significantly from high efficiency cells
  - Higher efficiency results in reduced array size, mass, and stowage volume

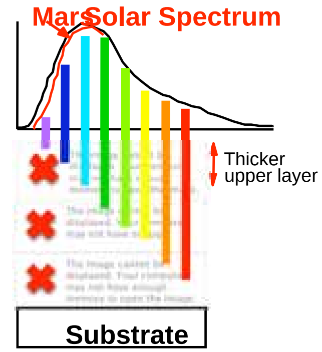
- High Power and High Voltage Arrays (> 20 kW and >200 W/kg)
  - This is a unique NASA need and all SEP missions require this type of array
    Cells and Arrays for Extreme Environments

- This is a unique NASA need because several code S missions experience extreme environments
  - LILT cells for solar system exploration missions beyond 4 AU
  - Dust mitigation concepts for Mars surface missions
  - High temperature and high solar intensity arrays for inner planetary missions
  - Arrays for high radiation fields of Jupiter

Advanced Solar Cell Technologies Under Development

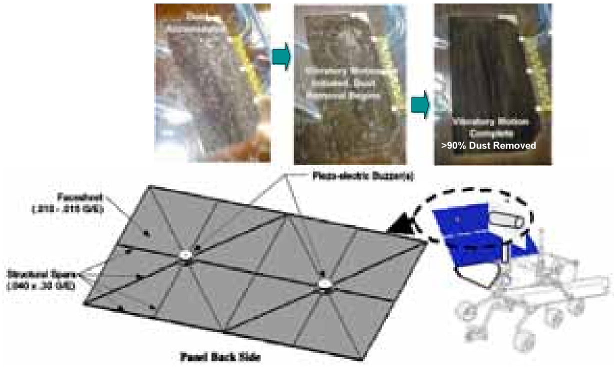


Multi Junction Crystalline Cell
Status:30%
Goal: 39%



Mars Solar Cells

Product Performance Targets:
- Specific Power*: 150-300 W/kg
- Stowage volume*: 30-70 kW/m^3
- Status: 100 W/kg

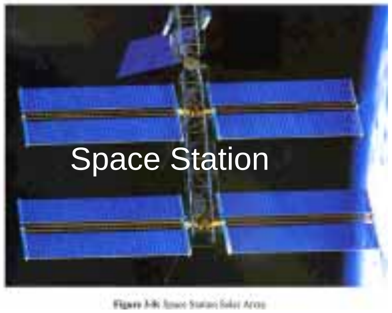


Solar Array Dust Mitigation Systems

Energy Storage Systems

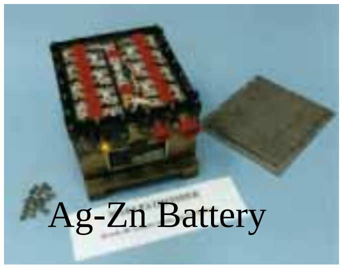
Space Applications of Energy Storage Devices

- Energy storage devices are used in space missions to:
  - Provide **primary electrical power** to launch vehicles,crew exploration vehicles, planetary probes, astronaut equipment
  - **Store electrical energy in solar powered orbital and Surface missions** and provide electrical energy during eclipse periods
  - **Meet peak power demands** in nuclear powered rovers, landers and planetary orbiters

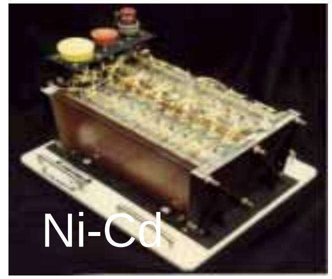


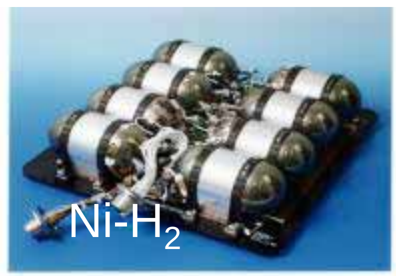
SOP Energy Storage Technologies

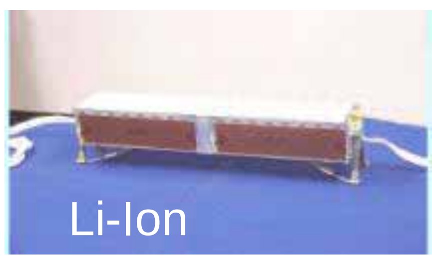
Primary Batteries



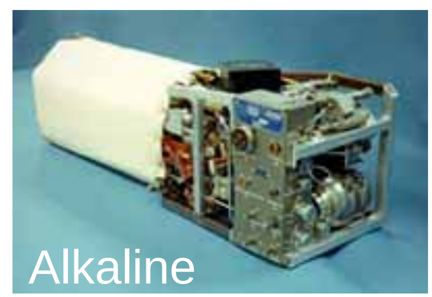
Rechargeable Batteries







Fuel Cells



Characteristics of SOP Primary Batteries

Type	Application	Mission	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Operating Temp. Range, °C	Mission Life (yrs)	Issues
$Li\text{-}SO_2$	Cell		238	375	-40 to 70	<10	Voltage Delay
	Battery	Galileo Probe Genesis SRC MER Lander Stardust SRC	90-150	130-180	-20 to 60	9	
$Li\text{-}SOCl_2$	Cell		390	878	-30 to- 60	>5	Severe voltage delay
	Battery	Sojourner Deep Impact DS-2 Centaur Launch batteries	200-250	380-500	-20 to 30	< 5	
$Li\text{-}CF_x$	Cell		614	1051	-20 to 60		Poor power capability

Limitations

- Moderate specific energy (100-250 Wh/kg)
- Limited operating temp range (-40 C to 70^{o}C)
- Radiation tolerance poorly understood
- Voltage delay

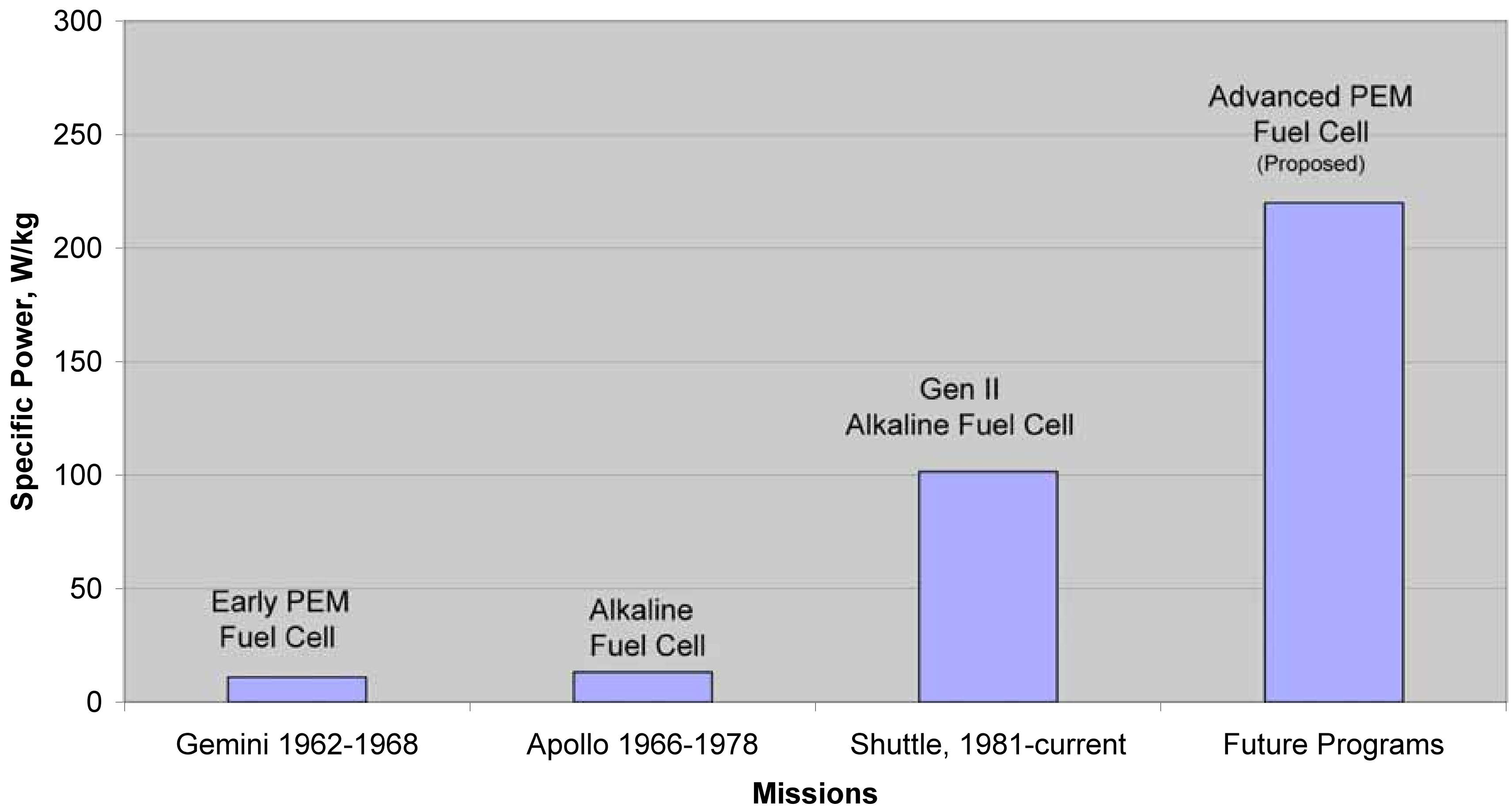
Characteristics SOP Rechargeable Batteries

Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life	Issues
Ag-Zn	Pathfinder Lander	100	191	-20 t0 25	2	100	Electrolyte Leakage Limited Life
Ni-Cd	Landsat, TOPEX	34	53	-10 to 25	3	25-40K	Heavy Poor Low Temp. Perf.
Super Ni -Cd	Sampex Battery, Image	28-33	70	-10 to 30	5	58K	Heavy Poor Low Temp. Perf
IPV Ni -H_2	Space Station, HST, Landsat 7	8-24	10	-10 to 30	6.5	>60K	Heavy, Bulky Poor Low Temp. Perf
CPV Ni-H_2	Odyssey, Mars 98 MGS, EOS Terra Stardust, MRO	30-35	20-40	-5 to 10	10 to 14	50 K	Heavy, Bulky Poor Low Temp. Perf
SPV Ni -H_2	Clementine, Iridium	53-54	70-78	-10 to 30	10	<30 K	Heavy Poor Low Temp. Perf
Li-Ion	MER-Rover	90	250	-20to 30	1	>500	Limited Life

Limitations of Ni-Cd & Ni-H2 batteries:

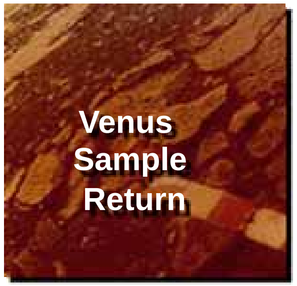
- Heavy and bulky
- Limited operating temp range (-10°C to 30°C)
- Radiation tolerance poorly understood.

Characteristics of Space Fuel cells



Summary of Energy Storage Technology Needs of Future Solar System Exploration Missions

1. **Low temperature batteries (**primary(<-100^{o}C) and rechargeable (<-60^{o}C) batteries) for planetary probes and Mars surface missions
2. **High temperature batteries** (> 475 ^{0} C) for inner planetary missions
3. **Long calendar life** (>15 years), high specific energy (>150 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions
4. **High specific energy** (>150 Wh/kg) and Long cycle life (>50,000 cycles) rechargeable batteries for Mars and earth orbital SEC, SEU & origins missions
5. **High specific energy** primary batteries (>600 Wh/kg) for planetary probes



Summary of Energy Storage Technology Needs of Future Exploration Missions

1. **Safe, High Specific Energy and Long Life Rechargeable Li-Ion Batteries** (32V, 1-15 kWh) are required for Crew Exploration Vehicle (CEV), Crew Launch Vehicle (CLV) , Heavy Lift Launch Vehicle (HLLV), Lunar Surface Ascent Module (LSAM), Astronaut Extravehicular Activity (EVA) Suit, Surface systems etc.,

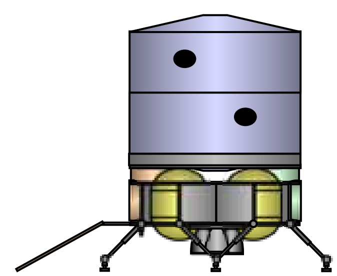
2. **High specific Power, Safe, and Long Life primary and Regenerative Fuel Cells** are required for a wide range of surface elements, including advanced EVA, pressurized and unpressurized rovers, and for large surface power plants as part of a PV/RFC power system.

   - 1KW max class for Advanced EVA PLSS,
   - 2-8 KW class for un-pressurized rovers
   - 25KW class for photovoltaic (PV) / regenerative fuel cell (RFC) power plant and pressurized rover applications.


Un Pressurized Rover 1-2 kW

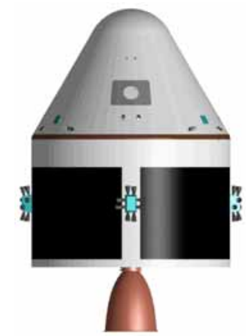

Lunar Pressurized Rover 3-10 kW


EVA (0.2-1.0 kW)


Lunar Habitat (15-30 kW)

Space-Rated Li-Ion Batteries

- Product
  - Develop space-rated high specific Energy Li-ion batteries for future human and robotic exploration missions
    - 200Wh/kh (Cell)
    - 160 Wh/kg (Battery)
    - 300 Wh/l (Battery)
    - > 30 K cycles (30%DOD)
    - -60 to + 60 C Operation
    - safe



(CEV 12-15 kWh)

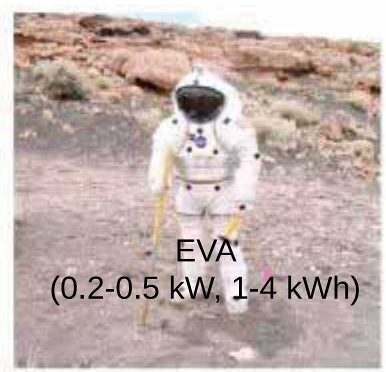
Crew Launch Vehicle

Un Pressurized
Rover 1-2 kW, 1-5 kWh

- Schedule
  - 2006-2010

- Sponsor
  - NASA-ESMD

- Team:
  - NASA-GRC(lead), NASA-JSC, NASA-JPL, NASA-MSFC
  - UT Austin, Caltech, USC and Industry:



EVA
(0.2-0.5 kW, 1-4 kWh)

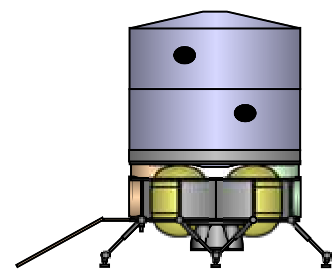
PEM Fuel Cells

- Product
  - Develop PEM primary and regenerative fuel cells for future human lunar exploration missions
    - 1-kW max class for advanced EVA portable life support systems (primary fuel cell)
    - 8-kW class for un-pressurized rovers (primary fuel cell)
    - 25-kW class for RFC surface power plants and pressurized rovers (Regenerative Fuel Cell).
- Schedule
  - 2006-2010
- Sponsor
  - NASA-ESMD
- Team:
  - NASA-GRC (lead), NASA-JSC, NASA-JPL,
  - UT Austin, Caltech, USC and Industry:

Un Pressurized Rover
(1-2 kW, 1-5 kWh)

EVA
(0.2-0.5 kW, 1-4 kWh)

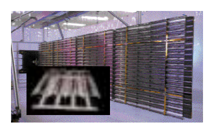
Lunar Pressurized Rover
3-10 kW, 25-100kWh



Lunar Habitat
(15-30 kW, 5MWH)

Summary and Conclusions

SOA Technology Capabilities

Technology Element	Capability
Power System	Direct Energy Transfer Shunt Regulator/Radiator 0.5 to 20 kW, 28- 120 V dc
Power Electronics	 22- 120 V dc -55 to 75C, up to a 1Mrad > 85% converter efficiency
Radioisotope Power Sources	 GPHS RTG 4-5 W/kg 6.5 % eff
Solar Cells	  Si cells 9-15% eff , TJ Cells 24-26% Rigid Panel 30-40 W/kg Scarlet : 40-60 W/kg
Rechargeable Batteries	 Ni-Cd  $Ni\text{-}H_2$ 30-40 Wh/kg >30,000 Cycles (30% DOD) >10 years -10 to 30 C

Space Power Technologies

	Past	Present	Future
Radioisotope Power Sources	 3-4 W/kg 6.5 % eff MHW RTG	 4-5 W/kg 6.5 % eff GPHS RTG	Segmented TE Stirling 5-10 W/kg 10-30- % eff
Solar Cells	 30-40 W/kg 9-15 % eff Si Solar cells Rigid Panel Array	 100W/kg 25% eff TJ Solar cells Flexible Panel Array	High eff. Cells Low Mass Array 35% Eff 250 W/kg @ 35%
Rechargeable Batteries	 35 Wh/kg >30,000 Cycles (30% DOD) -10 to 30 C Ni-Cd	 35 Wh/kg >60,000 Cycles (30% DOD) -10 to 30 C Ni-H_2	Li-Ion Batteries Li-Polymer Batteries ➢200 Wh/kg ➢50,000 Cycles ➢(30% DOD) ➢-60to 60C Batteries

Summary and Conclusions

- Power conversion and energy storage systems have been used in robotic and human space missions launched since 1960
  - Launch vehicles: silver zinc batteries
  - Robotic GEO, LEO spacecraft: solar arrays in combination with Ni-Cd, Ni-H_2
  - Robotic planetary missions: RTG's, solar arrays, Ni-Cd/Ni-H_2 batteries, Li primary batteries
  - Space shuttle: Alkaline Fuel Cells

- Future space missions have unique power conversion and energy storage requirements
  - Large power and energy storage capabilities
  - Mass and volume efficiency (2-10 X vs SOP)
  - Long life (> 15 years)
  - Ability to operate in extreme environments
  - Human rated safety and high reliability

Summary and Conclusions (continued)

- State of practice power conversion and energy storage systems have limited performance capabilities and do not meet all future critical space mission needs.
  - Limited operating temperature range (-20o-60oc for rechargeable, -40o – 60oc)
  - Radiation tolerance poorly understood
  - Heavy and bulky
  - Low power and energy capability

- Development of advanced power conversion and energy storage technologies required to meet future space mission needs
  - Radioisotope power systems: high specific power, high efficiency, long life,
  - Solar cells/arrays: high efficiency solar cells, LILT cells, low mass and low stowage volume arrays, high power arrays
  - Batteries: high specific energy, long life, RAD hard, low temperature batteries, human rated safety
  - Fuel cells: medium power PEM fuel cells, regenerative fuel cells, small fuel cells

Acknowledgments

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