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High Energy Power and Propulsion (HEP & P) Capability Roadmap

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Tom Hughes, Penn State, Applied Research Lab, Co-Chair
Jack Wheeler, DOE Headquarters, Co-Chair

April 7, 2005

Disclaimer:
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 HEP & P Team members, and is not the official view of NASA or DOE.

Agenda

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- Introduction – Tom Hughes
- Capability Roadmaps
  - Solar Systems – Rao Surampudi (for Henry Brandhorst)
  - Energy Storage Systems – Rao Surampudi
  - Radioisotope Systems – Bob Wiley
  - Nuclear Fission Systems – Sherrell Greene
- Conclusion/Summary – Joe Nainiger

HEP & P Capability Roadmap Team

Co-Chairs

- NASA: Joseph J. Nainiger, Glenn Research Center
- External: Tom Hughes, Penn State, Applied Research Lab
- DOE: John (Jack) P. Wheeler, DOE HDQs

Team Members

- Government
  - Elaine Kobalka, NASA Glenn Research Center
  - Stan Borowski, NASA Glenn Research Center
  - Jose Davis, NASA Glenn Research Center
  - Jeff George, NASA Johnson Space Center
  - Rao Surampudi, Jet Propulsion Laboratory
  - Sherrell Greene, Oak Ridge National Laboratory
  - George Schmidt, NASA Marshall Space Flight Center
  - Bob Wiley, DOE HDQs
  - Wayne Bordelon, NASA Marshall Space Flight Center

Team Members (continued)

- Industry
  - Samit K. Bhattacharyya, President, RENMAR Enterprises
  - Gary L. Bennett, Consultant
  - Dave Byers, Consultant
- Academia
  - James Gilland, Ohio Aerospace Institute
  - Henry W. Brandhorst, Jr., Director, Space Research Institute, Auburn University

Coordinators

- Directorate: Overall: Doug Craig, ESMD, Technical: Raynor Taylor, ESMD, (Day-to Day, Jay Jenkins, ESMD)
- APIO: Perry Bankston, Jet Propulsion Laboratory

Red = Sub-team lead

Capability Description

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- The High Energy Power and Propulsion (HEP & P) capability roadmap addresses the systems, infrastructure and associated technologies necessary to provide power and propulsion for human and robotic exploration of space and to provide power for human and robotic exploration of planetary surfaces.

Capability Breakdown Structure – HEP&P

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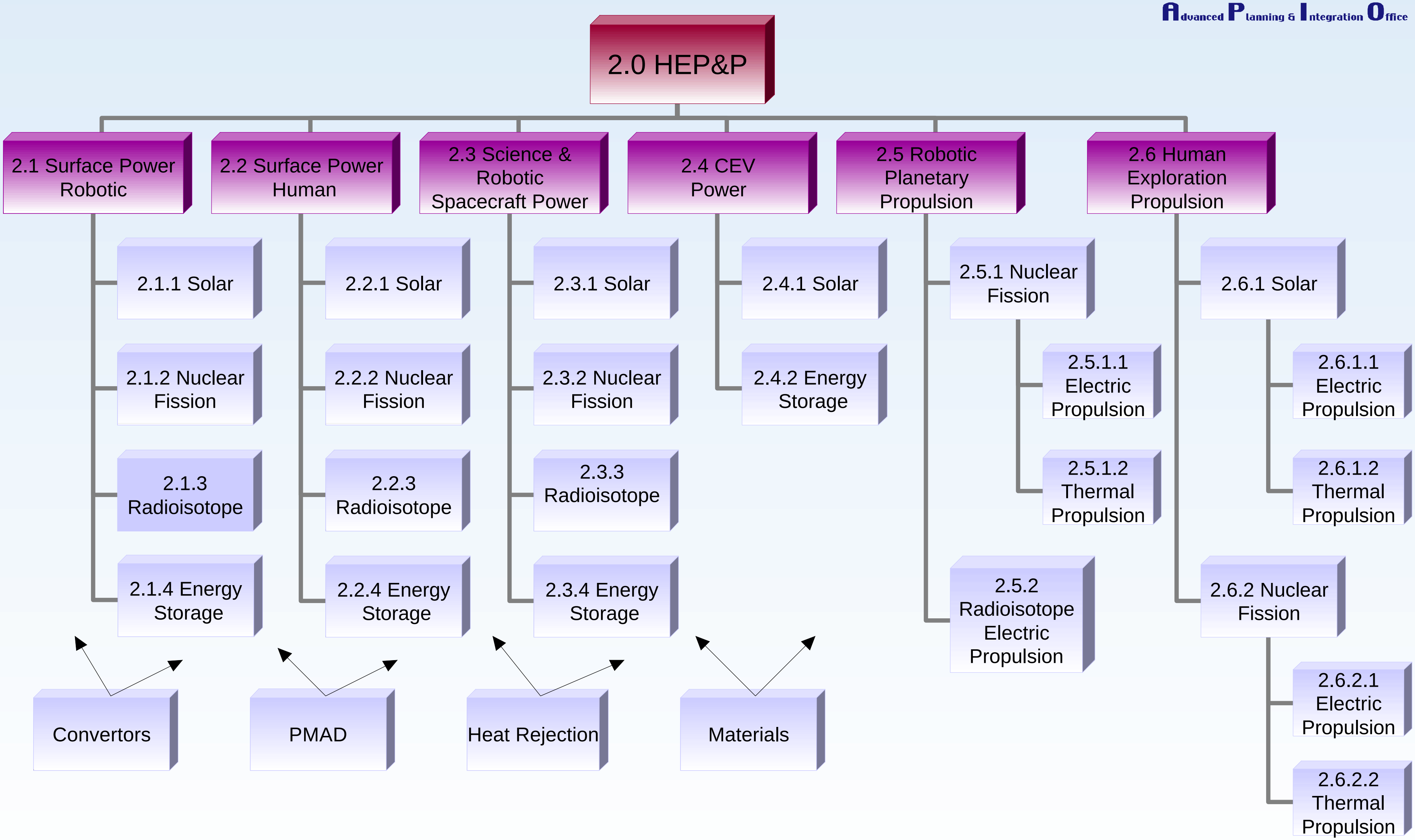

Benefits of High Energy Power & Propulsion

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High Energy Power and Propulsion Systems could:

- Enable extended human missions and presence
- Enable advanced propulsion (NEP, SEP, NTP,REP)
- Allow longer missions
- Allow reduced transit times
- Allow more extensive and powerful science mission instruments
- Reduce required spacecraft mass or increases available payload mass
- Enable exploration where solar energy is limited or absent
- Enable In Situ Resource Utilization (ISRU)

HEP & P Relevance to Exploration – Aldridge Commission Recommendation

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Aldridge Commission Report: " Finding 4: The Commission finds that successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs. There was significant agreement that helped the Commission identify 17 areas for initial focus….we identify the following enabling technologies…

- *Advanced power and propulsion* – primarily nuclear thermal and nuclear electric, to enable spacecraft and instrument operation and communications, particularly in the outer solar system, where sunlight can no longer be exploited by solar panels….

Recommendation 4-1:

The commission recommends that NASA immediately form special project teams for each enabling technology to:

- Conduct initial assessments of these technologies
- Develop a roadmap that leads to mature technologies
- Integrate these technologies into the exploration architecture; and
- Develop a plan for transition of appropriate technologies to the private sector"

Roadmap Process and Approach

- Created 4 sub-teams; Solar, Storage, Radioisotope and Fission
- Developed strawman requirements and assumptions in consultation with SRC-13 and other capability teams
- Sub-teams developed initial “independent” Capability Roadmaps based on strawman requirements and assumptions, current state-of-technologies and projected trajectories of advancing technologies
- Sub-team roadmaps “rolled up” into overall roadmaps in an iterative process that continues
- Process of highlighting decision points (choices) and technology gaps is current focus

Current State-of-the-Art for Capabilities

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Top Level Summary

- Fission Systems
  - Power (US Only)
    - SNAP-10A (1965)
    - SP-100 (1980-1992)
    - Ground tests of power conversion candidates (Brayton, potassium Rankine, etc.) in previous programs
  - Propulsion
    - Ion – Isp 3300 sec, Efficiency 70%, Life 10,000 hrs, Power 2.7 kW, TRL 9 (Deepspace 1)
    - Hall – Isp 1640 sec, Efficiency 67%, Life 4,000 to 8,000 hrs, Power 1.2 kW, TRL 9 (SMART 1)
    - MPD – Isp 1000 to 10,000 sec, Efficiency 45 to 60%, Life 500 hours, Power 1000 to 10,000 kW, TRL 3
    - PIT – Isp 4000 to 6000 sec, Efficiency 50%, Life pulsed, Power MW/pulse, TRL 3
    - Rover/Nerva Program 1959-1972, Highest Power 4100 MWt, Isp 875 sec, Continuous Operation 62 min.
- Radioisotope Systems
  - Power
    - RTG with GPHS – specific power 5.3 We/kg, efficiency = 6.6%
  - Propulsion
    - Same as ion above
- Solar Systems
  - Power
    - Solar array specific power – 40-60 We/kg, Solar cell efficiency – 26 to 28%
  - Propulsion
    - Same as above
- Energy Storage Systems
  - Primary Batteries – Specific Energy 90-250 Wh/kg, Mission Life 1-9 years
  - Rechargeable Batteries – Specific Energy 24-35 Wh/kg, Cycle Life > 50,000 @ 25% DOD, Mission Life > 10 years
  - Adv. Rech. Batteries – Specific Energy 90 Wh/kg, Cycle Life > 400 @ 50% DOD, Mission Life > 2 years
  - Fuel Cells – Specific Power 90 We/kg, Maintenance Frequency 2600 hours (Shuttle)

ASSUMPTIONS

- Nuclear power will be required to fulfill the VSE
- Advanced propulsion will be required to fulfill the VSE
- Solar power systems are effective in many applications
- Sub-capabilities such as PMAD, power conversion, heat rejection and materials technology are cross-cutting and apply to all roadmap capabilities
- Each roadmap path is intended to be technically achievable in a focused effort
- Roadmap paths will continue to be developed during the ongoing dialog with other capability and strategic roadmap teams
- New and emerging technologies must be pursued and integrated into the roadmaps in an organized fashion
- Power roadmap developed for CEV, but not shown due to current CEV acquisition
- Power and propulsion advanced concepts recognized as part of roadmap, but not yet included

Driving Missions for HEP & P

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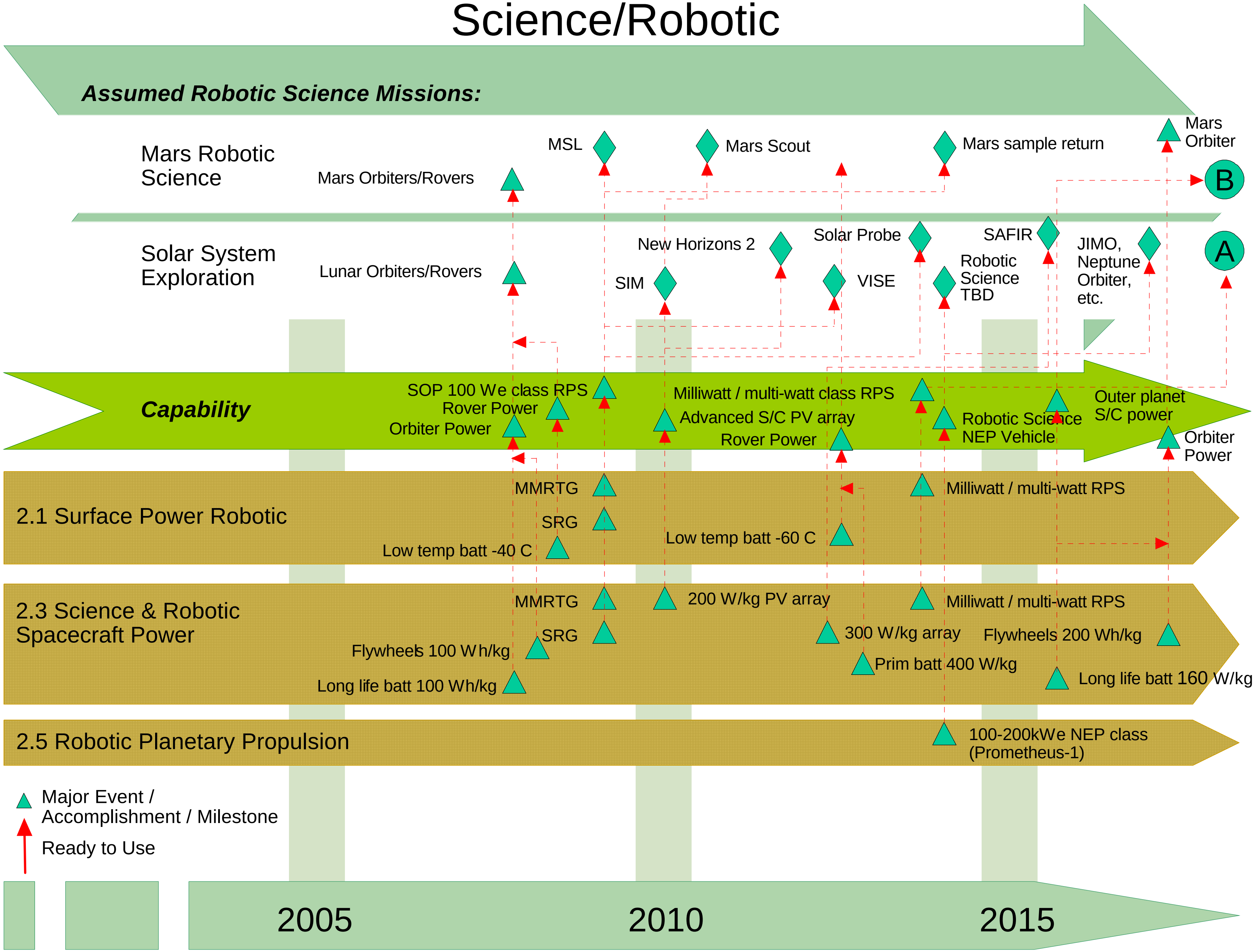
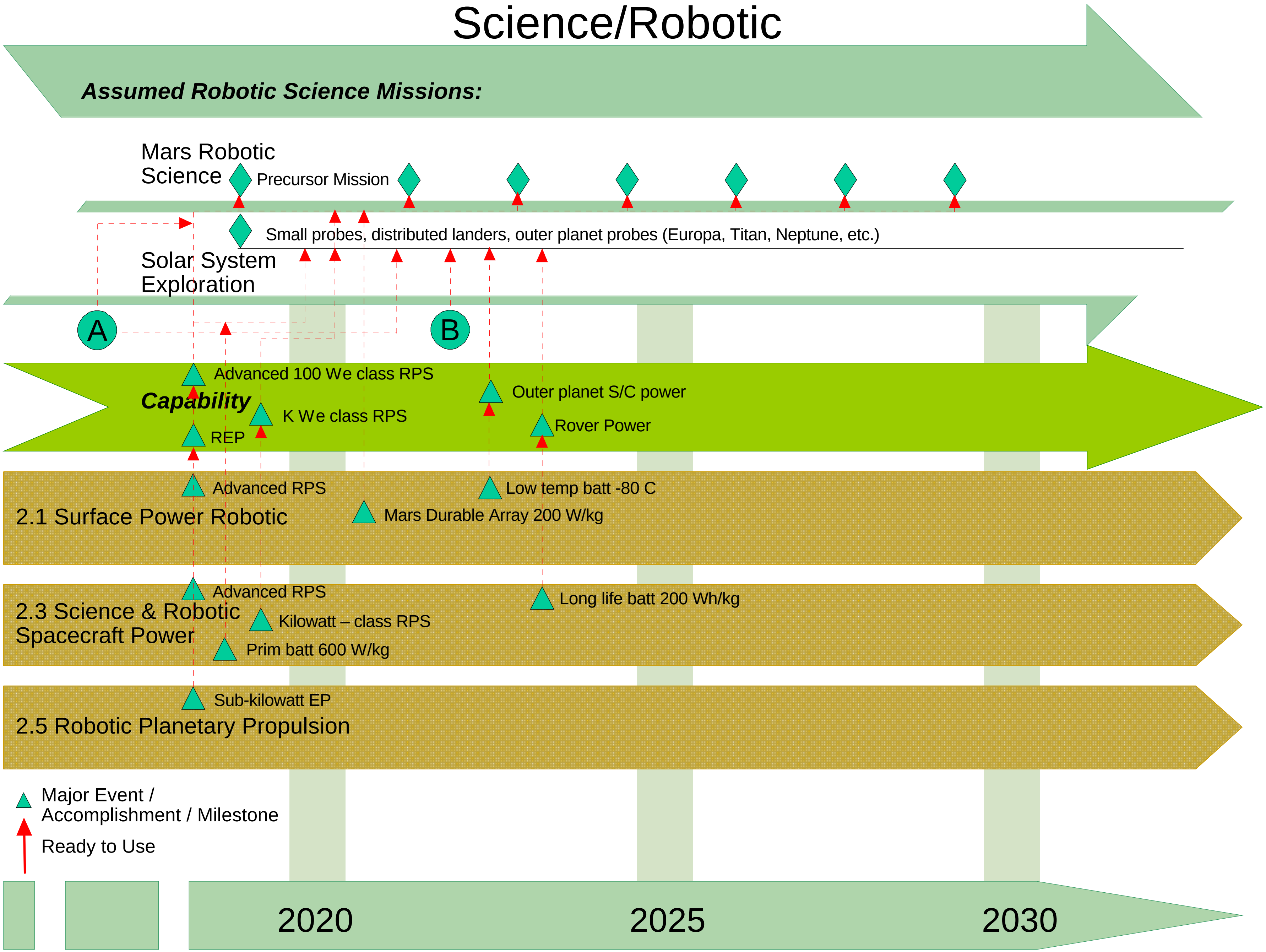
- Scientific
  - Lunar and Mars Orbiters
  - Planetary Landers
  - Outer Planetary Probes
  - Jupiter Icy Moons Orbiter(JIMO) and other outer planetary missions requiring high power and/or high degree of maneuverability/multiple destinations, Interstellar Probe
- Human Exploration
  - Crew Exploration Vehicle
  - Lunar and Mars Surface Power
  - Piloted and cargo propulsion systems

Capability Team 2:High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

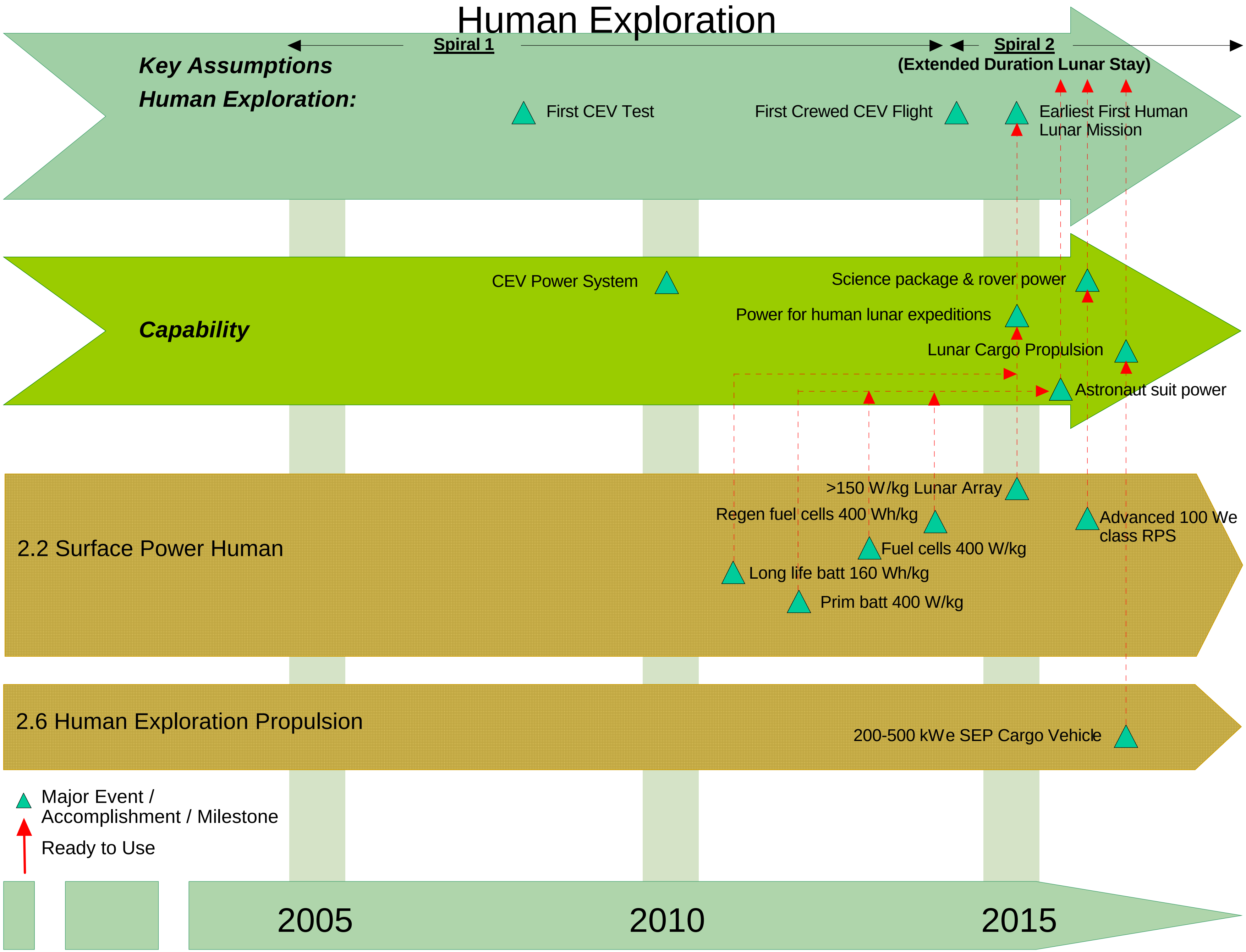
Science/Robotic



Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

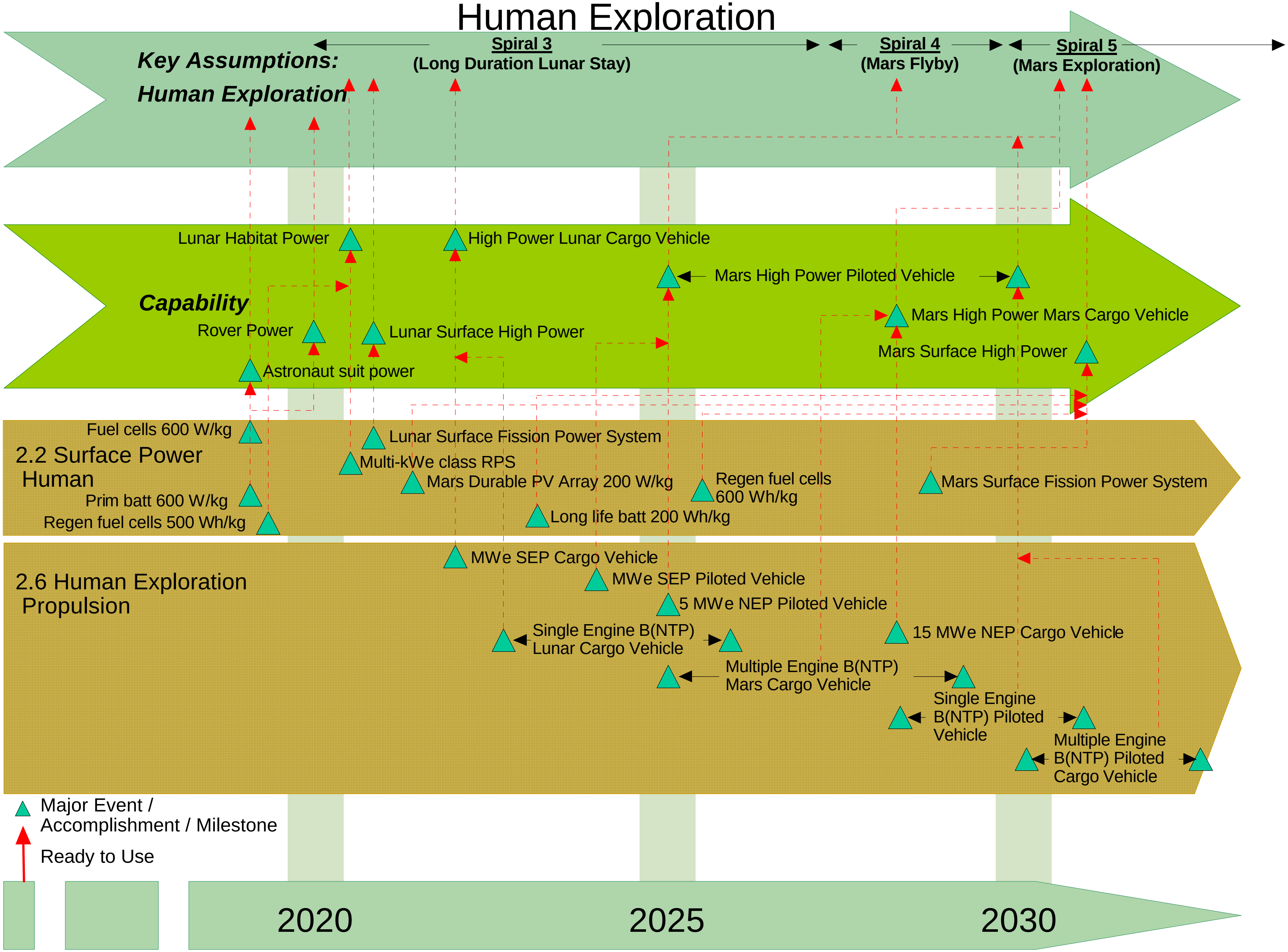


Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap



Capability Team 2: **High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap**

Human Exploration



Capability 2.1.1, 2.2.1, 2.3.1 2.4.1 2.6.1: Solar Power

Presenter: Rao Surampudi, JPL

Henry W. Brandhorst, Jr., Auburn University

Chair, Solar Sub-Team

April 7, 2005

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Capability Breakdown Structure – HEP&P

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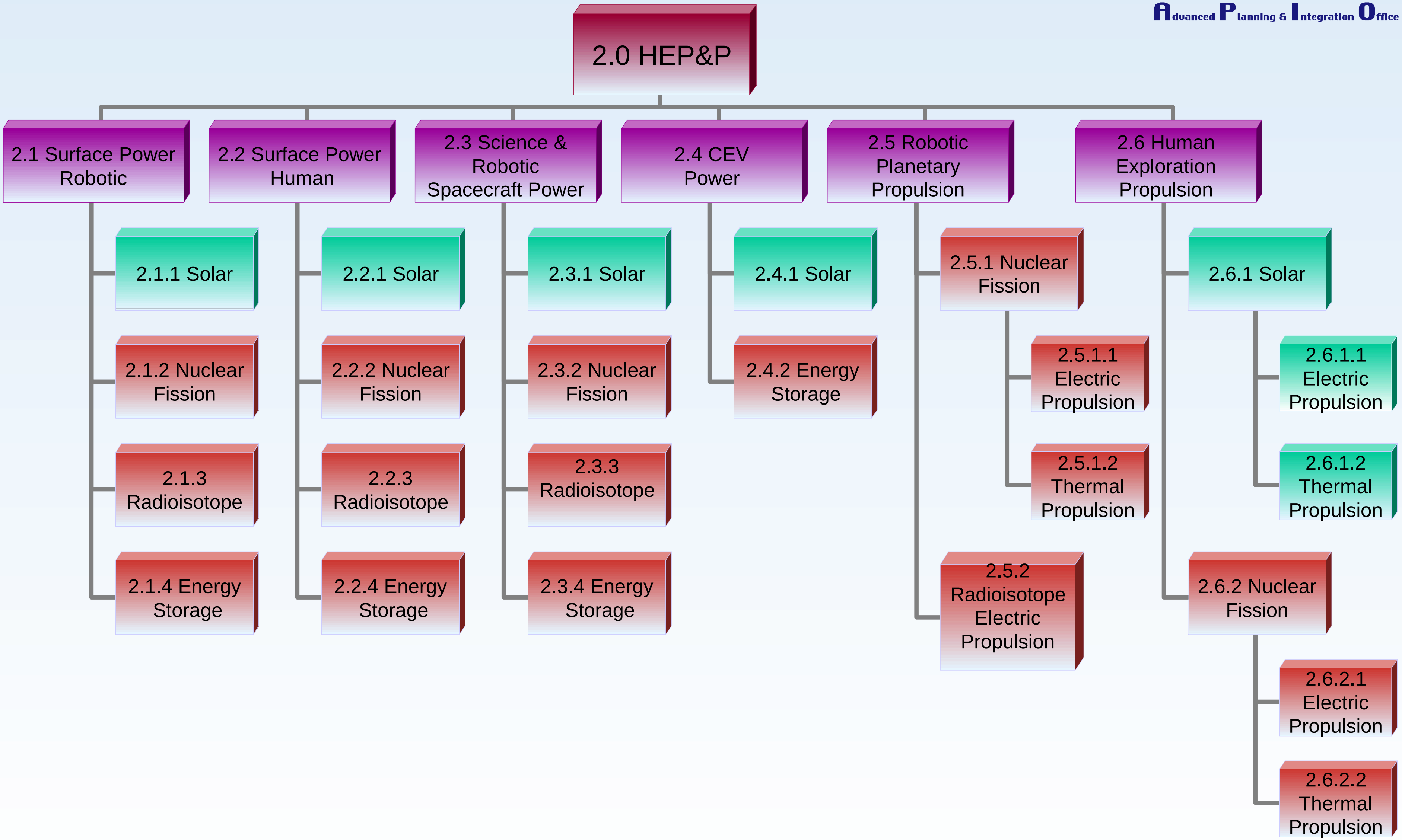
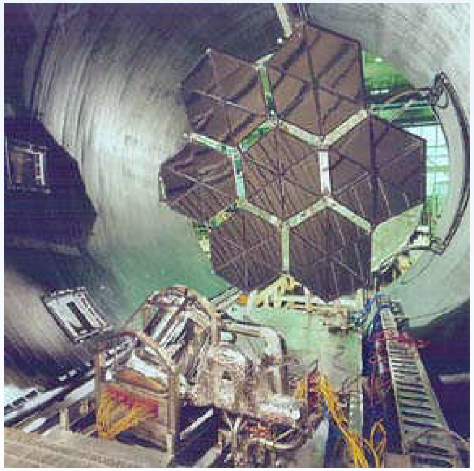


Solar Capability Description

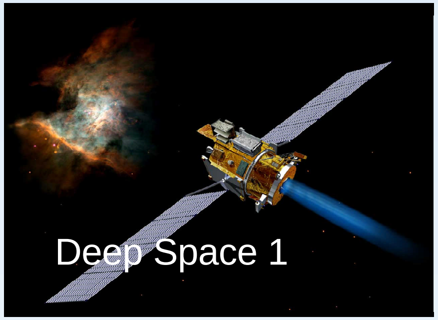
- Solar power system provides electrical power to space missions by converting solar energy into electrical energy either by direct or indirect conversion.
- Two types of solar power systems
  - Photovoltaic Power System/Solar Cell and Arrays
  - Solar Thermal Power System
- A photovoltaic power system converts converts solar illumination to electricity directly through the photovoltaic effect.
  - The key components: solar cells , substrate / panel, array structure and deployment mechanisms (and energy storage)
  - Photovoltaic power systems have been widely used in robotic science and human exploration missions
- A solar thermal power system converts input solar illumination to heat. The heat is then used to power either a thermal-to-electric power conversion subsystem for the spacecraft or surface application.
  - Static (Direct Current): (thermoelectric, TPV, TI)
  - Dynamic (Alternating Current): (Brayton, Rankine or Stirling)
  - Note: PMAD, Thermal, structures are not included

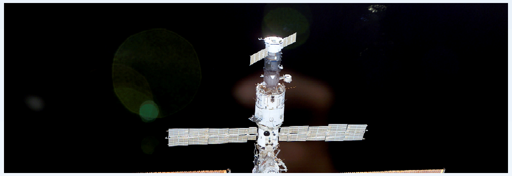


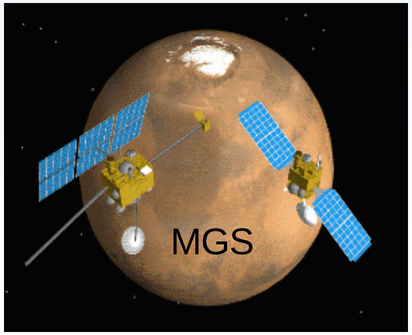
2 kW Solar Thermal System

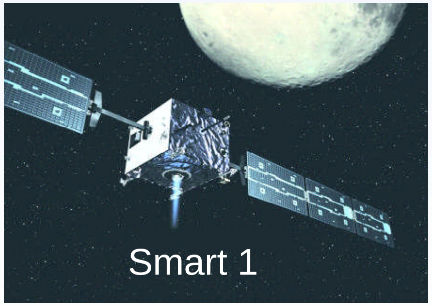
Applications of Photovoltaic Power Systems

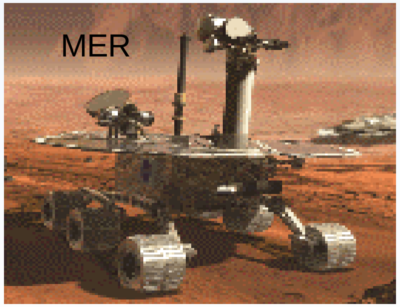
- Used on >99%* of the space missions launched to date:
  - Near sun – Venus, Mercury…
  - Outbound – Mars, Asteroids…
  - Earth: – Comsats, earth observing, weather, ISS, DoD…
  - SEP: Smart 1, Deep Space 1…
  - Surface: MERs, Pathfinder, ALSEP
- Other benefits
  - Modular, reliable
  - Established manufacturing base
  - Cost effective











Potential Future Missions for Solar

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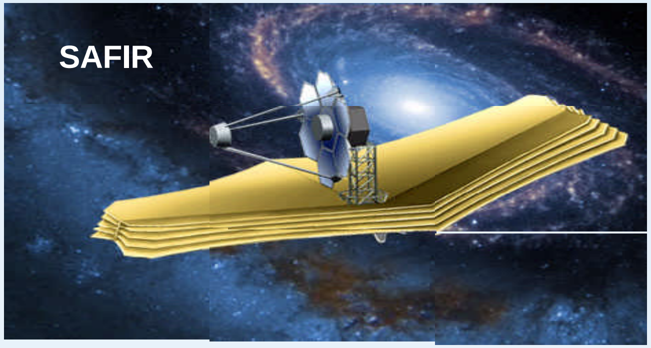
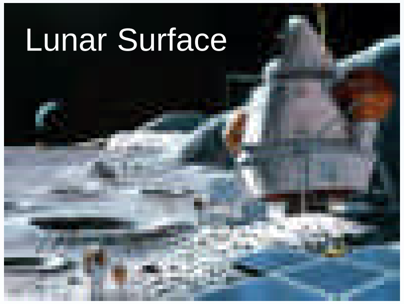
- Mission Types Considered
- Orbital Missions
  - Earth & Mars
  - Outer planets
  - Inner planets
- Surface Missions
  - Moon
  - Mars
- SEP Missions
  - Robotic science: asteroids…
  - Lunar cargo
  - Mars cargo & Human transp
    (considered for the purposes
    this study)



Space Interferometry Mission



What is / Why Solar Spacecraft Power?

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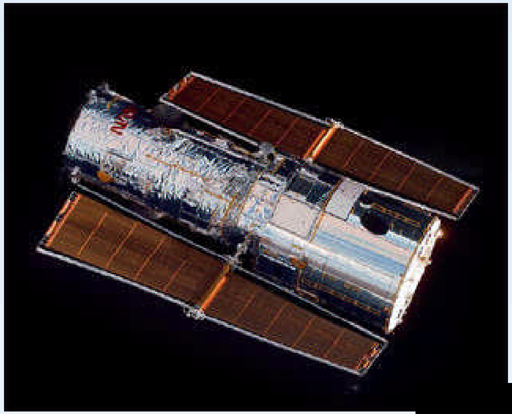
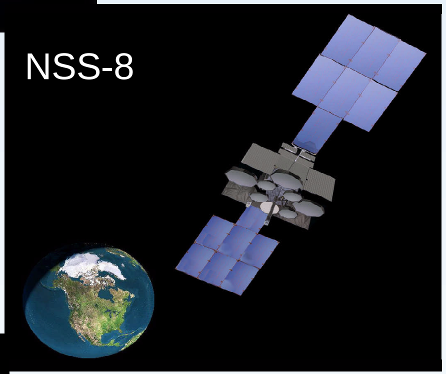
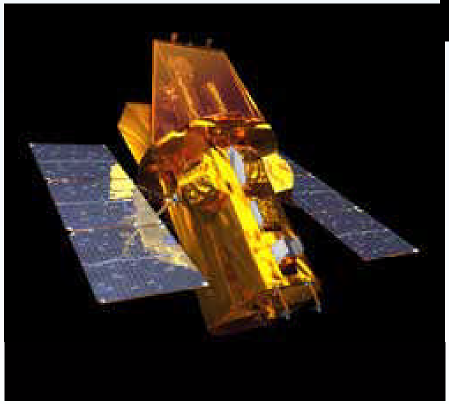
- Solar spacecraft power converts sunlight into electricity for robotic and human uses
  - Key Subsystems
    - Photovoltaic arrays provide electric power
    - Power management distributes and conditions power
    - Energy storage
    - Thermal management for PMAD
- Used on ~99% of space missions
  - Crewed and robotic systems
  - Modular, evolvable, early availability at high power levels
  - Major leverages from prior/on-going developments
    - DoD, Industry, DoE
  - Supports other exploration sectors



Hubble Space Telescope



NSS-8



Swift Gamma Ray Telescope

Commercial and
Increasing

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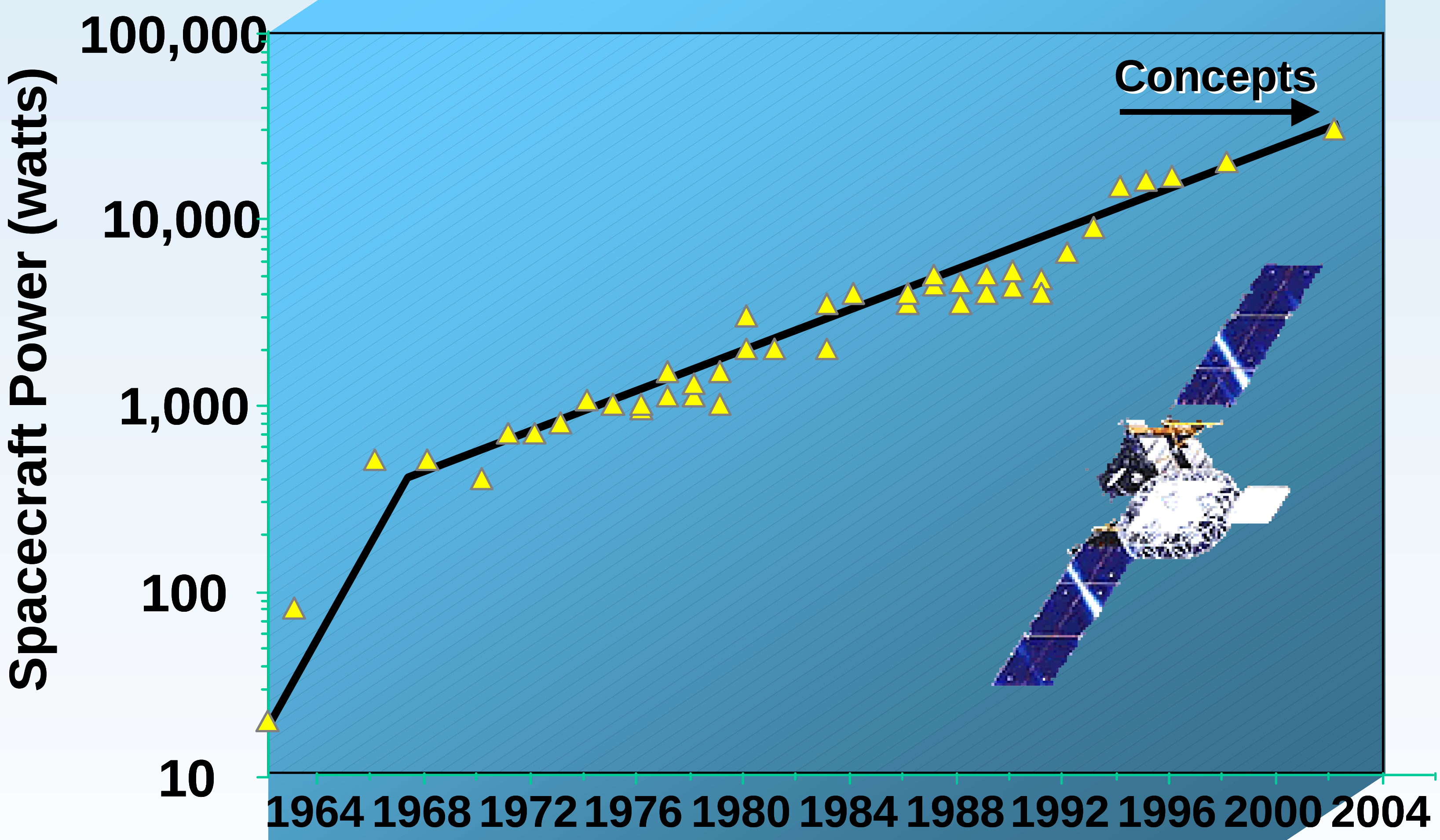

Courtesy: Hughes et.al.,
Includes DoD & Commercial

Spacecraft power levels have **doubled** every 5.5 years

Spacecraft Power

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- **History/State of Practice**

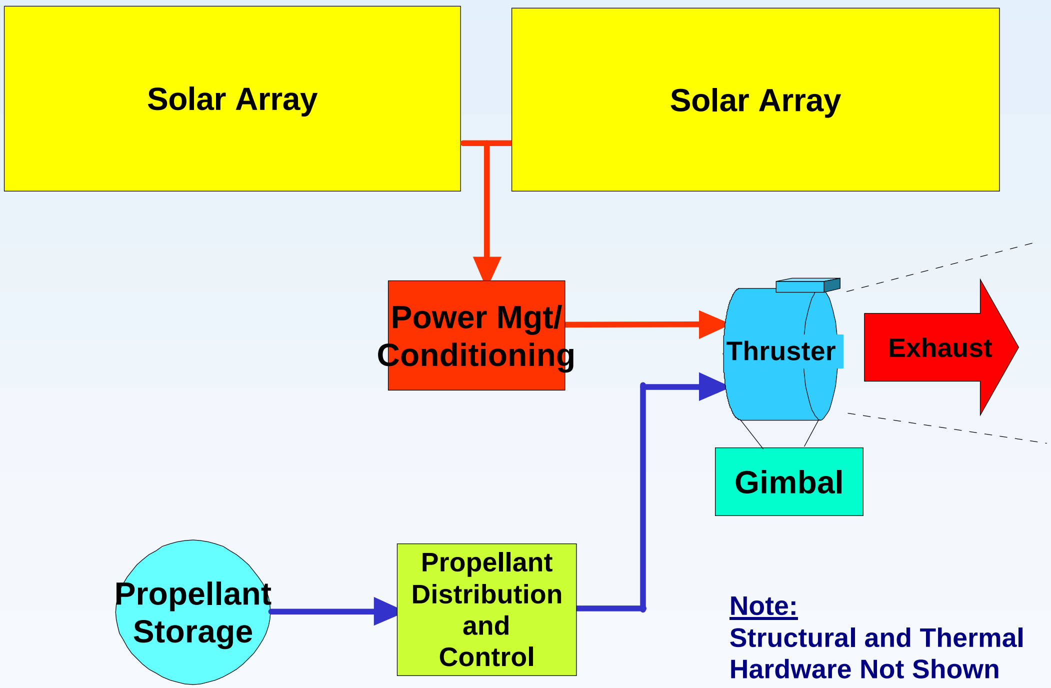
- **Capabilities Identified**

Candidate Advanced Technologies
  - Solar cell technologies

- **Missions/Strategic Drivers Identified**
  - Earth/Moon/Mars

What is Solar Electric Propulsion (SEP)?

- **Photovoltaic arrays** convert solar energy into electricity to accelerate a propellant in a **thruster**
  - SOA (less than about 7 kW)
  - Exploration capabilities need 0.2 to10 MW
- Key Subsystems
  - Solar arrays provide electric power
  - Power management & conditioning distributes and conditions thruster input power
  - Electric thrusters convert power/propellant to thrust
  - Thermal Management For Power Management
  - Structure



Status of Solar Electric Propulsion

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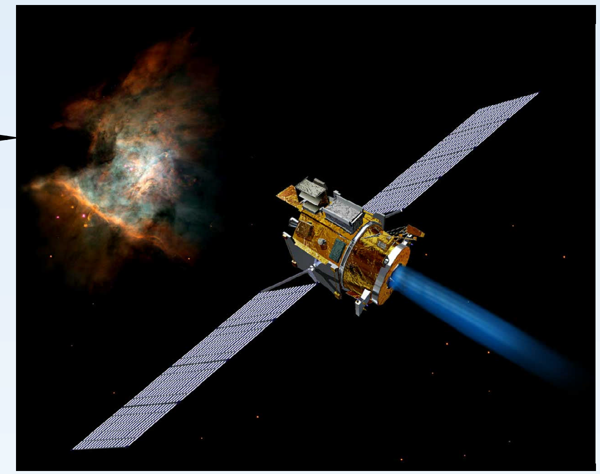
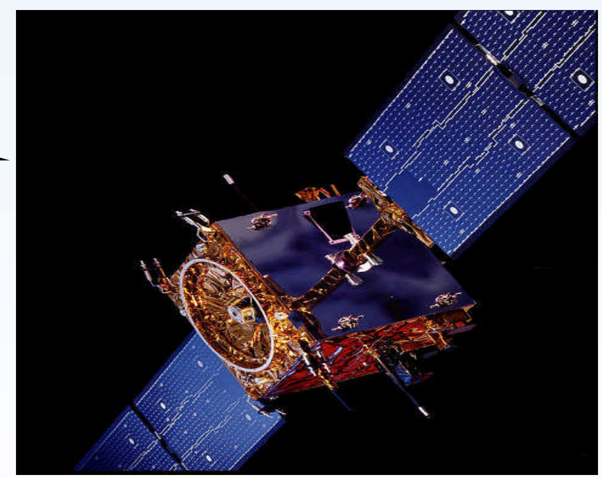
- Planetary Missions
  - Deep Space 1 (US)
    - 2.7 kW, asteroid/comet rendezvous
    - Concentrator array
    - Ion propulsion
  - HAYABUSA (Japan)
- Lunar and Earth OTV
  - Smart 1 (ESA)
    - Planar array
    - Ion propulsion
- High Power Earth Orbital
  - ComSats (6 kW)
  - Elite (USAF – 27 kW)





Electric Propulsion SOA/SOP

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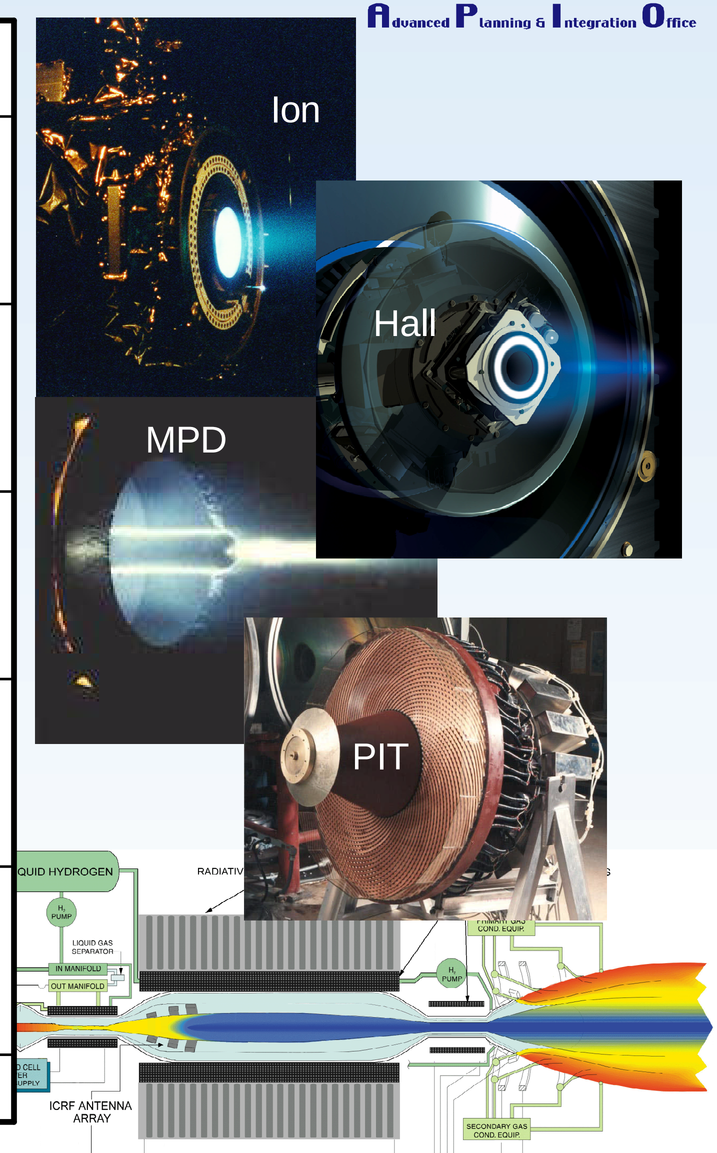
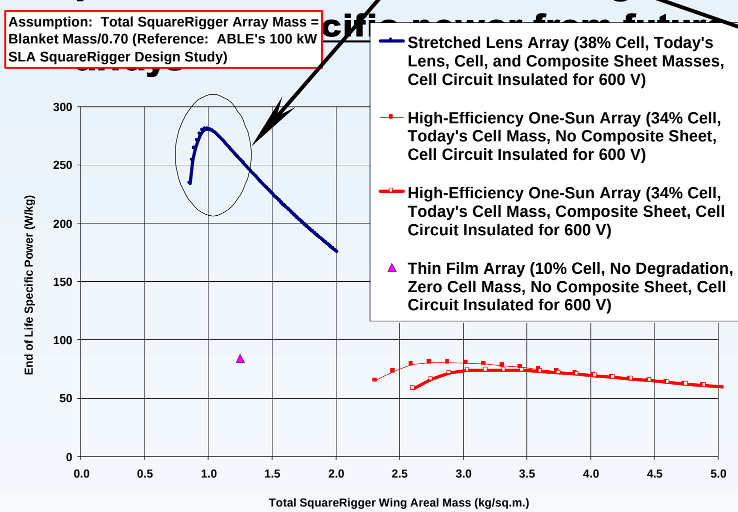
Thruster Concept	SOA/SOP		Capability Goal	
Ion	**Isp (s):**	**3300**	**Isp (s):**	**2000 - 8000**
	h[3] :	**0.7**	h :	**0.7**
	Life (kh):	**10**	**Life (kh):**	**30-100**
	Power (kW):	**2.7**	**Power (kW):**	**200 - 500**
	TRL:	**9(Deepspace-1)**		
Hall	**Isp (s):**	**1640**	**Isp (s):**	**2000 - 3500**
	h :	**0.67**	h :	**0.7**
	Life (kh):	**4-8**	**Life (kh):**	**8-30**
	Power (kW):	**1.2**	**Power (kW):**	**200 - 500**
	TRL:	**9 (SMART-1)**		
MPD[1]	**Isp (s):**	**1000 - 10000**	**Isp (s):**	**4000 - 8000**
	h :	**0.45 - 0.6**	h :	**0.65**
	Life (kh):	**0.5**	**Life (kh):**	**5 - 10**
	Power (kW):	**1000 - 10000**	**Power (kW):**	**250 - 2500**
	TRL:	**3**		
PIT[2]	**Isp (s):**	**4000 - 6000**	**Isp (s):**	**4000 - 8000**
	h :	**0.5**	h :	**0.65**
	Life (kh):	**Pulsed**	**Life (kh):**	**>10**
	Power:	**MW/pulse**	**Power (kW):**	**50 - 1000**
	TRL:	**3**		
Advanced Concepts	**Isp (s):**	**Not measured**	**Isp (s):**	**2000 - 10000**
	h :	**"**	h :	**0.55 - 0.65**
	Life (kh):	**"**	**Life (kh):**	**>10**
	Power (kW):	**300 - 3000**	**Power (kW):**	**200 - 5000**
	TRL:	**2**		

[1]Magnetoplasmadynamic [2]Pulsed Inductive Thruster [3]Thrust Efficiency

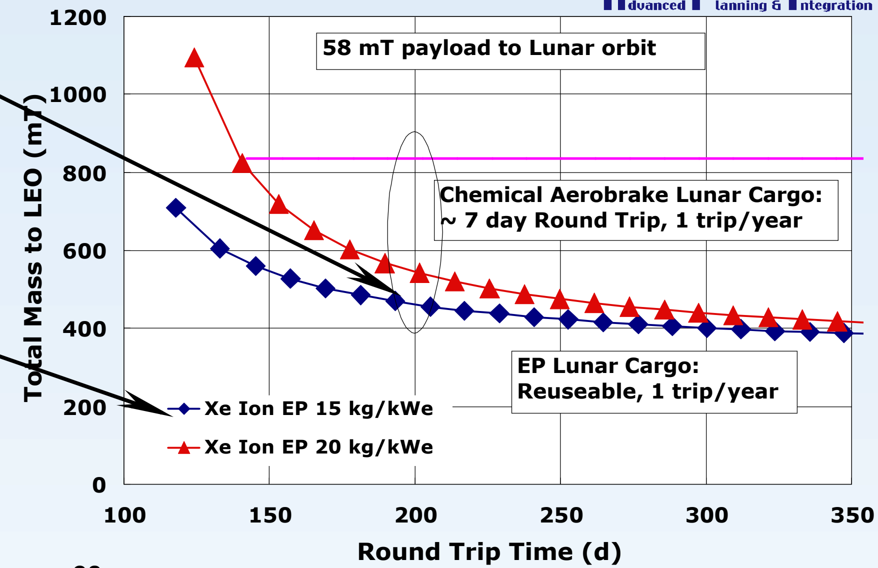


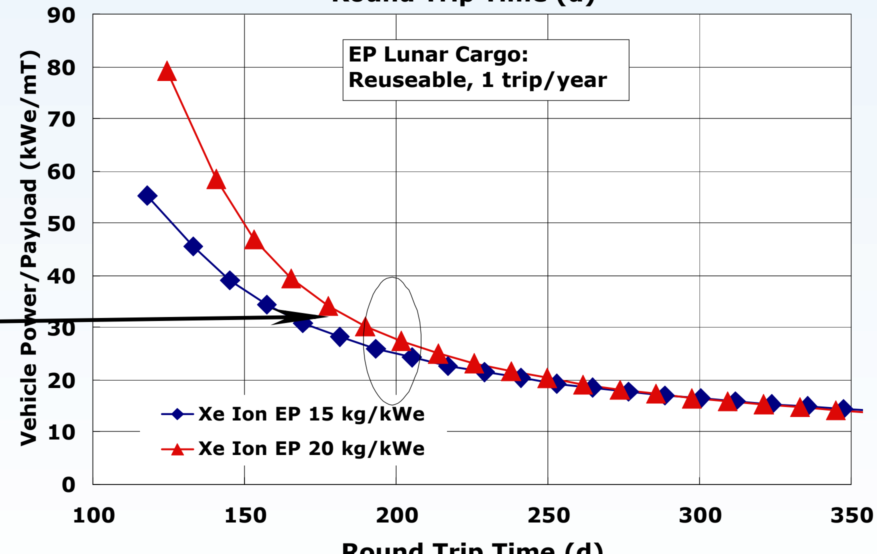
SEP Can Reduce IMLEO for Lunar Exploration

- **<u>~ 50% mass reduction</u> with SEP lunar cargo**
  - **IMLEO for 5 years of lunar cargo, 1/year**
  - **Based on previous SEI studies - 58 mT/yr payload**
  - **Near term array and thruster performance assumed: 15-20 kg/kWe**
  - **...cific power from futur... arrays**



7 round trips through the radiation belts





- **Early, small payloads require modest power levels**
  - **<u><1 year round trip</u>, <u>50 kW for 2 MT</u> payload**
  - **<u>Reusable</u>, capability useful for other areas**

Exploration Electric Propulsion (EP)

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- **History/State of Practice**
  - Power (• 7 kW) (3 kW single string)

- **Capabilities Identified**

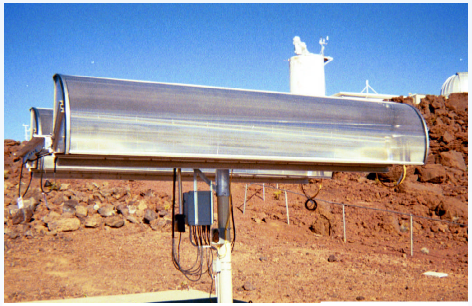
- **Candidate Advanced Technologies**
  - Solar cell technologies

- **Missions/Strategic Drivers Identified**
  - Lunar Cargo Missions

What is Solar Surface Power?

- Solar surface power converts sunlight into electricity for robotic and human uses
  - Solar Photovoltaic
  - Solar Thermal
    - Moon only
- Key Subsystems
  - Photovoltaic arrays provide electric power
  - Solar collectors collect sunlight and provide heat to a conversion unit that produces electricity
  - Power management distributes and conditions power
  - Energy storage
  - Thermal management
  - Structures
- Megawatt-class terrestrial photovoltaic and thermal power systems are operating around the world

100 kW Terrestrial Array with Si Cells (TX)



1.3 kW Array with MJ Solar Cells HI)

25 kW Solar Stirling (CA)

Solar Surface Power

story/State of Practice

Lunar

- **Capabilities Identified**

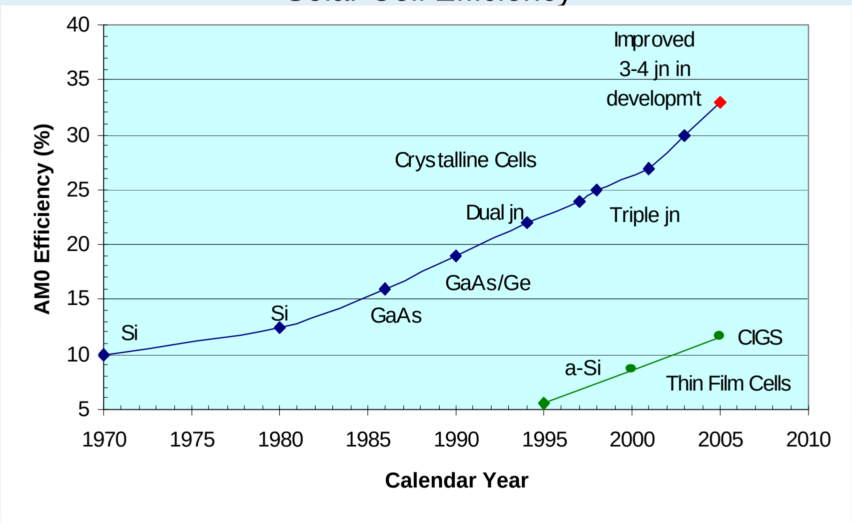
Candidate Advanced Technologies

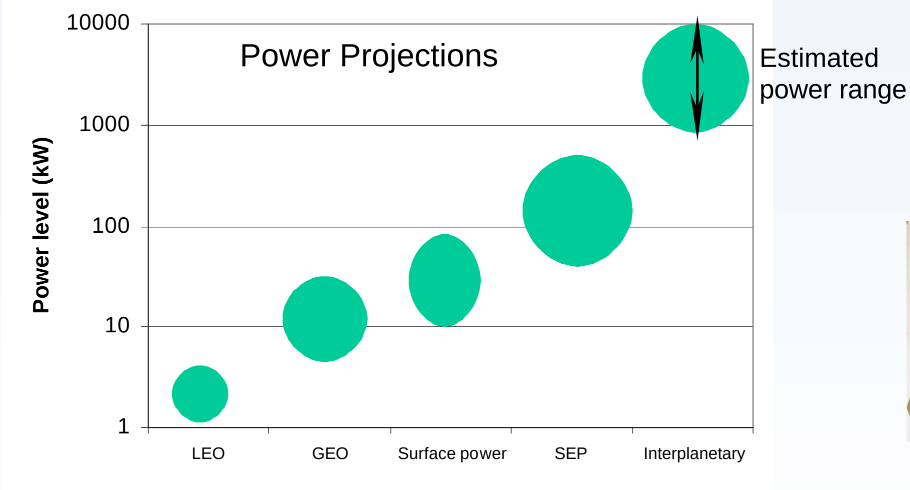
– Robust power systems for lunar and Mars surface operation

- **Missions/Strategic Drivers Identified**

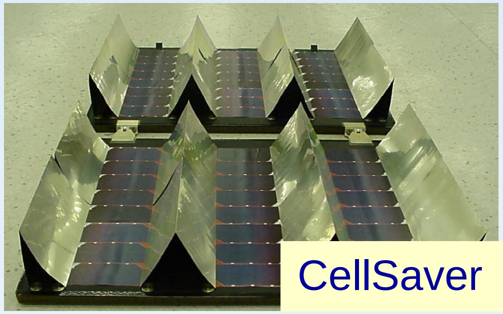
Potential Photovoltaic Array Advances

Solar Cell Efficiency



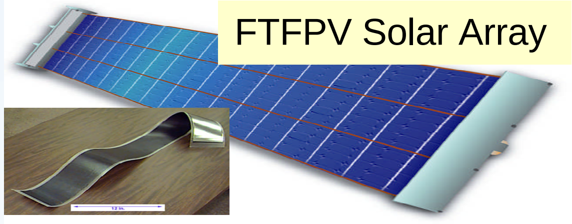


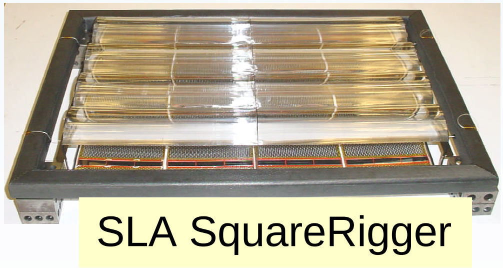
Commercial



NASA ST-8

USAF





NASA
HR&T BAA

2.1.1, 2.2.1, 2.3.1, 2.4.1: Spacecraft & Surface Power Roadmap

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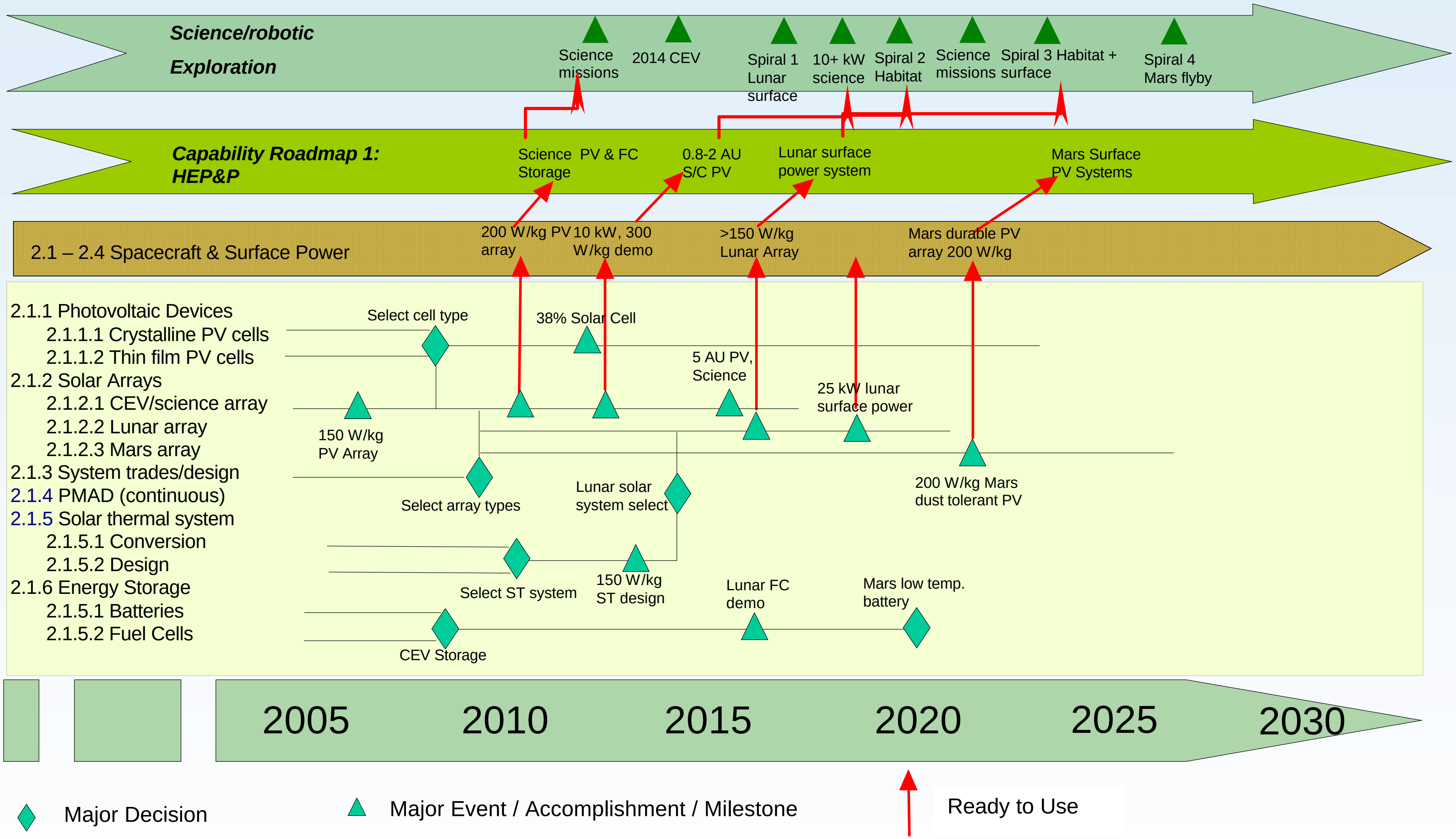
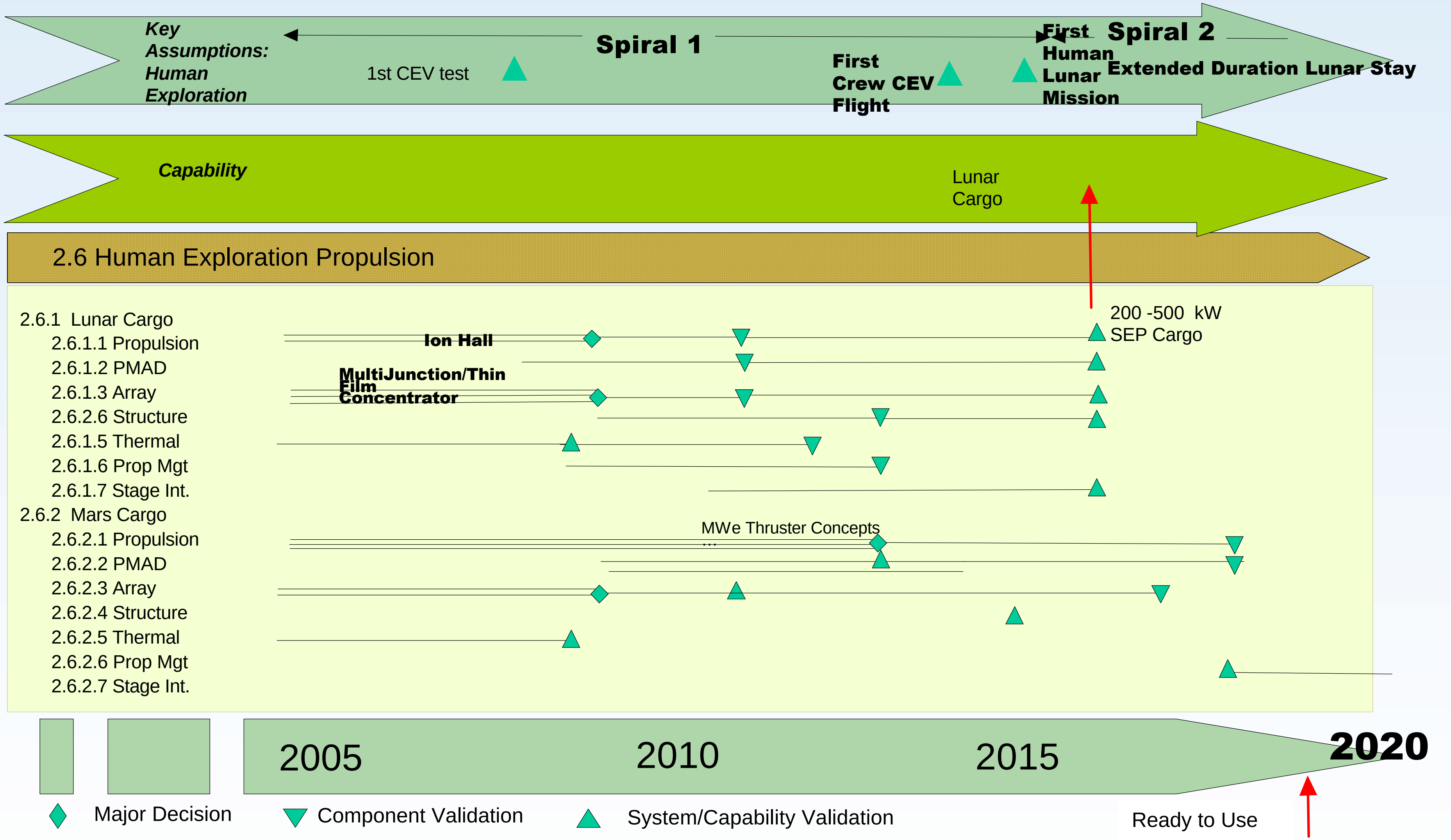


2.6.1 Solar Electric Propulsion Roadmap



2.6.1 Solar Electric Propulsion Roadmap

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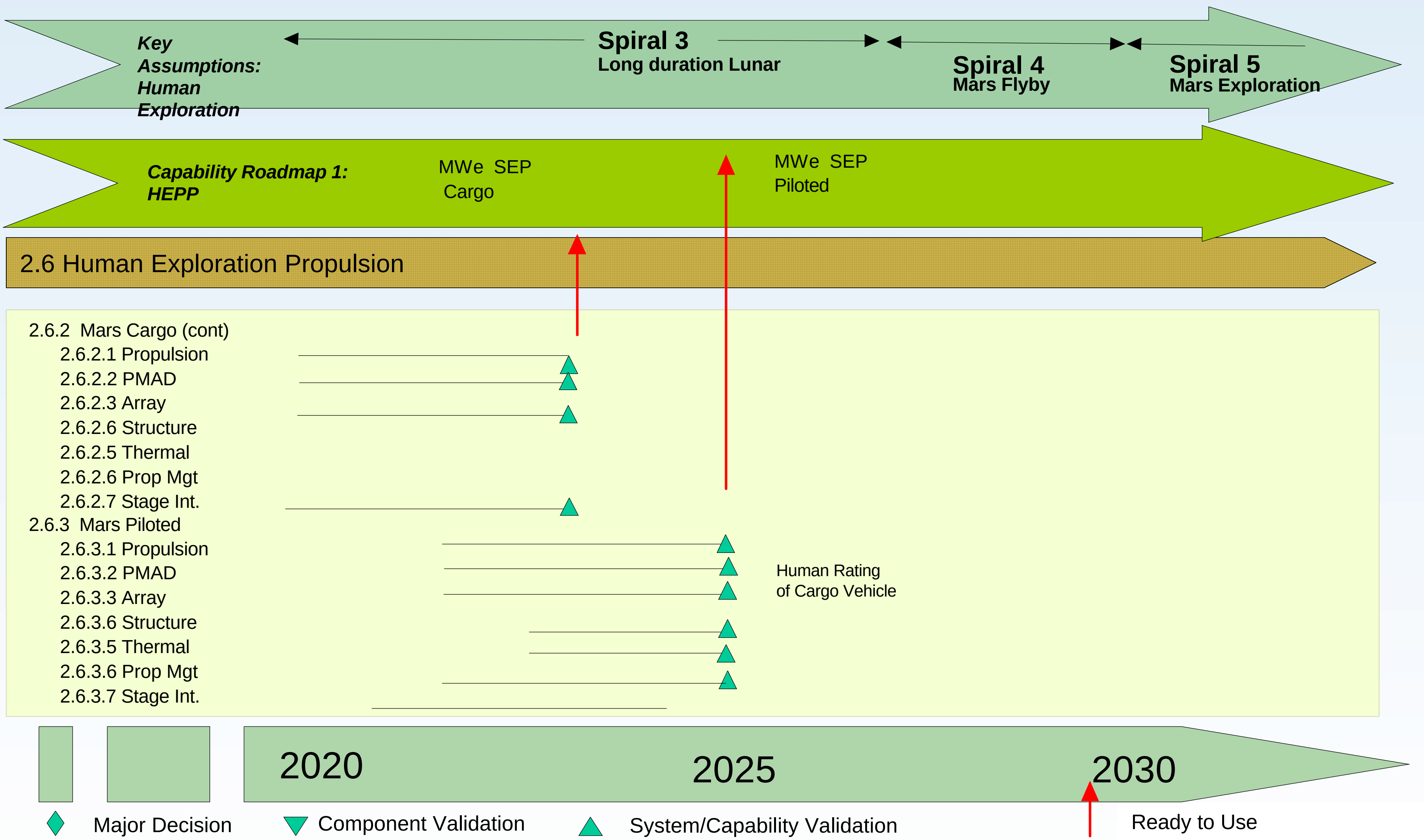

Summary

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- Solar power/propulsion is routinely used for all space sectors
  - Power levels and electric propulsion applications increasing
  - Established for use from LEO to Mars surface, a robust supporting base exists
- Major improvements are being realized in cell, array and propulsion technologies that can translate into:
  - Significant mission performance increases
  - Realizable new missions for NASA, commercial, DOD and others (spin offs)
  - Can provide early availability for robotic science and lunar SEP
  - Supports later lunar and Mars missions as well
- High power systems (MW class) will require focused solar and other technology thrusts:
  - Large, high power, radiation robust, low cost solar arrays
  - High power electric propulsion systems
    - Ground test facilities
  - In-space operations (e.g. assembly, refueling, refurbishment…)
  - GN&C, advanced structure and thermal management concepts
  - Surface power adaptations for the moon and Mars
- Reusable SEP could have a major impact on the exploration infrastructure
- Advanced concepts were not included in this briefing
  - Several may well have substantial impact over the next decade

Energy Storage System Capability Roadmap

Rao Surampudi, JPL
Energy Storage System Sub-Team Chair
Henry Brandhorst, Auburn University
Energy Storage System Sub-Team Co-Chair

April 7, 2005

Capability Breakdown Structure – HEP&P

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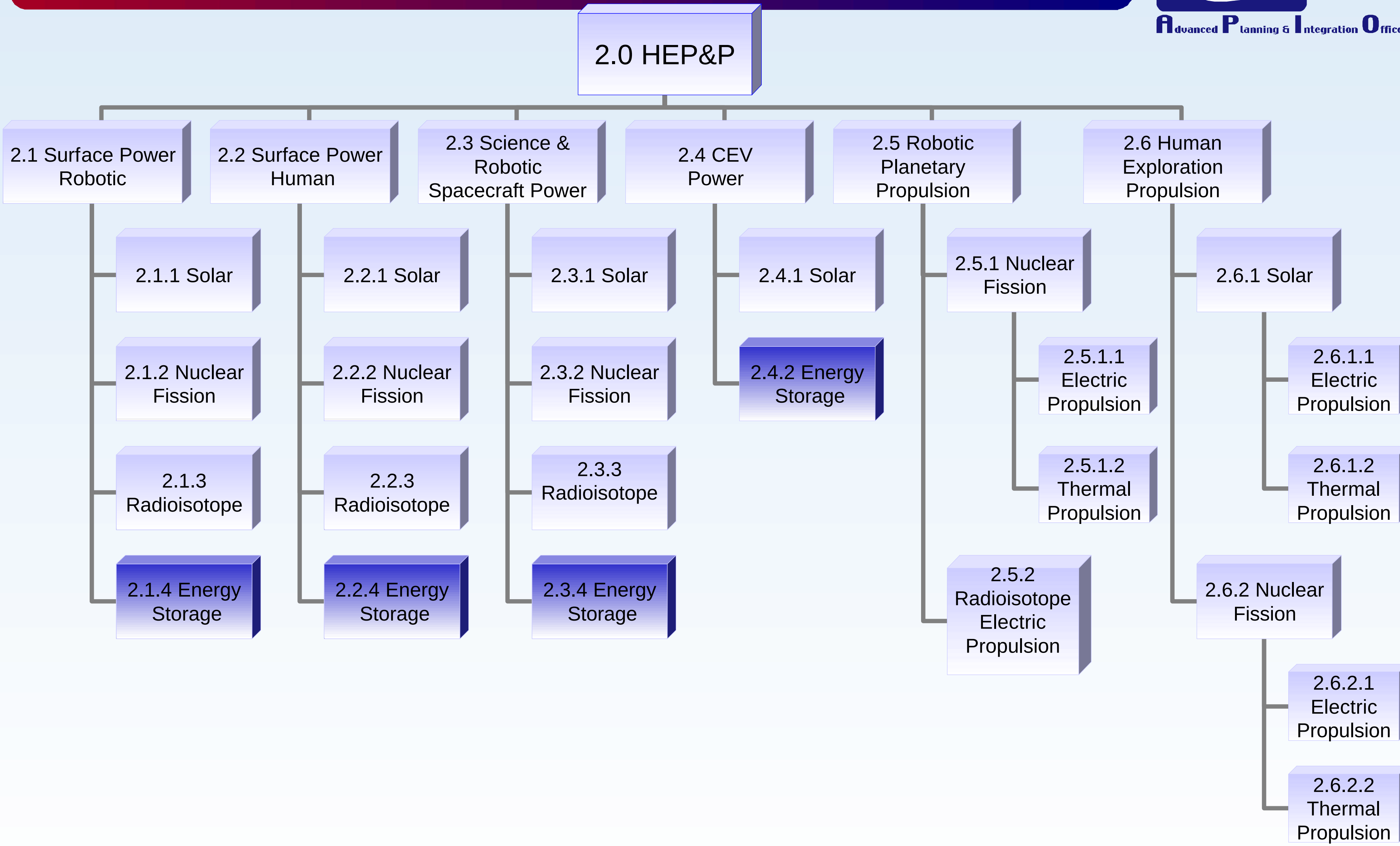

Types of Energy Storage Systems

Electrochemical Energy Storage Systems

- **Capacitors**
- **Primary Batteries**
- **Rechargeable Batteries (Secondary)**
- **Fuel Cells (Primary)**
- **Regenerative Fuel Cells**

Mechanical Energy Storage Systems

- **Energy Flywheels**
- **Energy / Momentum Flywheels**

Energy Storage Systems: Capabilities and Applications

System	Capability	Application
Capacitors – **Double-layer, ultra super**	**Stores very low amounts of energy. Provides high power for short duration (seconds). Can be recharged electrically several times.**	**RPS Powered Missions.**
Primary Batteries – **Ag-Zn, Li-SO_2, Li-$SOCl_2$**	**Provides up to several watts to hundreds of watts of power for several minutes/ hours to days. Can not be recharged. One time use only.**	**Launch vehicles, probes, and astronaut equipment.**
Rechargeable Batteries – **Ni-Cd, Ni-H_2, Li-Lion**	**Can store up to tens of kWh of energy. Can be recharged electrically several times.**	**Earth / Mars Orbital Missions; Outer / Inner Planetary Orbiters; Surface Missions; Astronaut Equipment**

Energy Storage Systems: Capabilities and Applications

System	Function	Application
Fuel Cells – **Alkaline, PEM**	**Provide medium – high power (hundreds of W to several kW) for several days. Can be recharged with chemicals.**	**Surface Missions; Shuttle / CEV**
Regenerative Fuel Cells – **Alkaline, PEM**	**Can store up to several MWh of energy. Can be recharged electrically several times**	**Lunar Habitat; Mars Habitat**
Flywheels – **Energy only; Energy and momentum**	**Can store up to tens kWh of energy. Provide power during eclipse periods and peak power demands. Can be recharged electrically several times.**	**Earth Orbital Missions (GEO & LEO);**

Energy Storage Systems: Metrics/Requirements for Space Applications

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General Requirements

Mass and Volume Efficiency

- –High Specific Energy (Wh/kg)
- –High Energy Density (Wh/l)

High Power Capability (Peak/continuous)

- –High Specific Power (W/kg)
- –High Power Density (W/l)

High Charge/Discharge Efficiency

- –Charge/discharge Efficiency (%)

Charge Retention

- – Minimal Capacity Loss on

Mission Dependent Requirements

Long Operational and Storage Life

- –Cycle Life (cycles@ % DOD):
- –Calendar Life (Years)

Operation at low and high temperatures

- –Operational capability (with minimal performance losses) at low temperatures
- – Operational capability with minimal performance losses) at high temperatures.

Energy Storage Systems: Current State-of-Practice

System	Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Cycle Life	Mission Life (yrs)	Issues
Primary Batteries	Ag-Zn Li-SO2, Li-SOCl2	Delta Launch Vehicles Cassini Probe MER Lander Sojourner Rover	90-250	130-500	-20 to 60	1	1-9	• Limited operating temp range • Voltage delay
Rechargeable Batteries	Ni-Cd, Ni-H2	TOPEX HST Space Station	24-35	10-80	-5 to 30	> 50,000 @25%DOD	>10	•Heavy and bulky • Limited operating temp range
Adv. Rech. Batteries	Li-Ion	Spirit & Opportunity Rovers	90	250	-20-30	> 400 @ 50% DOD	>2	Cycle Life
			Power Rating (kW)	**Specific Power (W/kg)**	**Power Density (W/l)**	**Efficiency %**	**Maintenance Frequency (hrs)**	
Fuel Cells	Alkaline H2-O2	Apollo, Shuttle	10	90	155	70%	2600	Heavy and Bulky Limited to short missions

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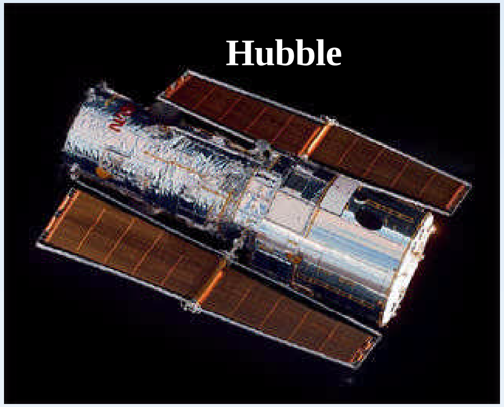
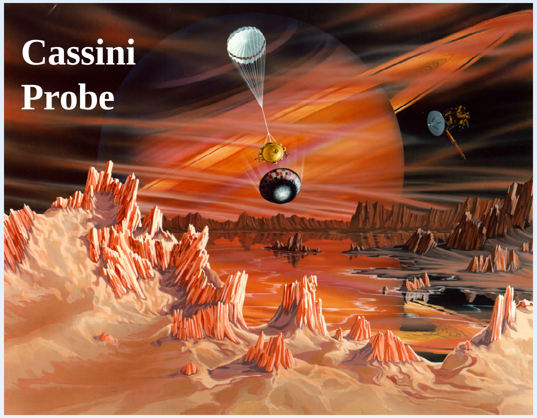
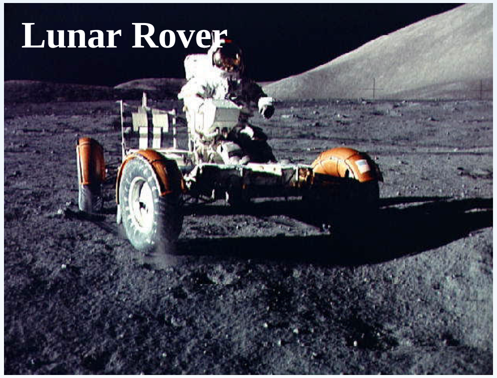
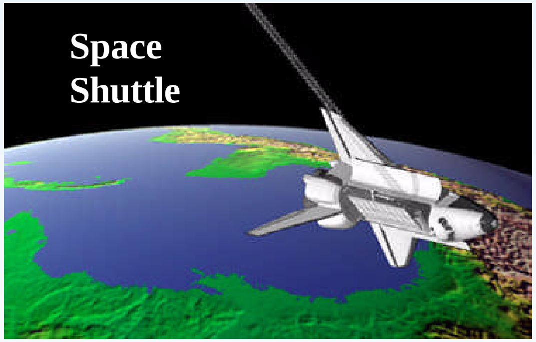
Energy Storage Systems: Past Applications



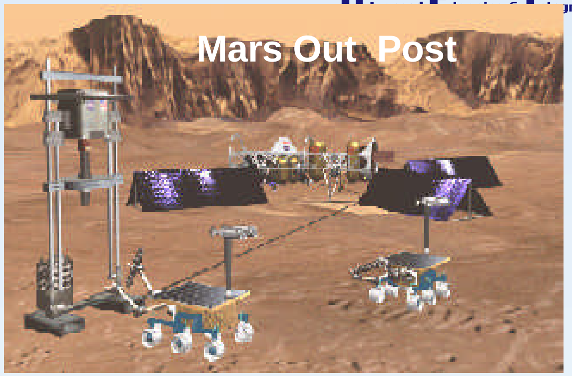


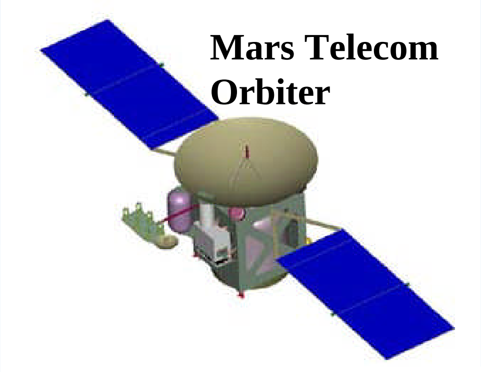


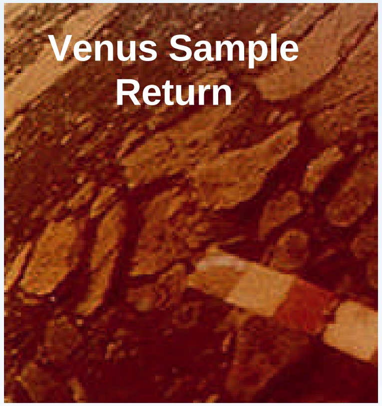


Energy storage systems have been used in 99% of the robotic and human space missions launched since 1960

Energy Storage Systems: Future Space Applications



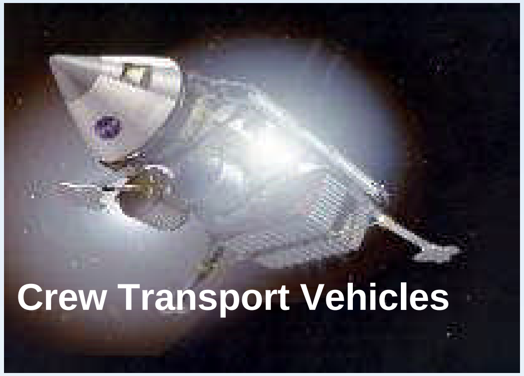


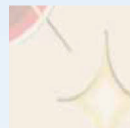


Future human and robotic exploration missions require advanced energy storage systems.

- **Critical capability requirements include: mass and volume efficiency (2-10 X Vs SOP), long life and the ability to operate in extreme environments.**

Crew Exploration Vehicles





CEV-LEO, CEV –Lunar, CEV-Mars

Capabilities Needed

- **TBD**

Capability of State of Practice Systems

- **System: Alkaline Fuel Cells**

Status of Advanced Energy Storage Systems

- **TBD**

Human Lunar/Mars Surface Habitat

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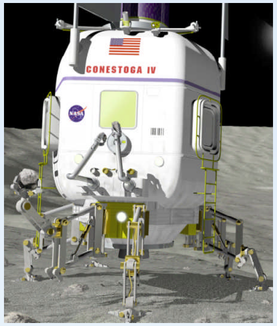
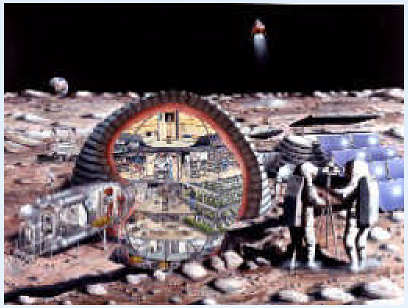




Long Duration Lunar/Mars Surface Habitat,

Capabilities Needed

- **Power 20-40 kW,**

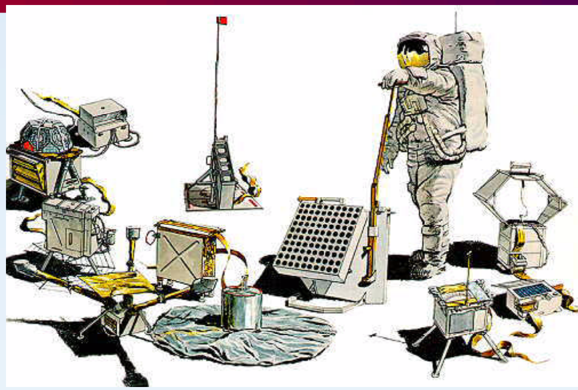
pabilities of State of Practice Systems

- **System: Ni-Hydrogen Batteries**

v. Status of Adv. Energy Storage Systems

- **Potential Systems: Regenerative H_2-O_2 Fuel Cells, Adv. Rechargeable Li-Ion Batteries,**

Astronaut In space and Surface Mobility/EVA



Astronaut Suit, EVA Tools & Instruments

Capabilities Needed

age Systems

bilities of State of Practice Systems (EVA)

ial Systems: Small Fuel Cells, Li-Ion / Polymer Batteries

Robotic/Human Landers / Rovers

Robotic & Human Rovers

Landing Systems /

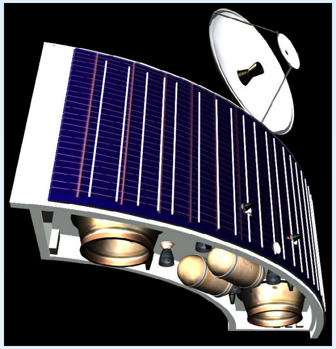
Capabilities Needed

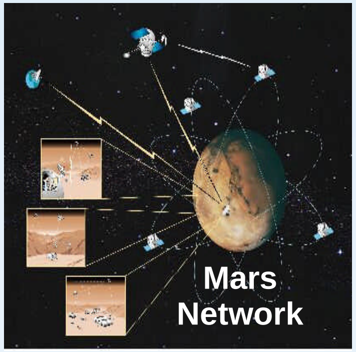
- **Power : 0.1 to 5.0 kW**

bilities of State of Practice Systems

Ion batteries, Polymer Batteries/Fuel Cells

Solar Powered Earth/Mars Orbiters





Lunar/ Mars Telecom Orbiters

Capabilities Needed

Energy Storage: 1-5 kWh

abilities of State of Practice Systems

- **System: Ni-H_2 Batteries**

Radioisotope Powered Robotic Orbital /Surface Missions


Europa Orbiter

Capabilities Needed

- **Power : 100-200 W**

y, Energy Storage Systems

apabilities of State of Practice Systems

- **Potential Systems: Li-Ion/Li-Polymer**
- **System: Li-ion Batteries**

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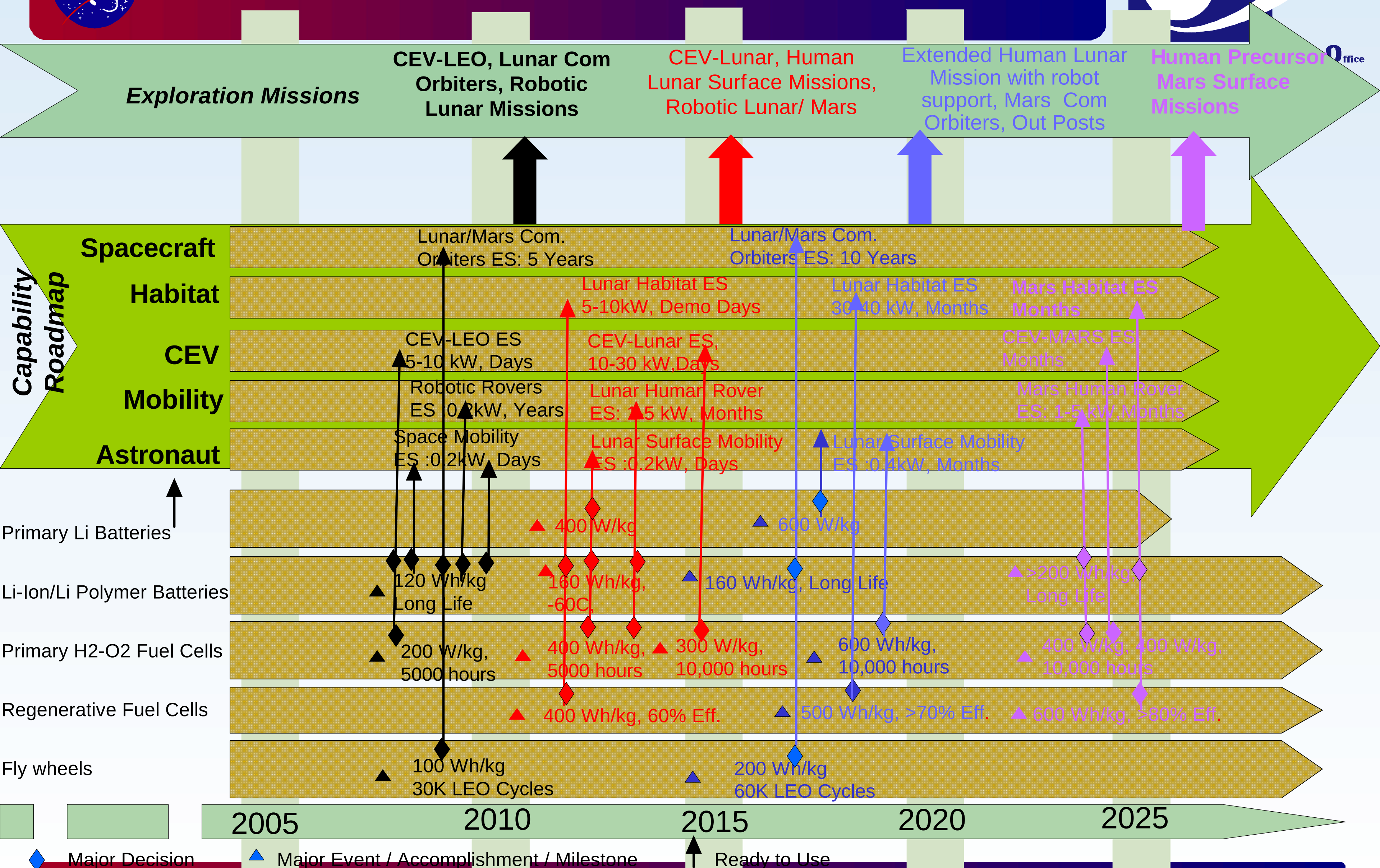
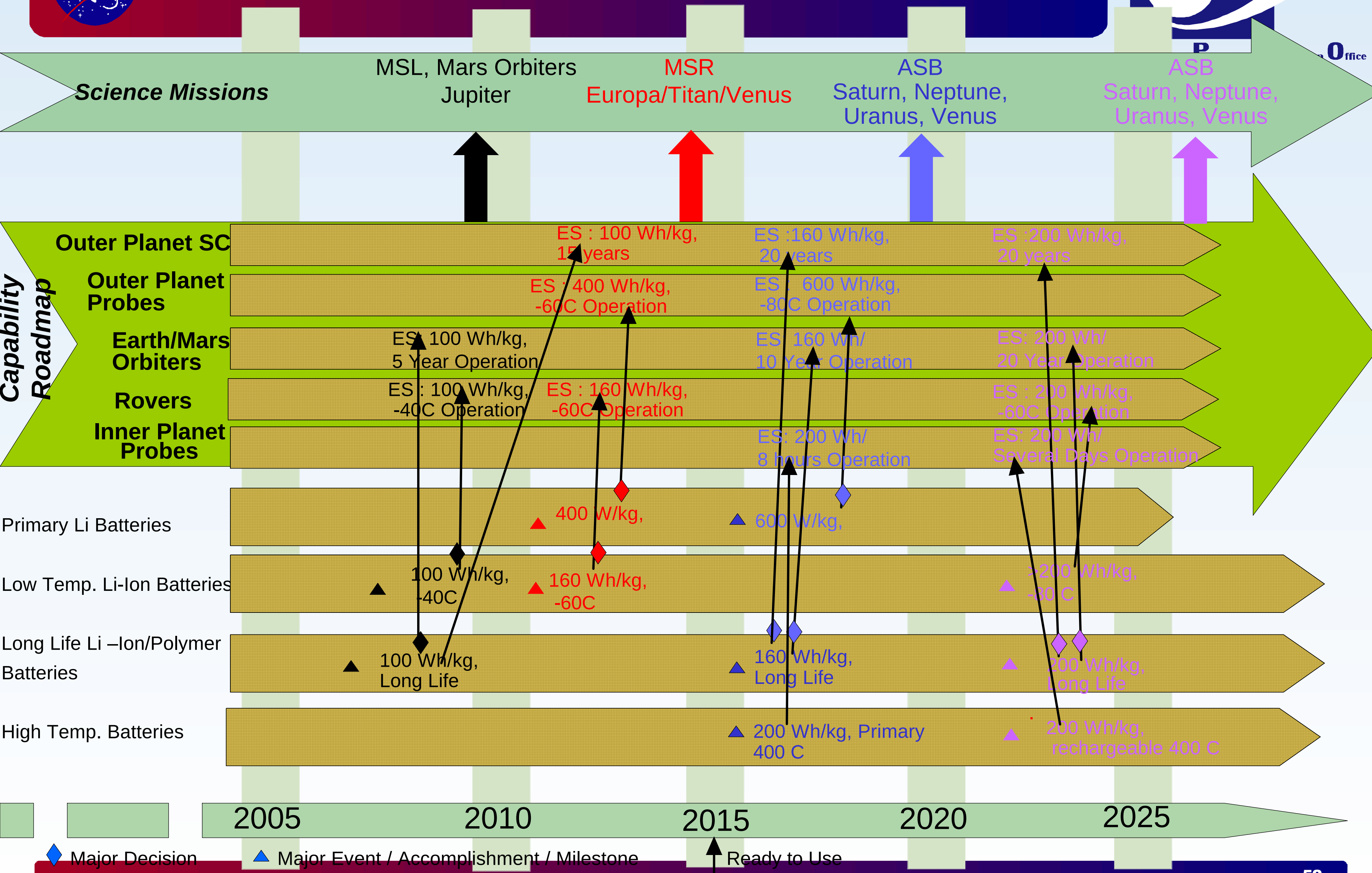
Energy Storage System Capability Roadmap-1



Energy Storage System Capability Roadmap-2



Summary

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- Critical capability requirements for future space missions include:
  - Mass and volume efficiency (2-10 X Vs SOP)
  - Long life (> 15 years)
  - Ability to operate in extreme environments

- NASA has modest energy storage technology development programs. These programs are insufficient to meet future missions needs
  - ESMD program is reasonably strong, but requires modest augmentation
  - SMD has no technology development program

- DOD/DOE/Commercial industry are developing advanced energy storage systems specific to their needs.
  - NASA has unique requirements that are different from DOD/DOE
  - NASA may benefit significantly by working with AFRL/DOD, wherever synergism exists

- Building a strong robust energy storage technology program at NASA will have a significant impact on future missions

Radioisotope Power System (RPS) Capability Roadmap Status

Bob Wiley, DOE HQ

RPS Sub-Team Chair

April 7, 2005

Disclaimer: This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 RPS Sub-Team members, and is not the official view of NASA or DOE.

Capability Breakdown Structure – HEP&P

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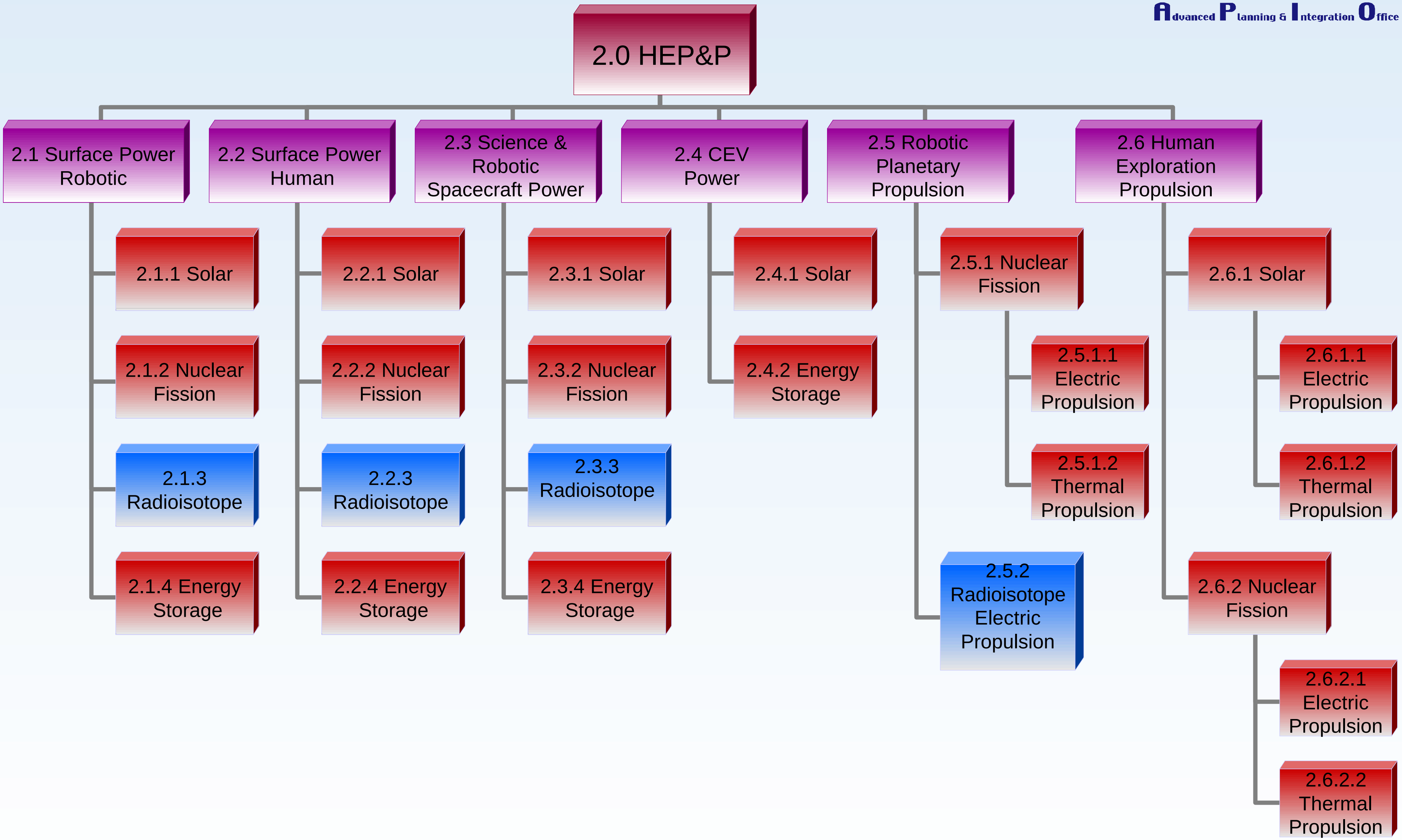
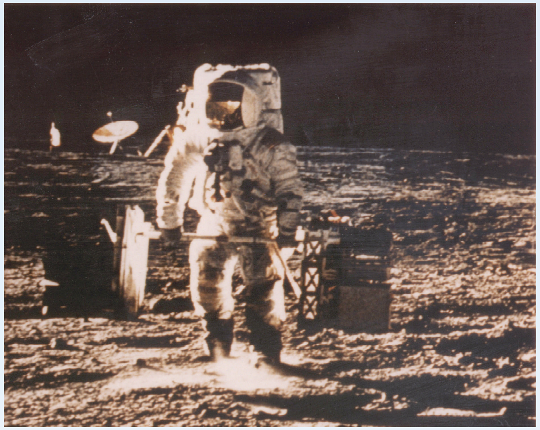
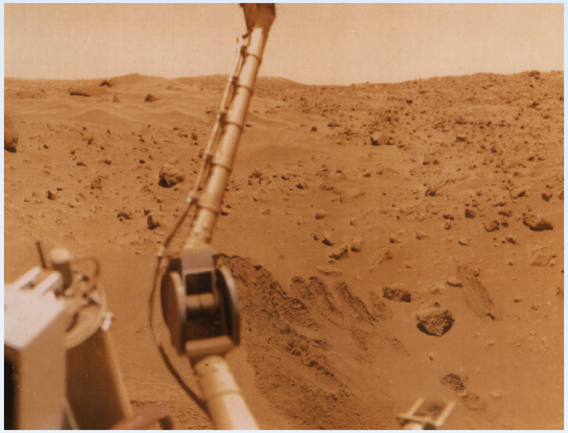


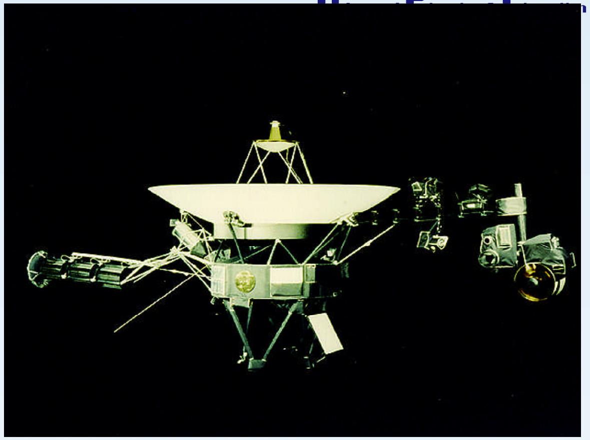
Past NASA Missions Using RPS – Including Moon and Mars



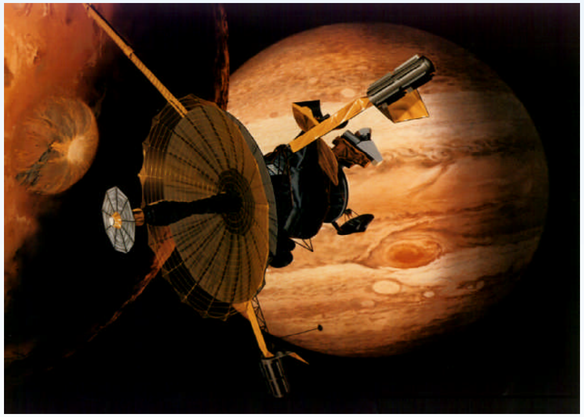
Apollo



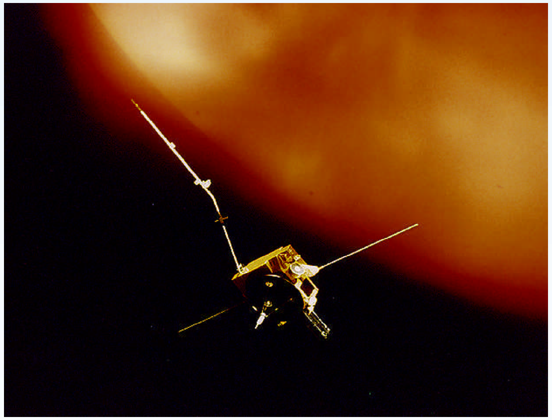
Viking



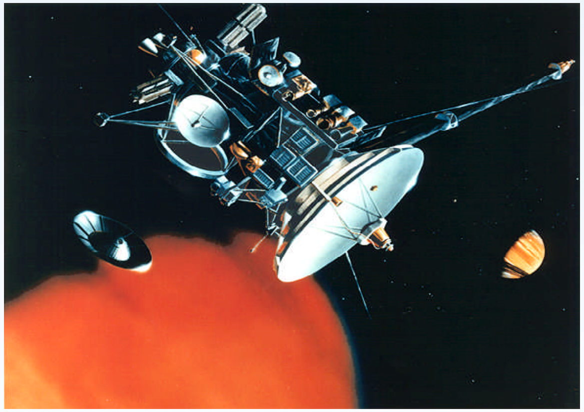
Voyager



Galileo



Ulysses



Cassini

Since 1961, 40 RTGs have been used on 22 US space systems.

Many Potential Future Science Missions Require RPS

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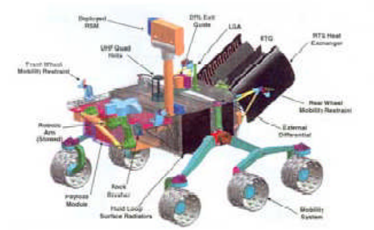
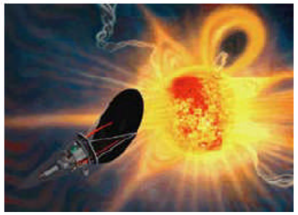
Near-term (2006 to 2015)

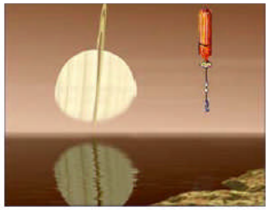
- New Horizons Pluto-Kuiper Belt Explorer (launch ~2006)
- Mars Science Laboratory (launch by 2009)
- Mars Scout Missions (launches 2011 & 2015)
- Solar Probe (launch ≥2012)

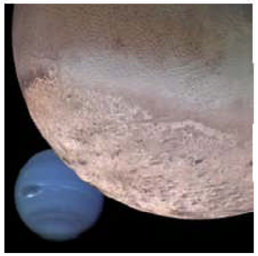


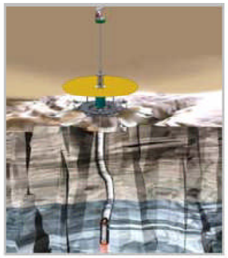


Vision Missions (≥2015)

- Medium Size (New Frontiers)
  - *Trojan/Centaur Recon Flyby*
  - *Asteroid Rover/Sample Return*
  - *Io Observer*
  - *Ganymede Observer*
- Flagship Class
  - *Europa Lander*
  - *Titan Explorer*
  - *Neptune-Triton Explorer*
  - *Uranus Orbiter with Probes*
  - *Saturn Ring Observer*
  - *Mercury Sample Return*
  - *Comet Cryogenic Sample Return*
  - *Interstellar Probe*
  - *Venus Sample Return*

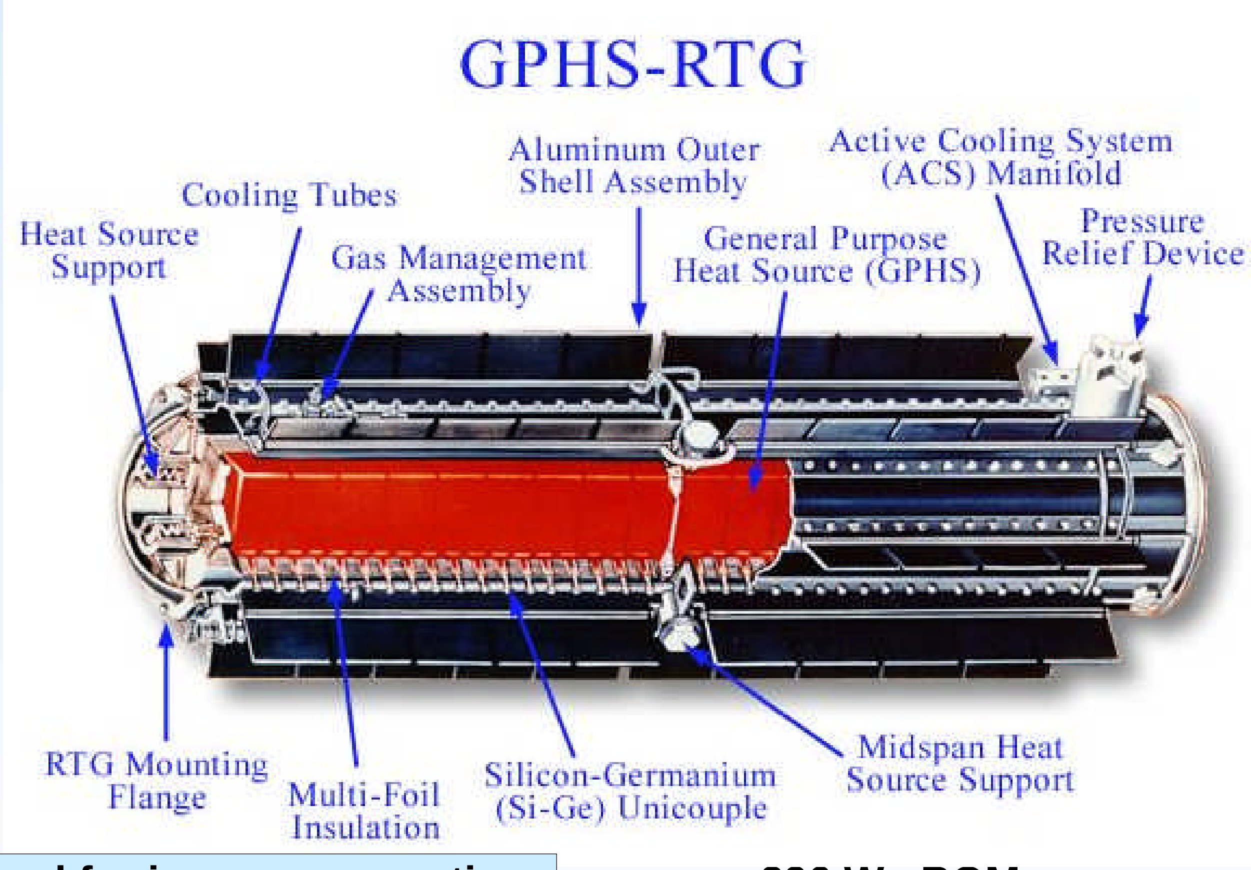






* *From NRC Space Science Decadel Surveys: "New Frontiers in the Solar System (2003)," and "The Sun to the Earth and Beyond (2003)."*

State-of-the-Practice Radioisotope Thermoelectric Generator



- Designed for in-space operation
- 18 GPHS modules
- SiGe thermoelectrics
- No longer in production

- 296 We BOM
- 56 kg (5.3 We/kg)
- 112 cm L x 40.6 cm D
- 6.6% system efficiency
- 30 year lifetime technology (Voyager)

State-of-the-Practice General Purpose Heat Source (GPHS)

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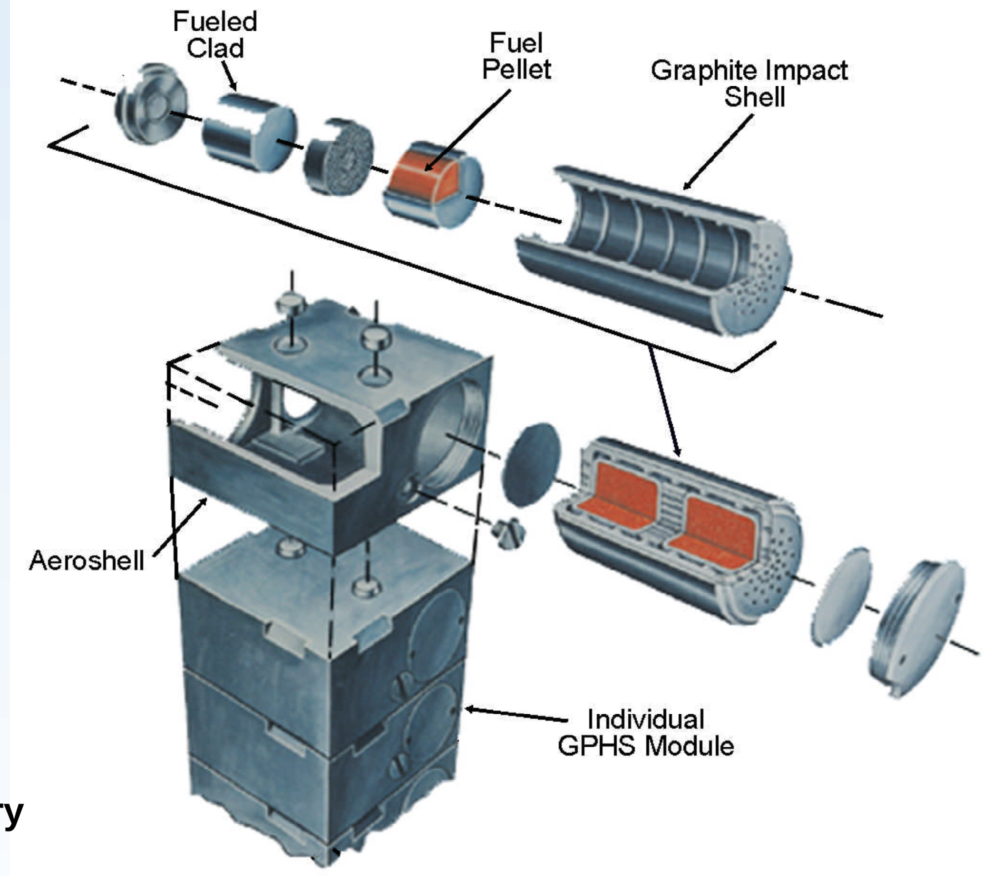
- Pu-238 dioxide fuel
  - Nominal 250 Wt from 4 fuel pellets
  - Alpha-emitter, 87-year half life
  - Nonweapons material
  - Highly insoluble
- Ir Cladding (encases the fuel)
  - Fuel containment (normal operations or accidents)
  - High melting point -- thermal protection
  - Ductile -- impact protection
- Graphite aeroshell (protects fuel & cladding)
  - Impact shell -- impact protection
  - Insulator -- protect clad during re-entry
  - Aeroshell -- prevent burnup during re-entry
- Mass 1.6 kg (0.6 kg Pu-238)
- Dimensions 10 cm x 9.3 cm x 5.8 cm



Mass, Efficiency and Life are the Key RPS Metrics

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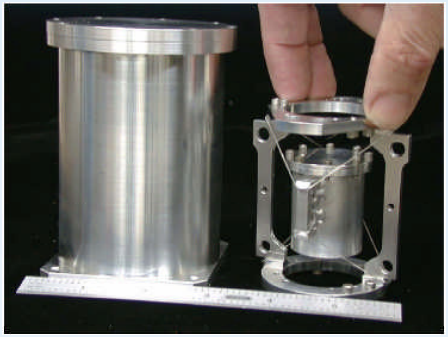
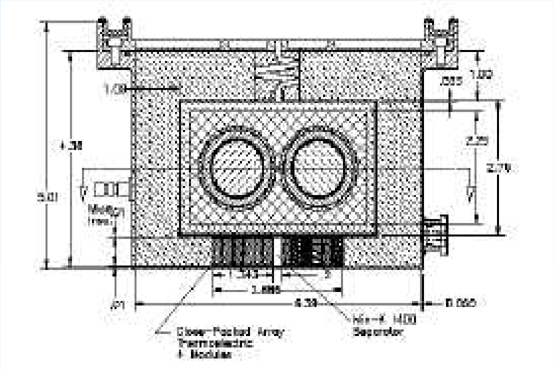
	BOM Power	BOM Specific power	System efficiency	Lifetime
State of Practice (GPHS-RTG)	296 We	5.3 We/kg	6.6%	30 years (Voyager)
Milliwatt/ multi-watt class	10-100 mWe 1-20 We	Low - TBD	5-20%	5-14 years
SOA 100 We class	110+ We	3-4 We/kg	6-20%	14+ years
Advanced 100 We class	110+ We	8-10 We/kg	8-40%	14+ years
Kilowatt class	1-2 kWe	8-10 We/kg	8-40%	5-14 years
Multi-kilowatt class	5 kWe	10-12 We/kg	30-40%	5+ years

Milliwatt and Multiwatt RPS



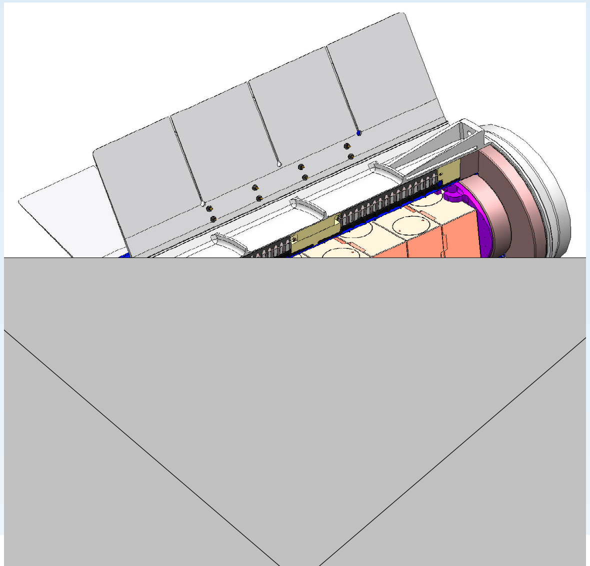
- **Milliwatt-class RPS**
  - 10-100 mWe of interest
  - RHU-based heat source

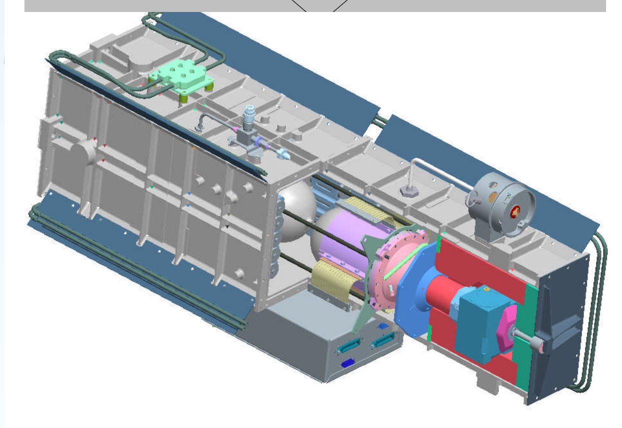


- **Multiwatt-class RPS**
  - 1-20 We of interest
  - GPHS-based heat source

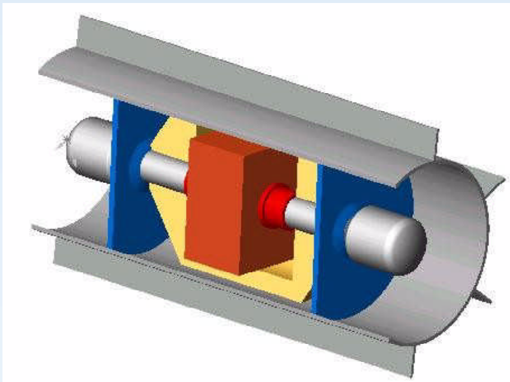
- **DOE to issue solicitation in 2005 for system design and non-nuclear testing of engineering-type units**
- **Funded by NASA Science Mission Directorate**

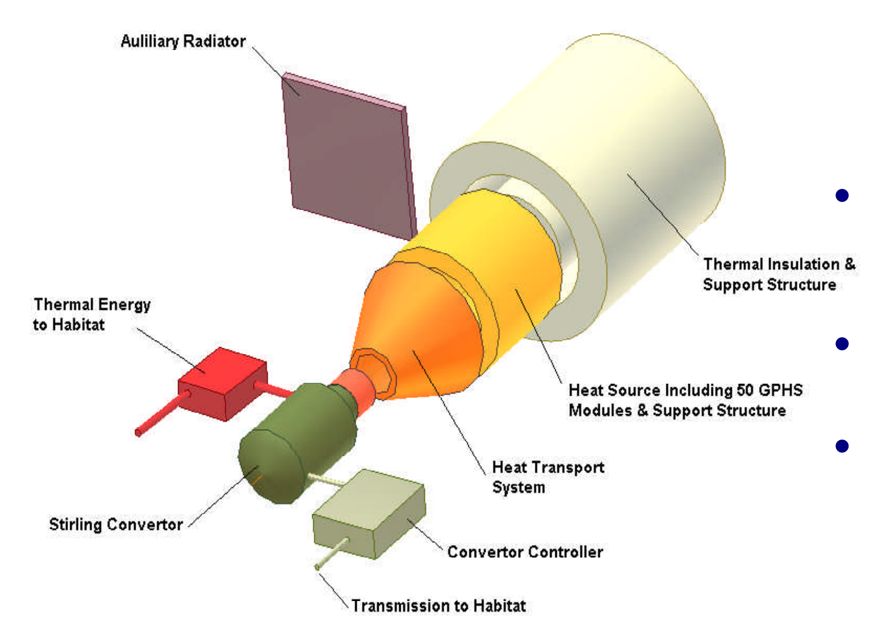
State-of-the-Art 100 We Class RPS





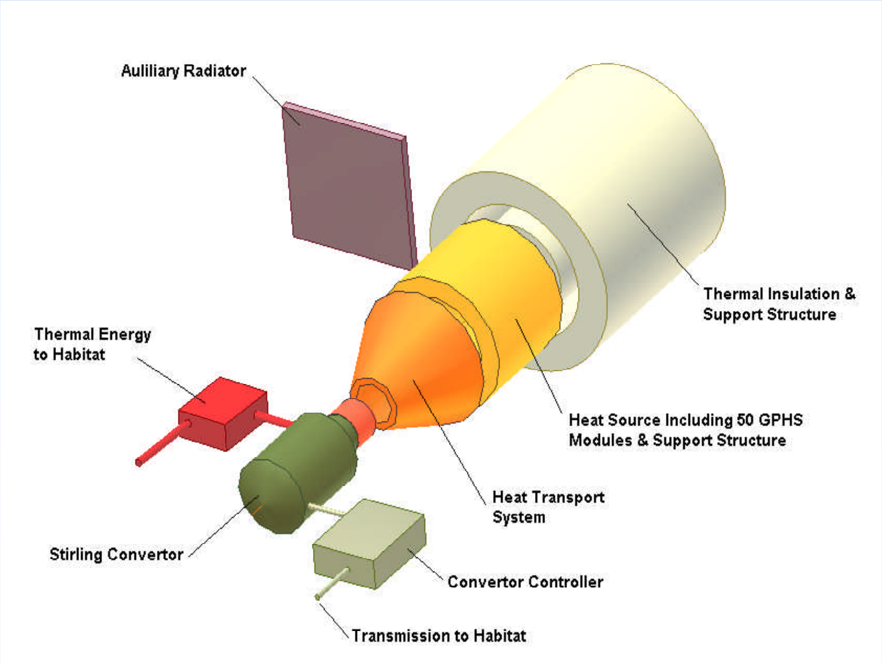
Advanced RPS Options

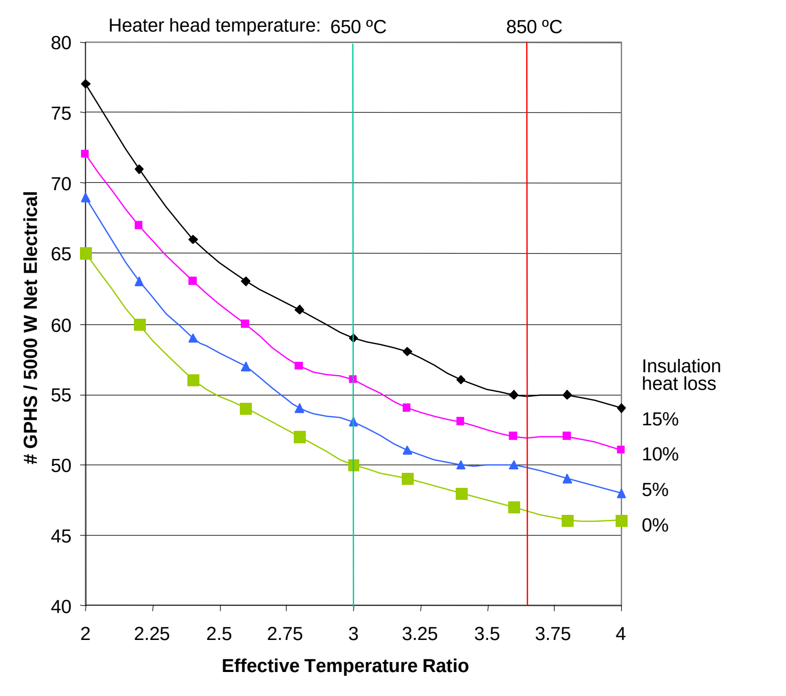




- Capability option for Spiral 2 robotic missions (landers/rovers), Spiral 3-5 human missions, and radioisotope electric propulsion (REP)
- Based on GPHS heat source
- Development candidates
  - Advanced 100-We class @ 8-10 We/kg
  - Kilowatt-class (1-2 kWe) @ 8-10 We/kg
  - Multikilowatt-class (5 kWe) @ 10-12 We/kg
- Technology gaps exist for such lightweight systems – need improved conversion systems, heat rejection and PMAD
- Lightweight RPS enhances mission payload fraction and REP performance
- Application of kilowatt and multikilowatt-class capability may be limited by GPHS processing throughput

Multi-kilowatt RPS Option for Spiral 3-5 Missions





- **5 kWe module; ~ 400 kg**
- **Provides both power and heat**
- **Only modest shielding or separation distance needed to limit radiation dose**
- **Relatively low-risk development needs**
  - **High efficiency energy conversion**
  - **Light-weight thermal management and PMAD**

- **Pu-238 Required Per Module Is Comparable to Total Flown on Cassini**
  - **Cassini: 3 x 18 = 54 GPHS modules**

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RPS Research and Technology Development

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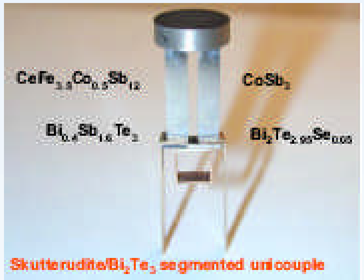
RPS Power Conversion Technology (RPCT) Project

- **Ten competitively awarded NRA contracts aimed at improving efficiency, specific power and reliability of future RPS**
  - **Five research (TRL• 3) and five development-focused (TRL• 5) for milliwatt (~40 mW) and nominal (~100 W) systems (scalable to 1-10 W)**
  - **Contracts initiated in 2003. Each consists of three 1-year phases**
- **Selections covered Stirling, thermoelectric, thermophotovoltaic (TPV), and Brayton power conversion technologies**
- **Of development contracts, only Stirling continuing**

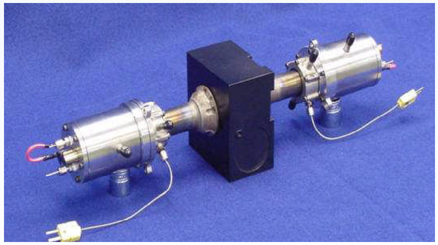
Segmented Thermoelectric Research @ JPL

- **Direct-funded research on higher efficiency thermoelectric technology**
- **Demonstrated 12.5% efficiency with single unicouple: skutterdite/Bi2Te3 at 700-87** °C • T
- Developing sublimation-inhibiting coatings and insulation



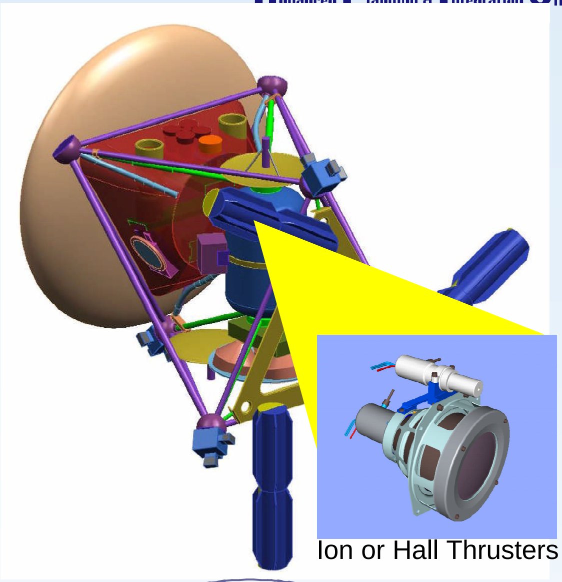
Advanced Stirling Research @ NASA GRC

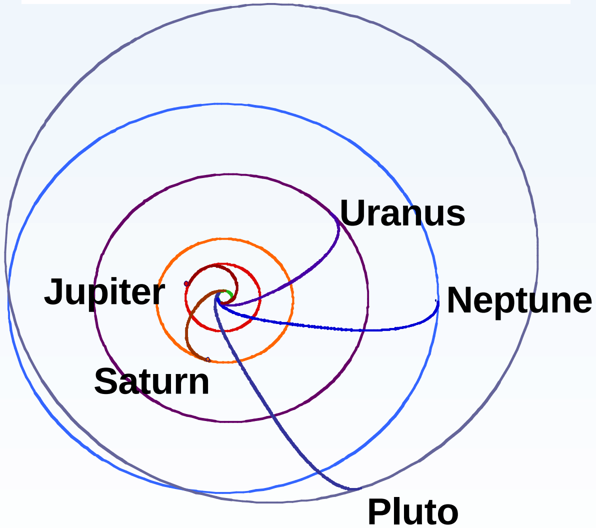
- Direct-funded research on technologies for 2nd Generation SRG
- Achieved 36% engine efficiency (AC out) on 85-watt testbed at 650-30 °C • **T**
- **Focus on potential use of higher temperature materials, mass reduction, and improvement in controller reliability/operation**
- **Identified and evaluated candidate materials**
- **Developed simulation of new controller operation**



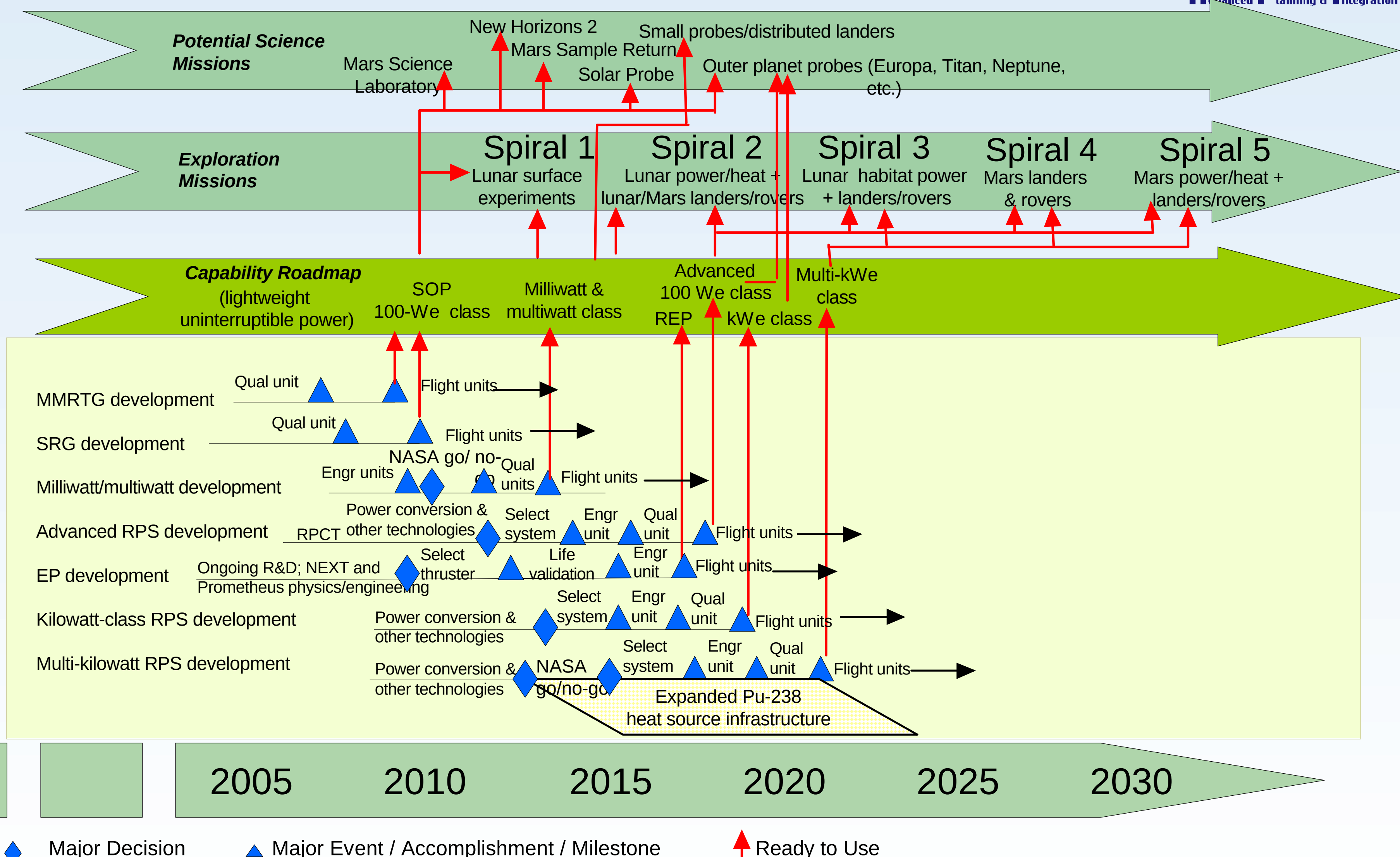
Capabilities Provided by REP

- REP best suited for science missions employing robotic spacecraft
- With existing medium launchers, could enable rendezvous with small planetary bodies and deep space objects
  - Launch system boosts spacecraft to velocities above earth escape (positive C3)
  - REP provides portion of in-space acceleration, deceleration and maneuvers about target
  - Small spacecraft with up to several 100's kg payloads
- With existing heavy launchers, could provide propulsive augmentation for orbital missions to outer planets
  - Chemical and/or solar electric propulsion serves as main propulsion up to distance of Mars/asteroid belt
  - REP used for "end game" propulsion maneuvers for deceleration and orbital changes about planetary body
- Implementation requires modest investment in technologies that could be fielded by end of this decade
  - High-specific power radioisotope generators based on advanced Stirling engine or segmented thermoelectric technology currently under development
  - Long-lived 100 We to ~1 kWe-class electric thrusters capable of 5-10 year lifetimes
  - Lightweight bus and payload technologies





RPS Capability Roadmap



RPS Plays a Vital Role in NASA's Future

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- For many Science missions, the RPS (power and heat) is enabling.
  - Most outer planet and beyond spacecraft
  - Certain solar and inner planet missions
  - Certain Mars and other surface applications
- For Exploration:
  - RPS can be fielded to support early lander/rover missions.
  - RPS is an option for entry-level power and heat for Spiral 3-5 human missions and surface operations.
- Multimission RPS (MMRTG and SRG) are being developed with SMD funds, but no RPS is currently in production.
- Improved RPSs can be developed to provide full range of capabilities.
  - Robotic spacecraft and surface missions
  - Radioisotope Electric Propulsion (REP)
  - Spiral 3-5 human surface missions
- Lightweight components are needed to fill technology gaps for RPS system development.
  - High-efficiency energy conversion (reduced Pu-238 cost)
  - Heat rejection
  - PMAD

High Energy Power and Propulsion Fission Sub-Capability Roadmap Status

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Oak Ridge National Laboratory

Presented to
National Research Council

April 7, 2005

Disclaimer:
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 Fission Sub-Team members, and is not the official view of NASA or DOE.

Presentation Outline

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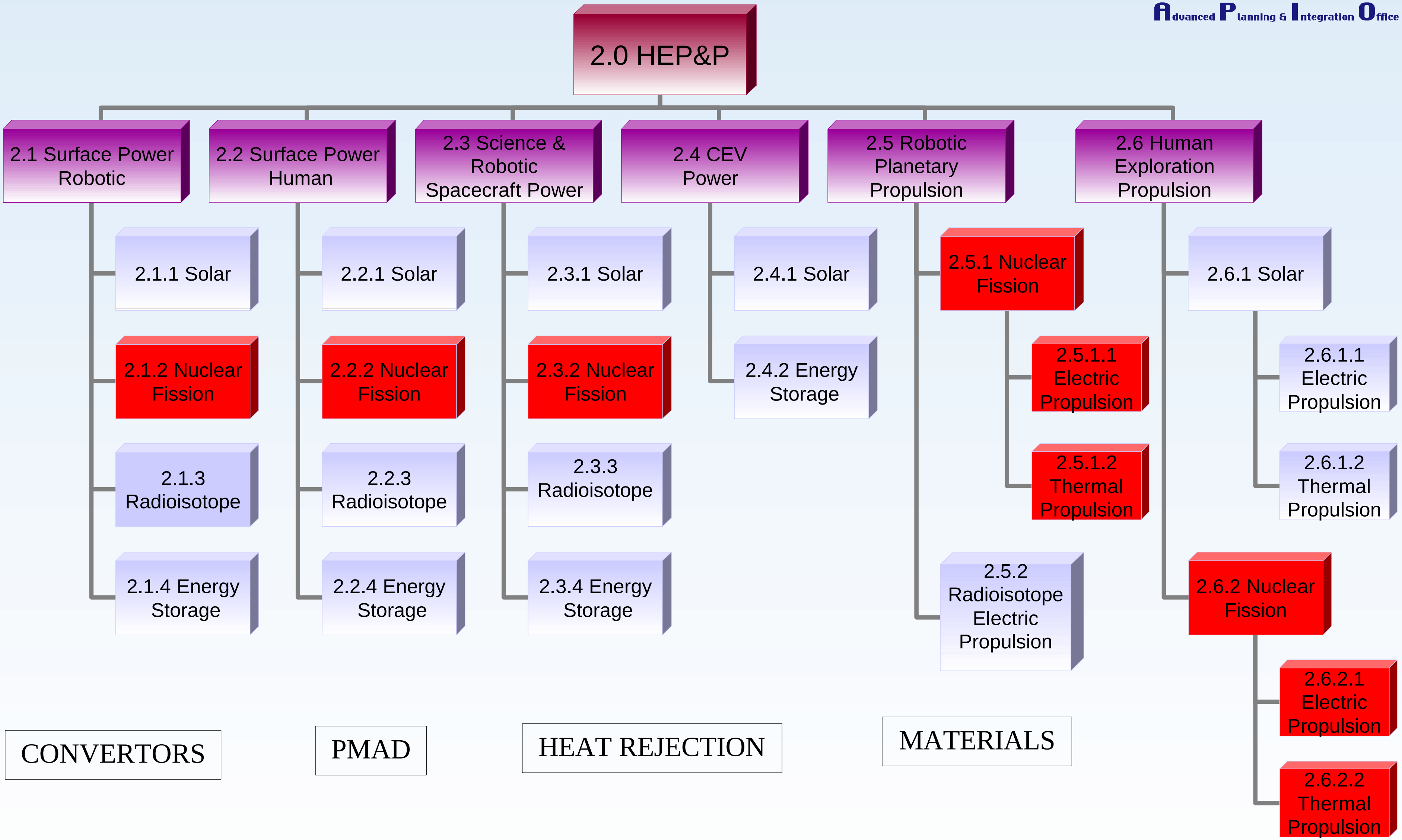
- Space Fission Propulsion and Power Introduction
- Nuclear Electric Propulsion (NEP)
- Surface Power (SP)
- Nuclear Thermal Propulsion (NTP)
- Bi-Modal Nuclear Thermal Propulsion (BNTP)
- Summary

This Presentation Addresses All Space Fission Power and Propulsion Capabilities Within CRC-2 Scope



Fission Technology Enables Or Enhances...

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- Fuel energy densities ~ 10^7 that of chemical systems
- In-space Power and Propulsion
  - Power and propulsion independent of proximity to sun or solar illumination
    - Constant power level available for thrusting and braking
  - Go where you want, when you want
    - Expanded launch windows
    - Enhanced maneuverability
    - Faster trip times / reduced human radiation dose
- Surface Power
  - Provides power-rich environments
    - Telecom
    - Habitat
    - Insitu Resource Utilization / Propellant Production (ISRU / ISPP)
  - Enables planetary global access
  - Enables Lunar overnight stays

Space Fission Power and Propulsion Are Characterized By Key Parameters

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- **Power:** Thermal and/or electric power generated by system
- **Mass:** Total power or propulsion system mass
- **Lifetime:** Length of time of operation at full power (or equivalent)
- **Specific Mass (a):** Ratio of total power and/or propulsion system mass to electric power distributed to spacecraft
- **Engine Thrust-to-Weight:** Thrust produced per unit engine mass
- **Initial Mass In Low Earth Orbit (IMLEO):** Total spacecraft mass launched and assembled in low earth orbit (LEO) prior to mission start
- **Specific Impulse (Isp):** Thrust per unit mass flow of propellant
- **Efficiency (h):** Ratio of electric or jet power input to thermal power

Space-Based Fission Systems Differ From Earth-based Commercial Power Systems

- Highly-Enriched-Uranium (HEU) fuel
- Mass
- Power densities and temperatures
- Fuels / coolants / materials systems
- Power conversion and heat rejection technologies
- Shielding technologies
- Automated or autonomous operation and control
- Limited or no maintenance & refueling
- Space or planetary operational environments

U.S. Has Pursued Several Aerospace Nuclear Development Programs Since 1945

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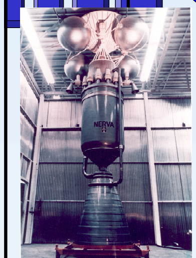
ANP — 1946-1961, Aircraft Nuclear Propulsion Project

1953, "Nuclear Energy For Rocket Propulsion", R. W. Bussard

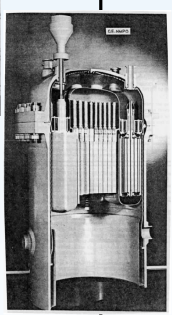


Rover/NERVA — 1955-1973, Nuclear Thermal Rocket

SNAP-2, 8, 10, 50 — 1957-1973, Systems for Nuclear Auxiliary Power

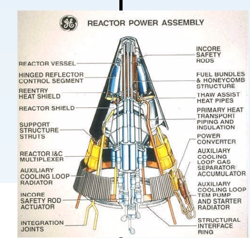
MPRE — 1958-1966, Medium Power Reactor Experiment

1965, SNAPSHOT



710 — 1962-1968, 710 Reactor

SPR — 1965-1968, Adv. Space Nuc. Power Program (SPR)



SPAR / SP-100 — 1984-1992, SP-100

MMW — 1985-1990

SNTP — 1987-1993

2003 - NSI & Prometheus

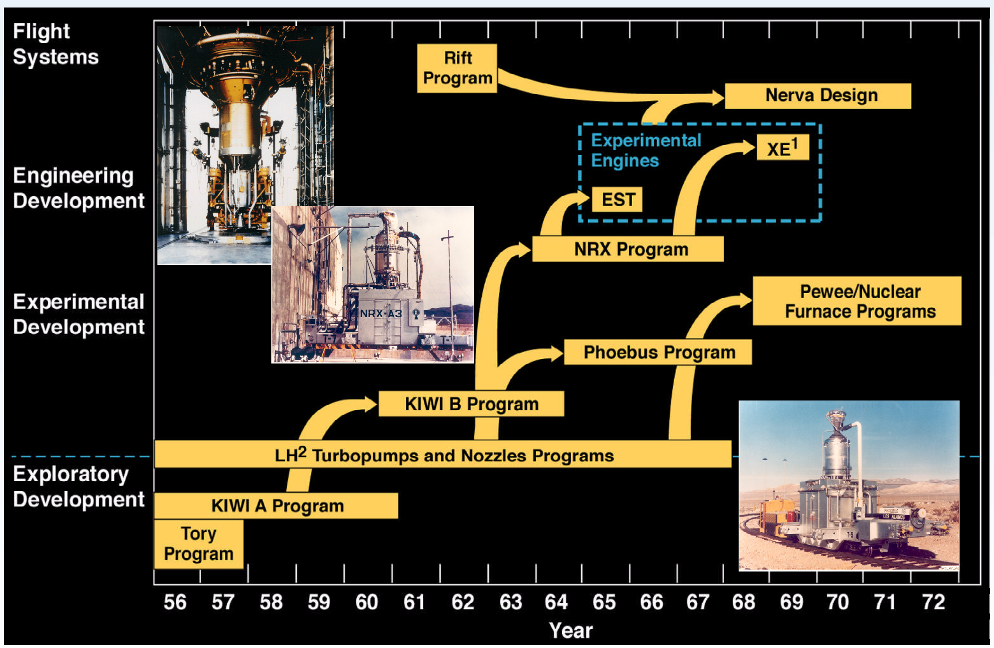
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005

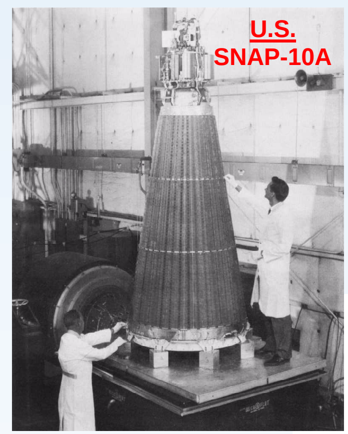
Significant Space Fission Technology Development Has Been Conducted

No U.S. Flight and Ground Test Experience Since 1972

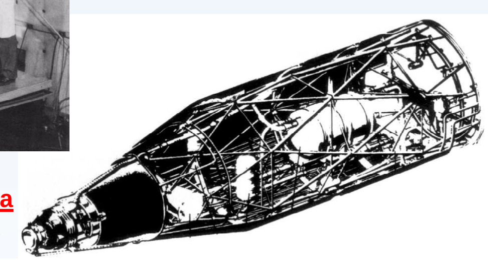
- **Nuclear Thermal Propulsion**
  - **20 Ground Test Reactors Operated**

- **Space Power**
  - **36 Systems Flown (1 U.S., 35 Russian)**
  - **5 U.S. ground test reactors operated**

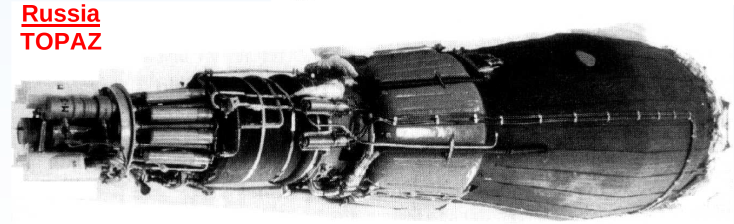




Russia
BUK



Russia
TOPAZ



Nuclear Fission Flight System Development Programs Require Sustained Effort

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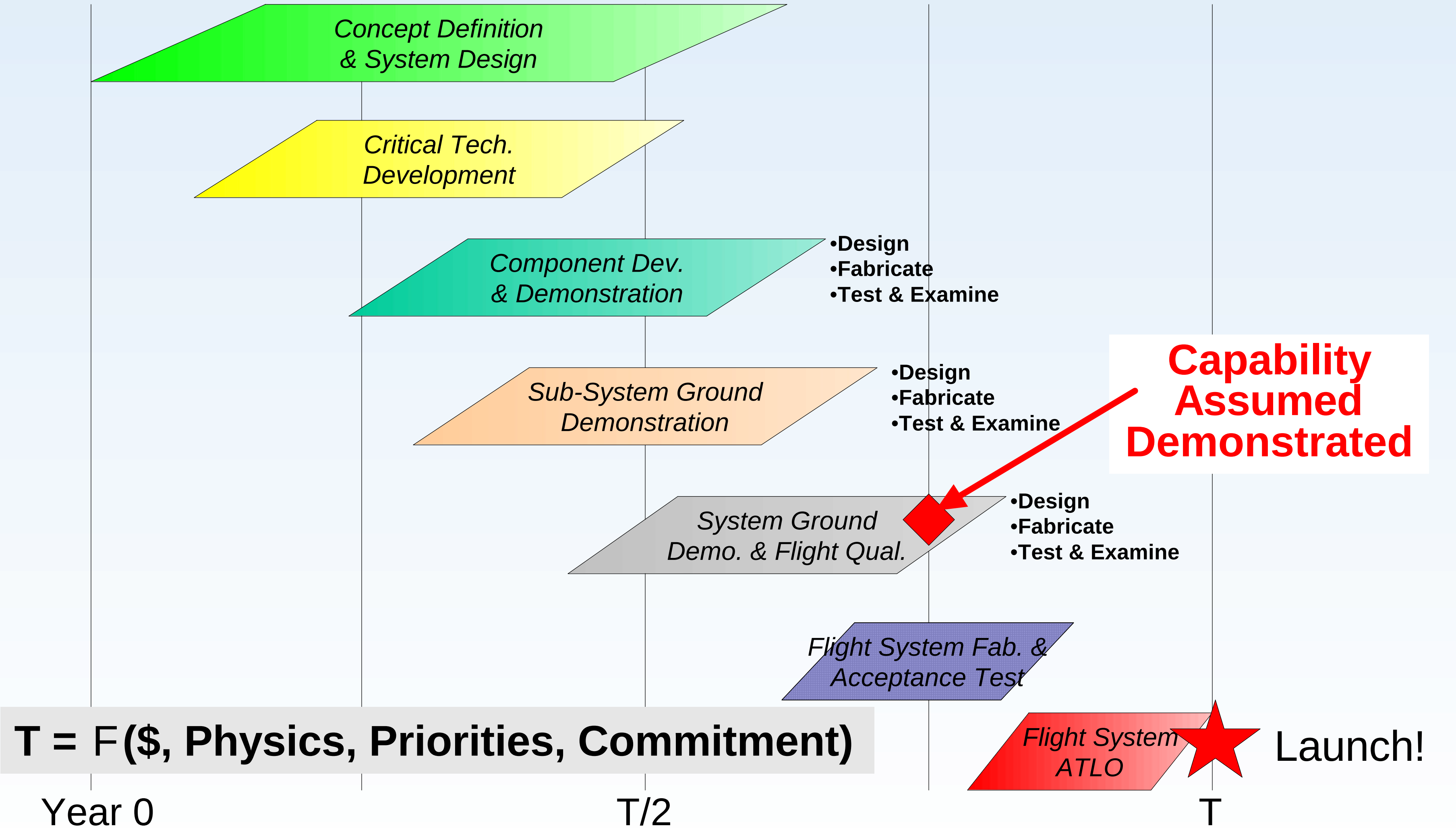

CRC-2 (HPE&P) Is Developing Fission Sub-Capability Roadmap

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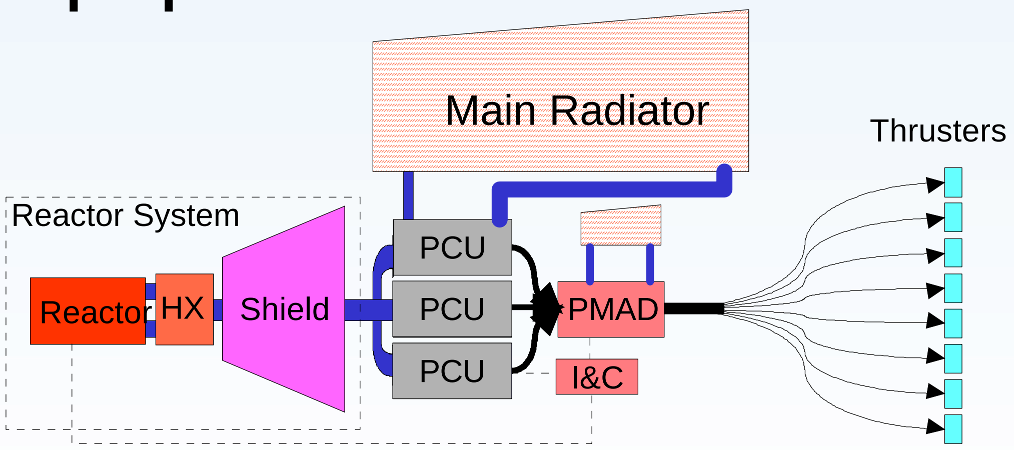
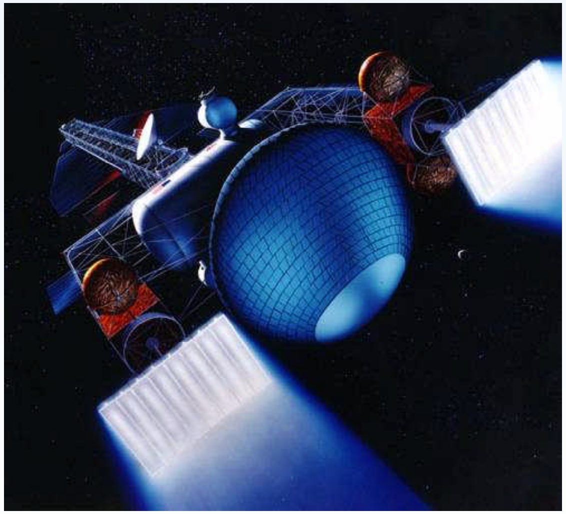
- **Philosophy**
  - Address scope of VSE
  - Update prior major studies (SEI, CRAI, etc.) strategies and recommendations to accommodate
    - Current technology status
    - Current infrastructure status
    - Current thinking with respect to likely missions and mission architectures
- **Process**
  - Develop initial "independent" MMW-NEP, Surface Power, and NTP and BNTP Capability Roadmaps
    - Assume no resource constraints
    - Only technology and knowledge constraints
  - Integrate four roadmaps to leverage synergisms, identify intersections and off-ramps, and eliminate gaps
  - Integrate Prometheus-I/II plan as available
  - Overlay strategic objectives, mission bogies, funding profiles as information becomes available

Nuclear Electric Propulsion

- Compact system capable of providing spacecraft propulsion and electrical power for deep space robotic missions or near-Earth cargo and piloted Mars missions.
- Primary subsystems include: reactor system, power conversion unit(s), power management and distribution unit, heat rejection system, and electric thrusters.
- Characterized by extended operation and minimum propellant mass.





Benefits of Nuclear Electric Propulsion

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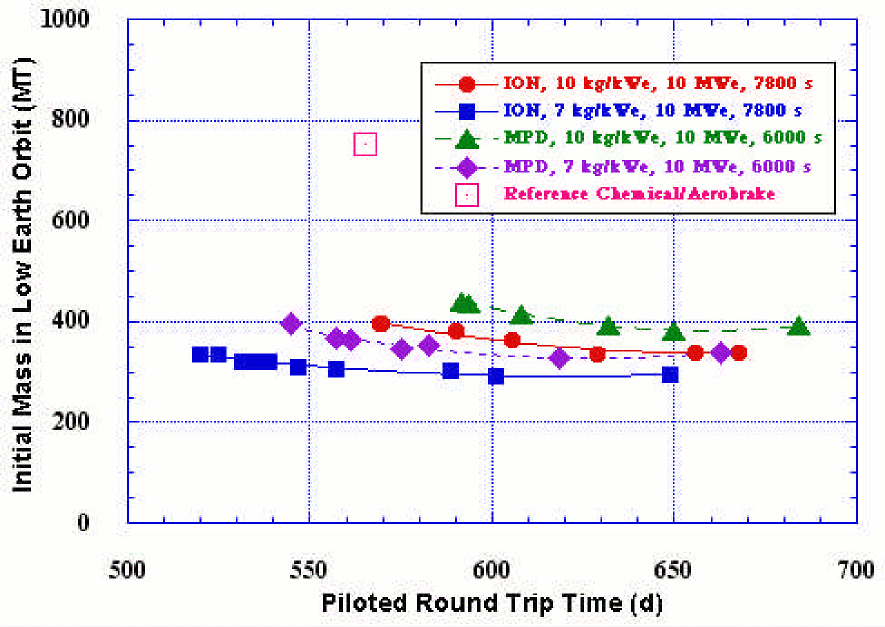
- Propulsion and electrical power from single system
- Constant power source for on-board life support and science instruments
- High specific impulse enables low initial propellant mass and re-supply mass
- High power system (1-10 MWe) supports large cargo, deep-space science, and short trip times for piloted missions to Mars.
- Provides increased flexibility for launch opportunities compared to chemical rockets



Desirable Nuclear Electric Propulsion Performance Characteristics*

Mission	Specific Mass (kg/kWe)	Power (MWe)	Specific Impulse (ks)	Lifetime (yr)
Orbital transfer	10 – 30	0.1 – 1.0	2 – 8	3 – 10
Robotic interplanetary	30 – 50	0.1 – 1.0	5 – 10	10 – 12
Lunar cargo	10 – 20	0.5 – 5.0	3 – 10	3 – 10
Mars cargo	10 – 20	2 – 10	5 – 10	2 – 10
Mars piloted	< 10	5 – 40	5 – 10	2 – 10

*NASA TM 105707, "Summary and Recommendations on Nuclear Electric Propulsion Technology for the Space Exploration Initiative," April 1993

Preliminary Planning Assumptions: NEP Mission & Performance Evolution

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Science/Human/Cargo NEP Mission Studies

- 2002 JIMT
- 2002 DRM
- 2002 DRM
- 1994 Clark
- 1993 George
- 1992 George
- 1992 McDonald Douglas
- 1991 Boeing

Science/Human/Cargo NEP Missions

- Lunar Orbiter
- Jupiter Moon Tour
- Outer Planets
- Kuiper Belt

- Lunar Cargo
- Mars Cargo
- Mars Piloted

Entry-Level Science NEP Performance

- 200 kWe
- 3-yr life
- 70 kg/kWe
- Robotic
- Isp = 5000 s

High-End Human/Cargo NEP Performance

- 5 MWe
- 5-yr life
- 10 kg/kWe
- Human
- Isp = 10000 s

Current State-of-the-Art for Nuclear Electric Propulsion

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- Reactor subsystem (U.S. only)
  - 44 kW(t)/530 W(e) – SNAP-10A (1965)
  - 2400 kW(t)/100 kW(e) – SP-100 (1984-1992)
- Power conversion subsystem
  - Stirling: 12.5/25 kWe NASA MTI, Commercial SOA 10s-100s We
  - Brayton: 10 kWe, 1144 K PCS tested for 38,000 hr
  - LM-Rankine: 200 kWe K-Rankine turbine tested ~ 4000 hrs in MPRE (1962-67), ~ 160,000 hrs component tests
- Power management and distribution subsystem
  - 160 V; 57+ kWe; 400 K – ISS
- Heat rejection subsystem

Current NEP Sub-system Maturity Levels and MMW NEP Development Needs

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Subsystem	Current CRL	Development Needs for MMW NEP
Reactor	6 @ 43 kWt* 2 @ 2 MWt 1 @ 25 MWt	• High temperature fuel (1500-2000 K) • High burnup fuel (>10%) • High temperature structural materials (1500 K) • Rad-hard I&C (10^{23} n/cm^2 and 100 Mrad) • Robust shield material
Power Conversion	5-6 For static* 3-4 For dynamic	• Refractory metal components (1500 K) • High temperature bearings and seals • Rad-hard alternator insulation • Two-phase flow management (LM-Rankine)
PMAD	5-6 @ < 10 kWe 2 @ > 100 kWe	• High temperature semiconductors (600-700 K) • High power • Rad-hard electronics
Heat Rejection	6 @ ~ 100 kWt**	• High temperature, low mass materials • High temperature heat pipes
Electric Thrusters	6 @ < 10 kWe 2 @ > 100 kWe	• Scaling to high power • Or development of high power concepts

* SNAP-10A **TOPAZ

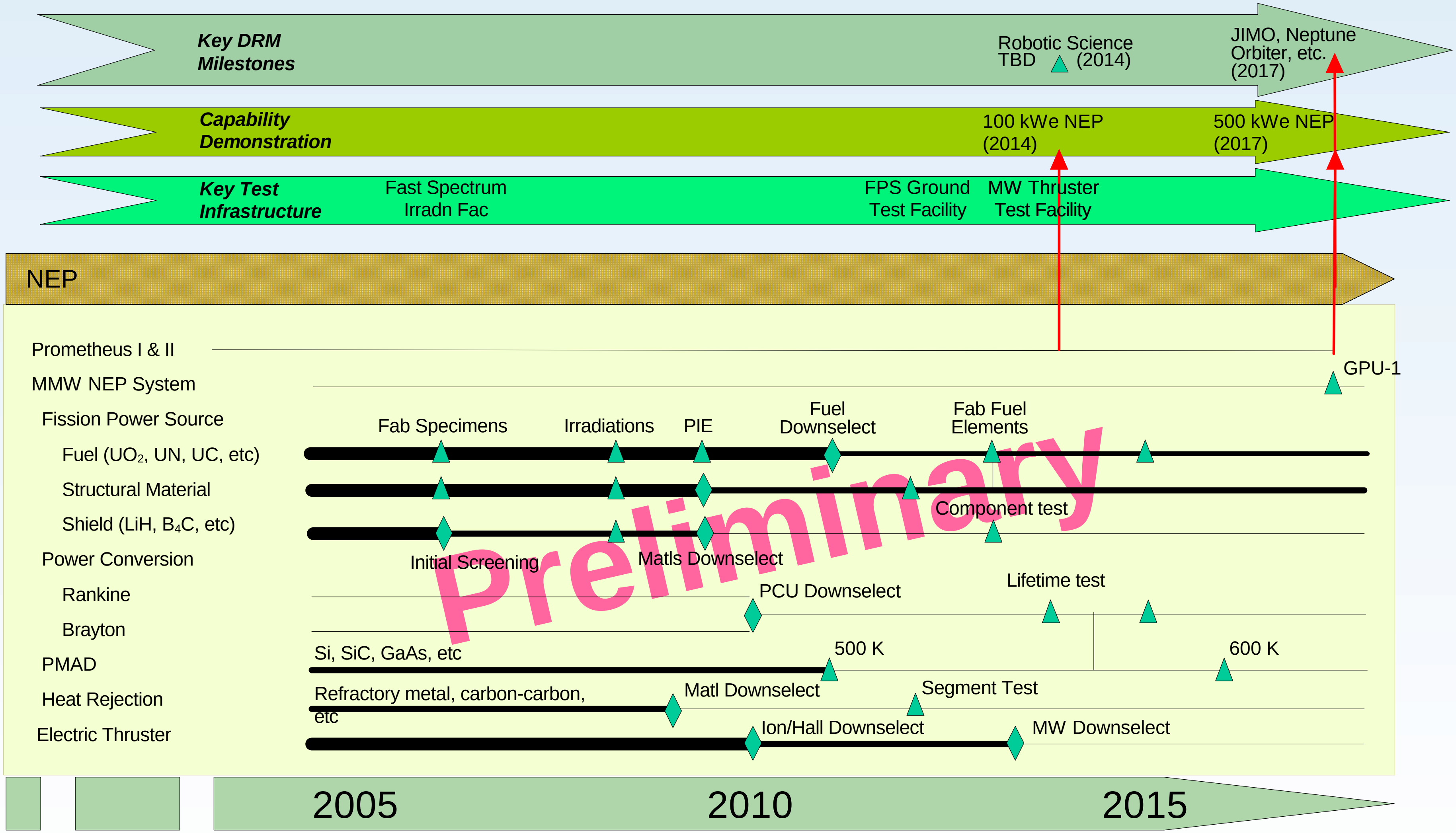
Preliminary

Metrics for Nuclear Electric Propulsion

Subsystem	Figure of Merit	Development Targets	
		Entry-Level (Science)	Long-term (Human Exploration)
Fission Power Source	Power Specific Mass Lifetime*	1 MWt 50-70 kg/kWe 3 yr	25 MWt 5-10 kg/kWe 5 yr
Power Conversion	Efficiency Lifetime*	20% 3 yr	35% 5 yr
PMAD	Temperature Specific Mass Power	500 K 30 kg/kWe 100 kWe	700 K 3 kg/kWe 1 MWe
Heat Rejection	Areal Density Temperature	10 kg/m^2 500 K	2 kg/m^2 900 K
Electric Thrusters	Power Specific Impulse Efficiency	100 kW 2 – 8 ks 70%	1 MW 2 – 10 ks >60%

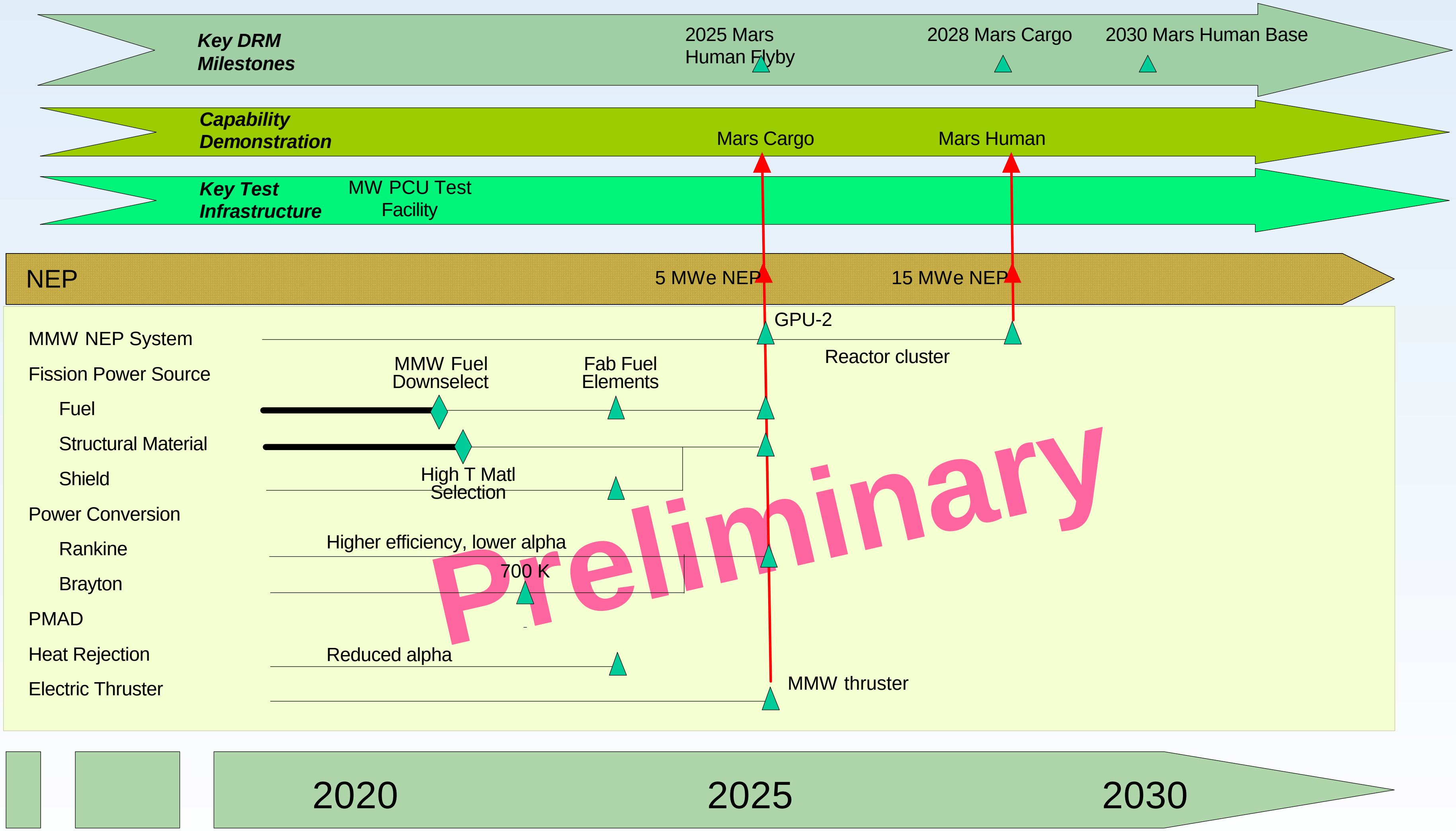
Lifetimes exceeding 10 yr are required for many NEP science missions.

NEP Capability Roadmap (2005–2020)



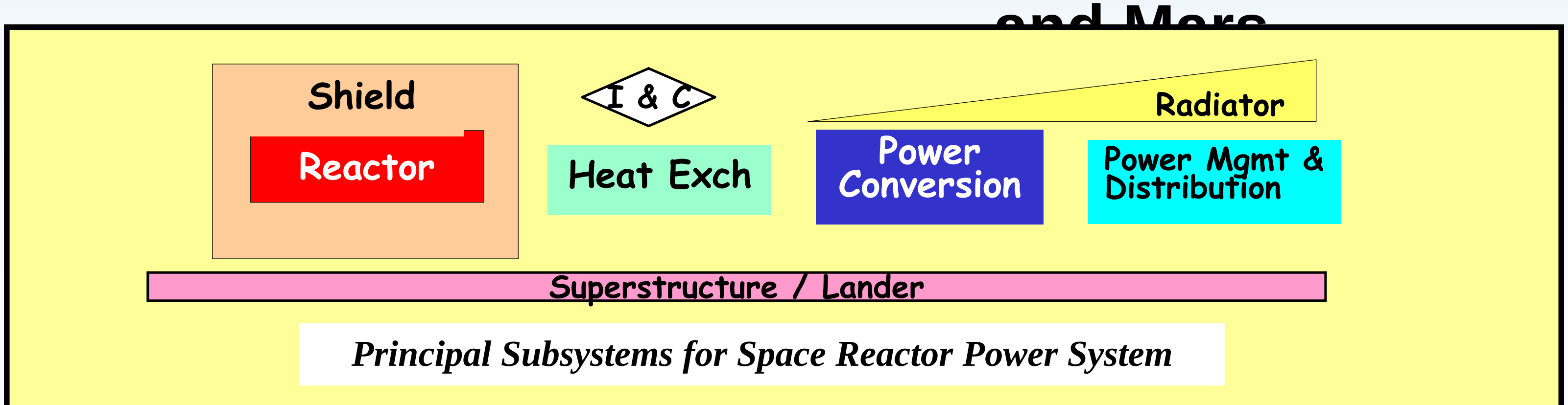
NEP Capability Roadmap (2020–2030)

Advanced Planning & Integration Office



Surface Fission Power Capability Description

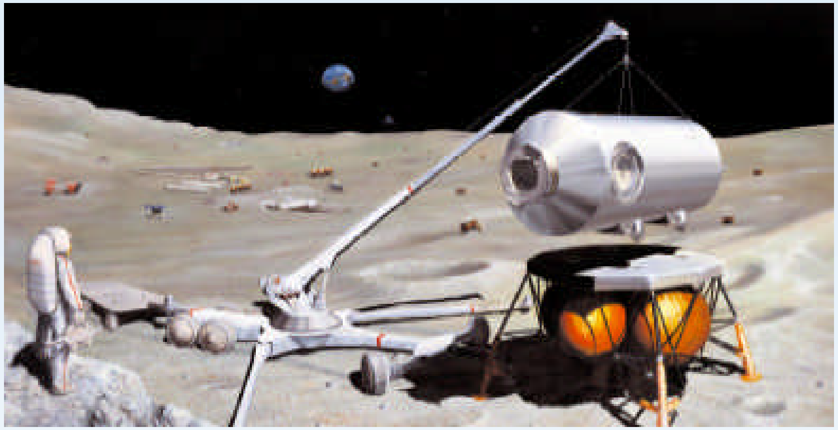
Surface fission power **provides the primary power generation and distribution for both robotic pathfinder and human exploration missions to the surface of the moon and Mars**

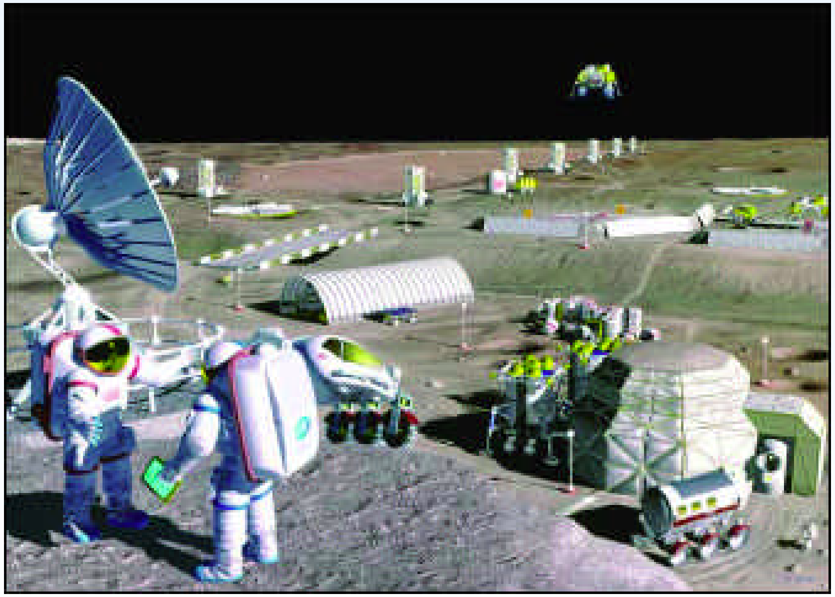


Principal Subsystems for Space Reactor Power System

Surface Fission Systems Provide Power-Rich Environment

- Significant power (10s - 100s kWe)
  - Life support
  - Telecom
  - ISRU/ISPP
- Power independent of the sun
  - AU
  - Latitude
  - Diurnal cycle
  - Topography
- Enables repeat or extended mission durations with continuous source of power
- Compact, flexible, high-energy density power source





Key Mission Architecture Assumptions and Strategies

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Assumptions

- Robotic system operation should not preclude later human presence

- All systems must incorporate robust autonomous control
  - Must demonstrate operability prior to crew arrival
  - Must be capable of ISRU/ISPP and providing continual power for life support system (habitat) in absence of crew
  - Should not require astronaut's attention
- Safety & Reliability are technical focus
  - To ensure power is available for human life support

Strategies

- Gain early success on the moon
- Minimize technical development risk
- Provide high reliability and minimize mass (max performance)
- Assure extensibility to human Mars applications

Desirable SP Capability Performance Levels*

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Mission	Power (kWe)	Lifetime (yr)	Landed Mass (kg)
Robotic Lunar Outpost	10 – 30	3 – 10	5000
Human Lunar Base	30 – 100	5 – 10	5000
Robotic Mars Outpost	10 – 30	3 – 10	2000
Human Mars Base	30 – 100	5 – 10	2000

*NASA Exploration Team (NEXT) Human Exploration Requirements For Future Nuclear Systems, Version 1.0, 12/19/02

Current Roadmap Planning Assumptions: Mission Evolution and Performance Levels

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Surface Power Mission Studies

- 2002 NEXT Study
- 1992 FLO
- 1989 "90-Day Study"
- 1971 Lunar Base Synthesis Study
- 1959 Project Horizon

Surface Power Mission Evolution

- Lunar Human Base
- Mars Human Base

Surface Power Performance

Entry Level

- 30 kWe
- 3 yr life
- 10000 kg
- Human-rated
- Stationary
- Lunar

"Beta" Level

- 50 kWe
- 7 yr life
- 12000 kg
- Human-rated
- Stationary
- Mars

Differences Between Moon and Mars Must Be Considered in Design of Surface Fission Power System

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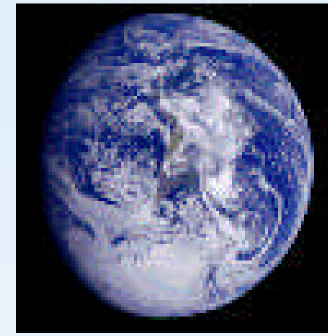
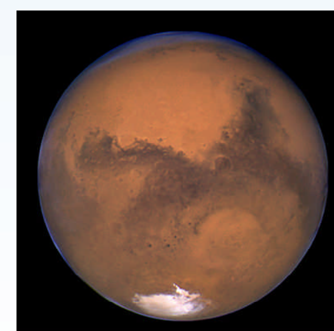
Parameter	Earth	Moon	Mars
Surface gravity, m/s^2	9.78	1.62	3.69
Mean atmospheric pressure, millibars	1013	None[a]	1Š10
Average atmospheric density, kg/m^3	1.2	None[a]	0.02
Average atmospheric temperature, K	288	None[a]	210
Diurnal atmospheric temperature range, K	184Š242	None[a]	140Š270
Day length	24 h	27.3 d	24 h 37 min
Minimum atmospheric temperature, K	183	None[a]	140
Maximum atmospheric temperature, K	329	None[a]	340
Atmospheric composition (by volume)	79% N_2 20% O_2 0.93% Ar 0.03% CO_2	Hydrogen[a] Helium[a] Neon[a] Argon[a]	95.32% CO_2 2.7% N_2 1.6% Ar 0.13% O_2 0.08% CO 210 ppm H_2O
Trace	Neon Methane Helium Krypton Hydrogen Xenon	Trace	Neon Krypton Zenon
Atmospheric optical depth	0.01Š3	None	0.1Š10
Wind speed, m/s	>90	None	2Š30
Atmospheric mean molecular weight, g/mole	29		43.34

[a]Lunar atmospheric density is 1×10^4 to 2×10^5 molecular/cm^3• 14 orders of magnitude less than that of Earth.





Note: Regolith chemical and isotopic compositions not shown.

Current Capability Readiness for Surface Fission Power

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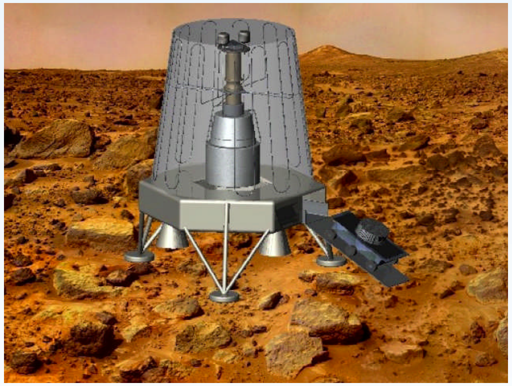
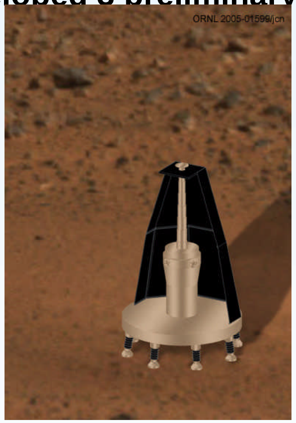
- Current CRL for Integrated SRPS for surface power - 2
- Comparable to in-space flight fission systems?
  - Fuels - UO_2 and UN near-term options
  - Materials
    - Viable concepts with SS/superalloys for low temp designs
    - Refractory systems for high temp operation requires development
  - Infrastructure
    - No fast-flux fuel and materials irradiation facilities in U.S.
    - Available system test facilities limited – no new facilities for space power since early 1970’s
  - Lander / deployment issues TBD
- Technology based on SNAP, SP-100, and terrestrial reactor (LMFBR & GCR) programs
- Limited design/assessment for surface fission power applications
  - Most previous mission studies “assumed” use of SP-100 reactor
  - Recent efforts by DOE-NE developed 3 preliminary conceptual designs



Robotic – 3 kW(e) – Homer

Heat Pipe Rx w/Stirling

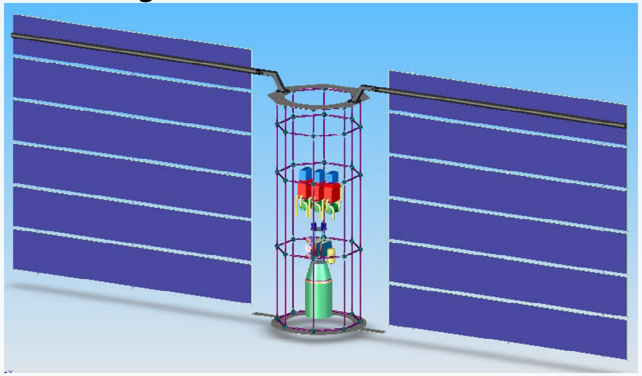
381 kg/kW(e)



Robotic – 12.5 kW(e) – PRESTO

Boiling Liquid Metal Rx w/Stirling

160 kg/kW(e)



Human – 50 kW(e) – LMR

Pumped Liquid Metal Rx w/Brayton

289 kg/kW(e) – not optimized

Maturity Level – Technologies for Surface Fission Power

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Mission Architecture (power requirements as function of mission phase and duration) influence reactor and PCS options

Preliminary

Reactor Candidate Technologies

- **Liquid-metal – TRL 3 (TRL 9 in 60's-70's for Russia and U.S.)**
  - Technology pedigree established (SNAP, SP-100, MPRE, LMFBR) and scalable
  - Flexible with Stirling, Brayton, Rankine, TE
  - Freeze/thaw and system complexity issues
  - Flown but not landed
- **Gas-cooled – TRL 3**
  - Technology pedigree from terrestrial program/scalable
  - Naturally couples only with closed-cycle Brayton PCS
  - Larger mass than LMR
- **Heat-pipe – TRL 2**
  - Passive cooling system/fewer dynamic components than LMR and GCG
  - Scalability questions above 100 kWe

Power Conversion Technologies

- **Thermoelectric – TRL 9 (flying today)**
  - Most mature – RTG pedigree, static system
  - Highest mass/lowest efficiency (5-8%)
  - Used on SNAP 10A
- **Stirling – TRL 4**
  - Free piston configuration operating with helium as working fluid/high efficiency
  - Maintain uniform hot head temperature
  - Efficiency: 20-25%
  - Rad-tolerance: TBD
- **Brayton – TRL 3-5**
  - Substantial experience with open-cycle systems
  - Space system employs closed cycle
  - 38,000 hr ground test by NASA
  - Efficiency: 15-20%
  - Large radiators
  - Rad-tolerance: TBD
- **Rankine – TRL 3-4**
  - Water Rankine systems used in most of world's 440 operating power reactors
  - Liquid-metal Rankine turbine ground demos in SNAP and and MPRE (4000 hr turbine test)
  - Efficiency: 15-25%
  - Smallest radiators
  - Rad-tolerance: TBD
  - 2-Phase fluid mechanics

Surface Power Capability Roadmap (2005–2015)

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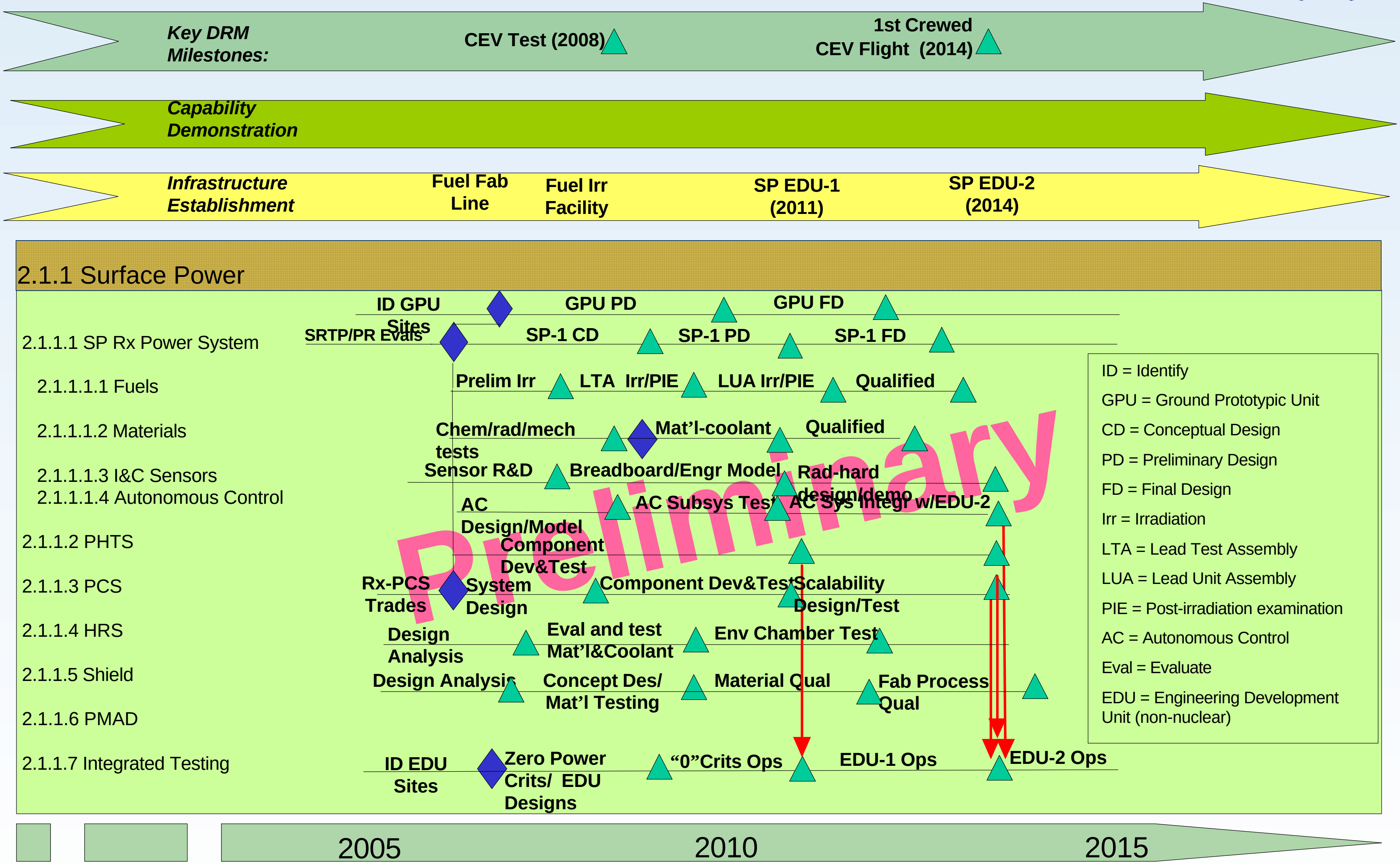

Surface Power Capability Roadmap (2015–2030)

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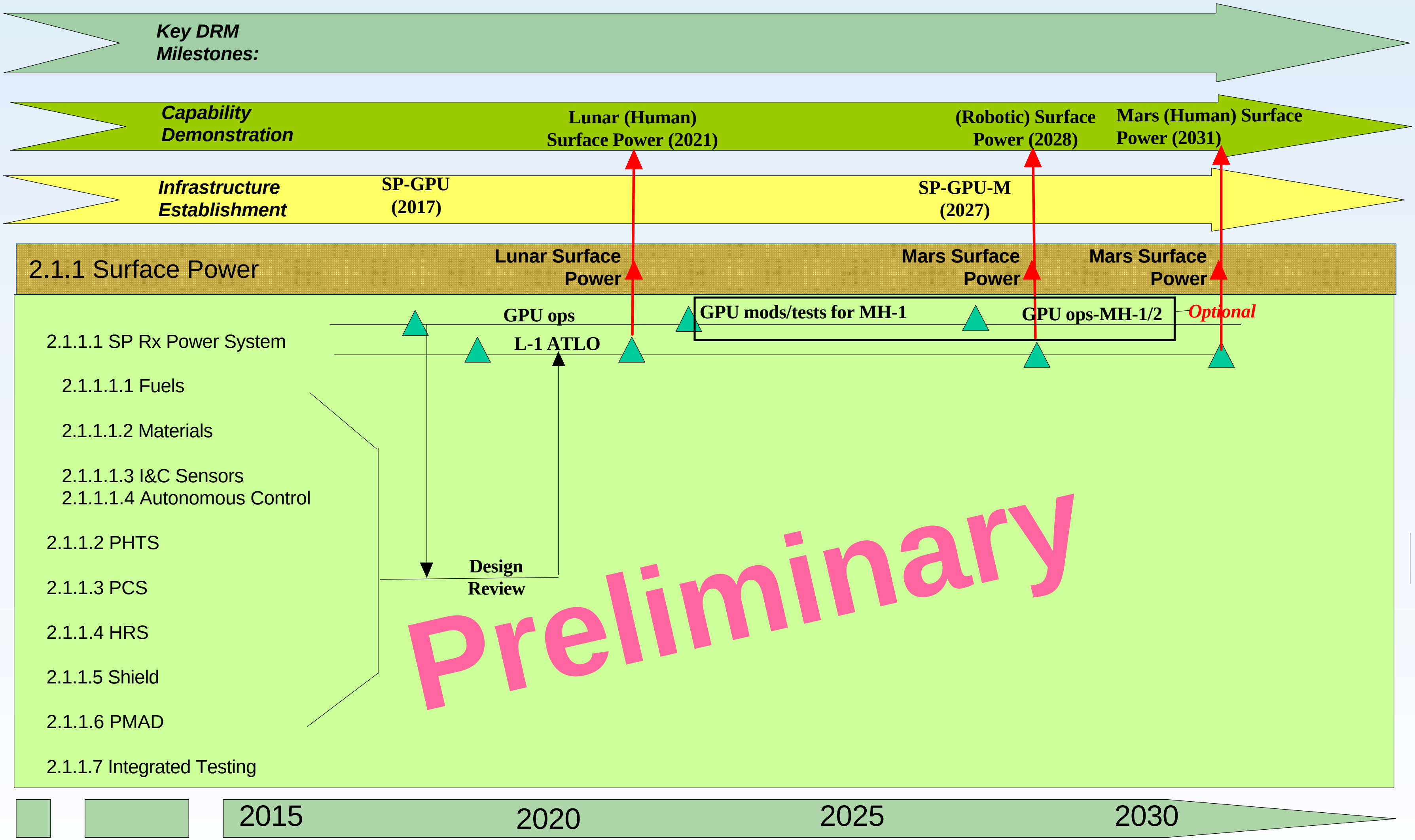
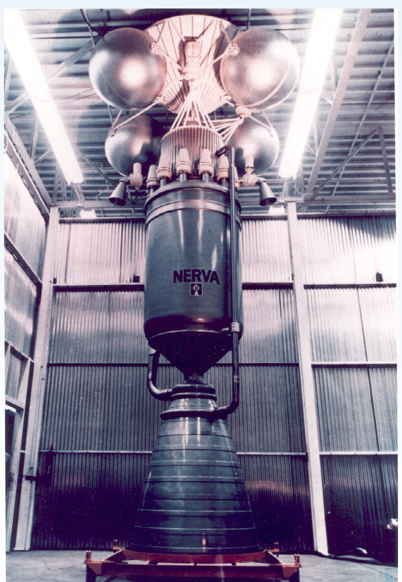


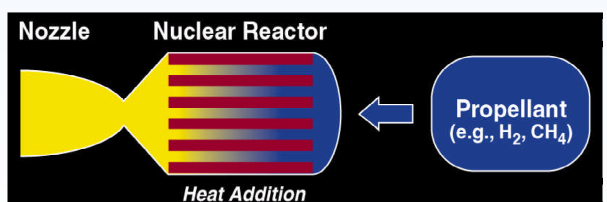
NTP Stage Integrates Nuclear and Non-Nuclear Subsystems

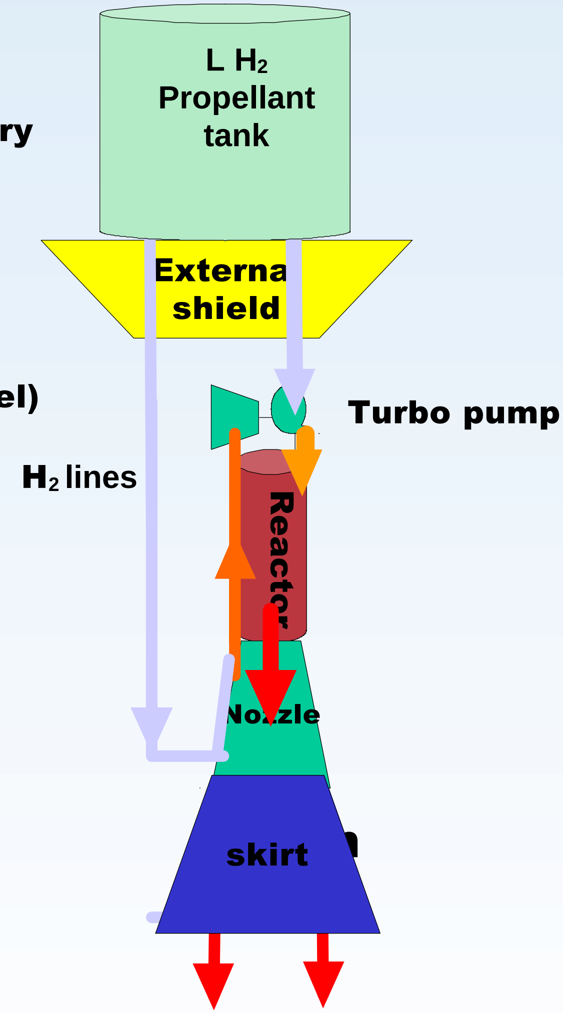
Expendable TLI Stage for First Lunar Outpost Mission using Clustered 25 klb$_f$ Engines -- “Fast Track Study” (1992)



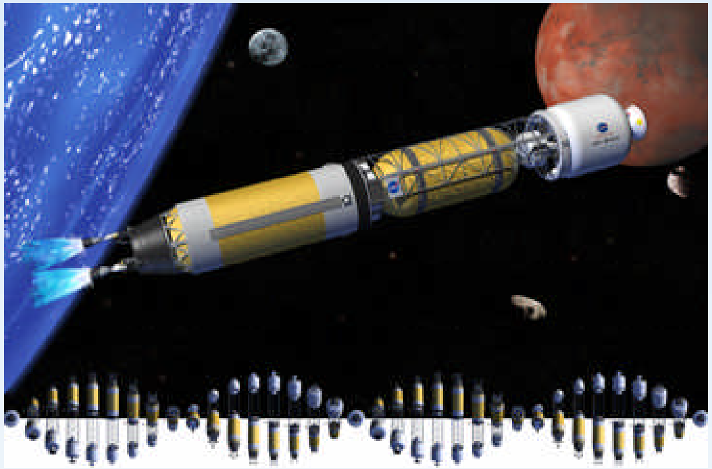
Full Scale Mockup a NERVA Engine

- Stage
  - Propellant storage and delivery
  - I&C
  - Engine
    - Reactor
      - Nuclear Reactor fuel
      - Structural materials/moderator/shield
    - Thrust Chamber (outer vessel)
    - Propellant feed system
      - Turbine
      - Pump
      - Plumbing/valves
    - Nozzle
      - Regen section
      - Skirt
    - I&C
  - External Nuclear Shield
  - Thrust Vector Control
  - Structure





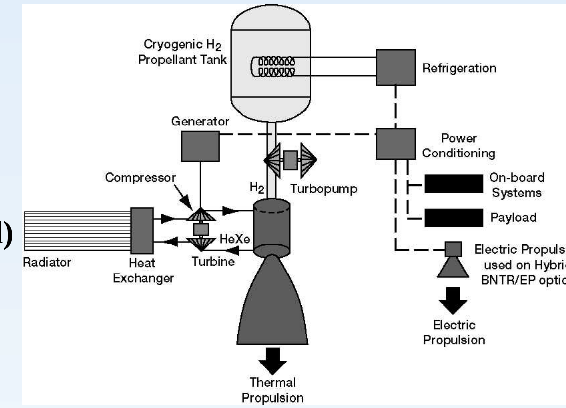
Bimodal Nuclear Thermal Propulsion (BNTP) Adds Electrical Power Capability

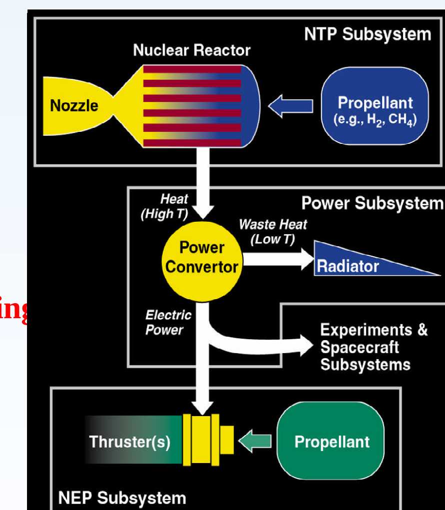


NASA 50 kW$_e$ BNTP Mars Crew Transfer Vehicle Designs. A 5 kW$_e$ Photovoltaic Array is shown above for Size Comparison

- Stage
  - Propellant storage and delivery
  - I&C
  - Engine
    - Nuclear Reactor
      - Fuel
      - Structural materials/moderator/shield
    - Thrust Chamber (outer vessel)
    - Propellant feed system
      - Turbine
      - Pump
      - Plumbing/valves
    - Nozzle
      - Regen section
      - Skirt
    - I&C
  - External Nuclear Shield
  - Thrust Vector Control/Structure
  - Power Conversion System

  - Pumps/valves/turbine/compressor/plumbing
    - Heat Exchanger
    - Radiator
  - PMADS





NTP & BNTP Provide Many Benefits

NTP

- Capable of high thrust, high thrust/mass ratio, and high specific impulse (2 times the best chemical rocket systems)
- Reduced transit times (reduced exposure for manned missions)
- Reduced IMLEO requirements
- Greater mission flexibility for VSE Mars (cargo and especially piloted) missions with respect to departure windows
- Potential for single small engine design to satisfy a broad variety of exploration missions
- Operated for only short duration (hours/mission) vs months for other systems

BNTP

- Provides continuous onboard power for spacecraft/crew
- Provides power for refrigeration of coolant to reduce boiloff
- Facilitates artificial gravity during transit flights
- One propulsion system capable of meeting ***"broad range" of robotic and piloted exploration missions***
- Allows hybrid mission - combining rapid transit times with NEP maneuverability

Candidate Missions for NTP and BNTP

Requirements / Missions	Engine thrust (klb$_f$)	T/W$_{eng}$	T$_{ex}$ (ºK)	I$_{sp}$ (s)	No. engines	P$_{elec}$ [kW(e)]	Tin* (K)	Power mode duration (days)	Total burn duration (hr)	No. burns
Robotic science	15	3	2550	875	1	$\lesssim$ 10	1150	~28–12.6 years	<0.5	1
Lunar cargo	15	3	2550	875	1–2	$\lesssim$ 10	1150	7–14	0.5–1.0	2–3
Lunar piloted	15–25	3–4	2550–2700	875–900	1–2	25	1150	45–90	~1.0	3
Mars cargo	15	3	2700	900	2–3	10–25	1150	270–300	0.5–1.0	2–3
Near Earth asteroid (NEA) piloted	15	3	2700	900–915	3	50	1150–1300	365	<1.5	3–4
Mars piloted	15–25	3–4	2700	900–925	3	50	1150–1300	545–900	<2.0	4–5

***Tin: Turbine Inlet Temperature.**

Assumed NTP & BNTP Mission Evolution and Target Performance

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NTP Mission Studies

- 2004 RASC (Mars Orbital)
- 1999 DRM 4.0
- 1998 DRM 3.0
- 1995 Fast Outer Planets
- 1993 DRM 1.0
- 1992 First Lunar Outpost
- 1990-91 SEI
- 1989 "90-day Study"

NTP Mission Evolution

- NTP Lunar Cargo
- NTP Mars Cargo
- NTP Piloted Mars

NTP / BNTP Mission Evolution

- BNTP Lunar Cargo
- BNTP Piloted Mars

Entry Level NTP & BNTP

- 15 klb_f (single engine)
- 1-hr Burn-time
- 0.5-hr max. single burn
- 3 restarts/mission
- T/W (klb_f/klb_m) = 3
- Isp = 875 s
- 15 kWe (BNTP only)

"Beta" Level NTP & BNTP

- 25 klb_f (single engine)
- 1.5-hr Burn-time
- 0.5-hr max. single burn
- 8 restarts/mission
- T/W (klb_f/klb_m) = 3+
- Isp = 925 s
- 25 kWe (BNTP only)

Current NTP / BNTP State-of-the-Art

Basic Engineering Feasibility of NTP Has Been Demonstrated

- Estimated current NTP CRL (stage) is 3-4 (?)
- NTP Pedigree
  - From 1959- 1972, 20 Nuclear Thermal Reactors were built and tested (17 test reactors, 1 safety test, 2 ground test engines) as part of the Rover/NERVA Program
    - Best Parameters Achieved:

Highest Power	4100 MWt
Peak Fuel Temperature	2750 K
Max. Hydrogen Exhaust Temperature	2550 K
Specific Impulse	875 s
Maximum Restarts	28
Accumulated Time at Full Power	109 minutes
Continuous Operation	62 minutes

  - Rover/NERVA program reached a technical maturity level sufficient to begin planning for a Reactor In-Flight Test (RIFT)
  - Additional fuel and materials tests conducted in Space Nuclear Thermal Propulsion Program (SNTP), GE 710 Program, and ANL Cermet Nuclear Rocket Program
  - High Temperature and pressure non-nuclear rocket components developed for the Space Shuttle and LOX/LH_2 Centaur in-space stage may have applicability to NTP
  - Demonstration of conformance with extant safety requirements (e.g. fuel fission product release, water/sand immersion criticality, etc.) will be required

- BNTP introduces additional issues
  - Short duration high power operation + long-duration low power operation
  - Clustering (if small engine)

- BNTP designs have been proposed but no technology development or demonstration
  - Estimated BNTP CRL (stage) is 2-3 (?)

NTP Technology Readiness

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TRL levels assessed relative to first mission (single-engine lunar cargo).

WBS	TRL rating	Basis for rating	Comment
Stage Propellant Storage and Delivery System I&C	 7-8 7-8	 - Centaur - S IV-B - Centaur	 - Relevant cryogenic stages have flown - Reactor radiation environment minimal
Engine Reactor Fuel Moderator/Structural Materials Propellant Feed System Nozzle Regen Rad. cooled extension I&C	 3 3 7 7-8 5-6 4-5	{ Fuel fission product release Infrastructure & fabrication status } - J-2, RL-10 - SSME - RL-10 B-2 - Rover/NERVA	Recapture improve fabrication and infrastructure - Radiation assessment on components needed. - Radiation assessment - ~300:1 deployed nozzle ratio - Radiation environment assessments
External Nuclear Shield	4-5	- SP-100 - XE	- Design, but no fab
Thrust Vector Control/Structure	7-8?	- Centaur - S IV-B	- Reactor radiation environment

NTP & BNTP Technology Needs (Gaps)

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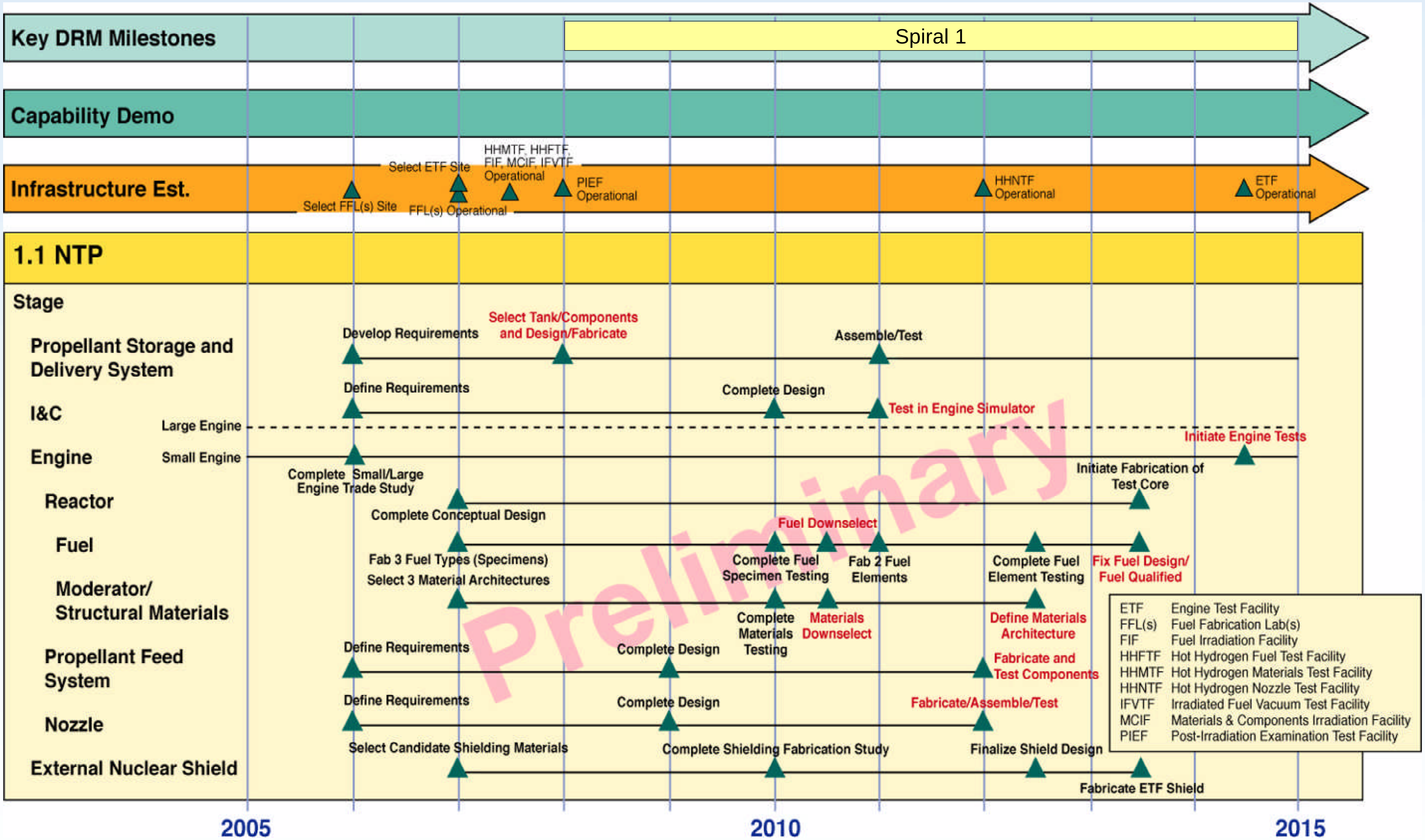
Preliminary

Hardware Tree Element	Need	Why
Stage Propellant Storage and Delivery System I&C	- Clustering - Radiation environment testing - Radiation environment testing	- Small engine - Reactor - Reactor
Engine Reactor Fuel Moderator/Structural Materials	- Water/sand immersion subcriticality - Fuel fission product retention - Recapture/improve fabrication	- Nerva-derived design - Clustering (Coupled physics & I&C) - Bimodal operation - Degraded infrastructure
Propellant Feed System Nozzle Regen. Cooled Rad. Cooled extension	- Radiation environment testing - Radiation environment testing - Radiation environment testing	- Reactor
I&C	- Radiation environment testing	- Reactor - Bimodal operation
External Nuclear Shield	- Design and materials fabrication - Rad-Hard I&C - Bimodal and Clustering Control	- Capability and infrastructure not currently present at DOE
Thrust Vector Control/Structure	- Radiation environment testing	- Reactor
Power Conversion	- 10s kWe Power Capability - Transition/Control demonstration - Radiation env. & life testing	- Bimodal operation - Reactor
Heat Rejection	- Radiation env. & life testing	- Reactor
PMAD	- 10s kWe Power Capability - Radiation env. & life testing	- Reactor

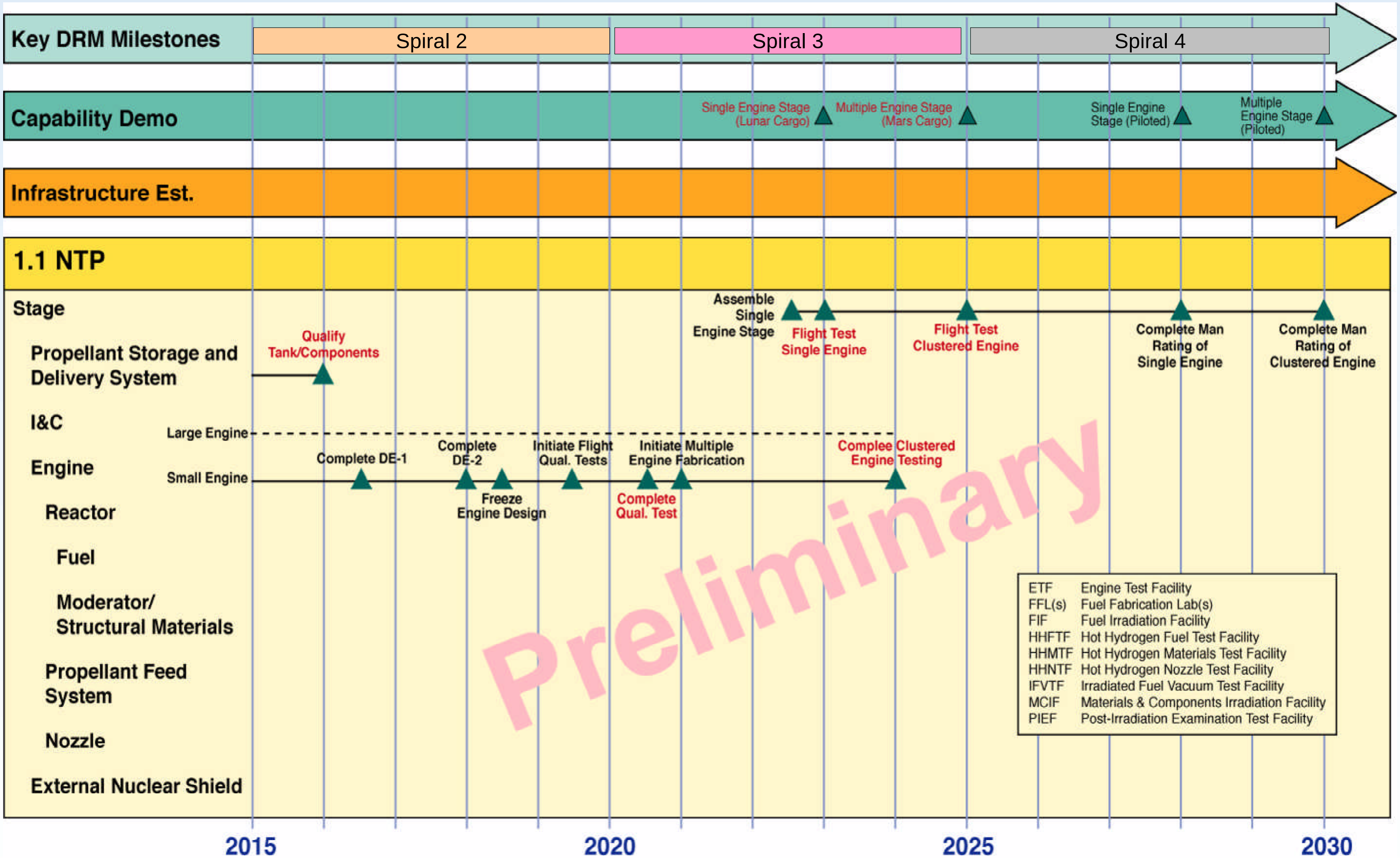
NTP Small-Engine Development Approach Maximizes Leverage of Legacy Technology

- Assumed Development Approach
  - Adapt Pewee engine design
    - Lower thrust
    - Adapt for water immersion sub-criticality
  - Utilize composite fuel
    - Adapt for acceptable fission product retention
    - Develop required coatings
    - Carry cermet fuel as backup
  - Nuclear furnace (NF) is not a precursor to first engine
    - Effort to qualify NF fuel refocused on qualification of engine fuel
    - Rely on expanded suite of separate-effects testing
    - Bypasses schedule and budget impacts of NF for initial mission
  - Ground test engines (developmental and flight)
    - Small engine may be testable in existing facilities
  - First flight
  - Post-flight Option: Build NF and expand fuels R&D as desired to enhance capability
    - Use fuel developed for first engine as NF driver fuel
- Use Strategy
  - Single non-human-rated engine for science and lunar cargo
  - Cluster non-human-rated engines for lunar or Mars cargo
  - Cluster human-rated engines for human Mars or asteroid exploration

NTP Capability Roadmap (2005–2015)



NTP Capability Roadmap (2015–2030)



BNTP Capability Roadmap (2005–2015)

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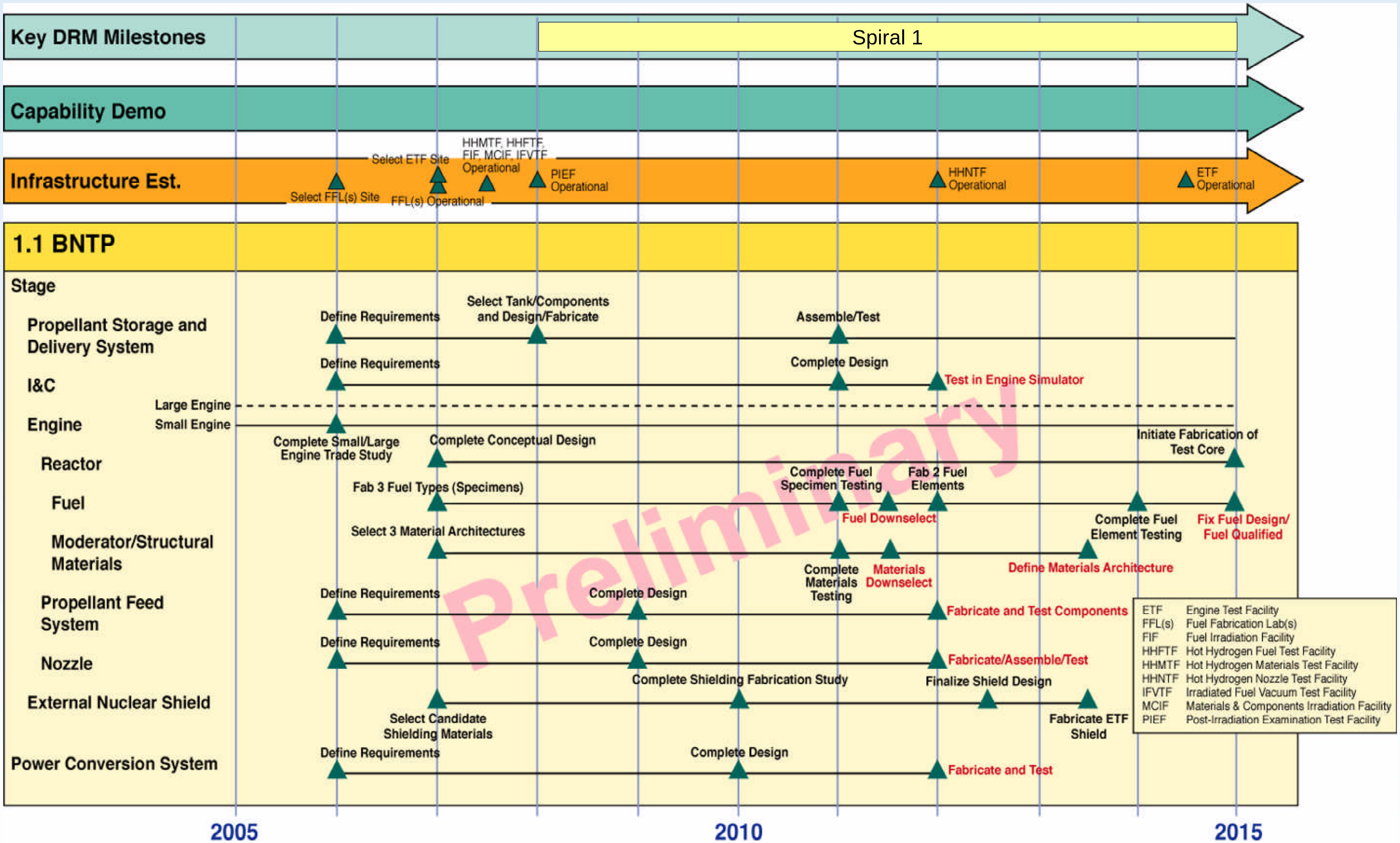
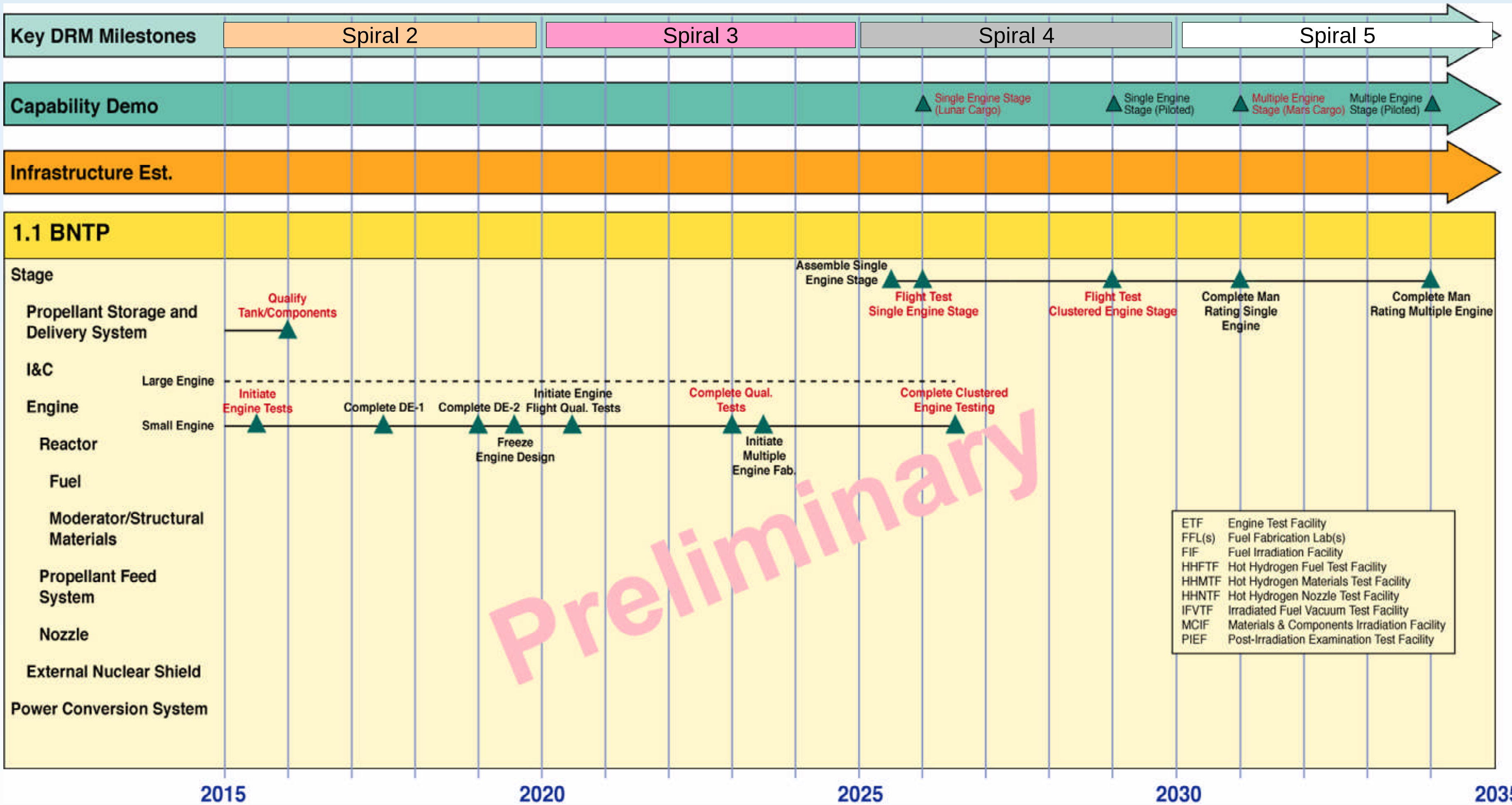


BNTP Capability Roadmap (2015–2030)



Summary

- Fission power and propulsion enable/enhance key elements of VSE
- Fission surface power and propulsion systems <u>can be available</u> to support human exploration and science missions within timeframes envisioned by the VSE…
  - Spiral 3 (2020+) – Surface power & NTP cargo for long-duration human lunar missions
  - Spiral 4 (2025+) – NTP, BNTP, & NEP for cargo & piloted missions to Moon and Mars
  - Spiral 5 (2030+) – Surface power & NTP/BNTP/NEP for human Mars surface missions
- ***IF*** aggressive and sustained technology development efforts are initiated immediately…
  - Fuels
  - Materials
  - Shielding
  - Power Conversion
  - Power Management & Distribution (includes NEP Power Processing)
  - Heat Rejection
  - Propulsion
- Significant, but dated technology base exists
- Technology (knowledge and art) recapture will be a key
- Infrastructure development can pace technology development
- Opportunities exist to leverage technology investments

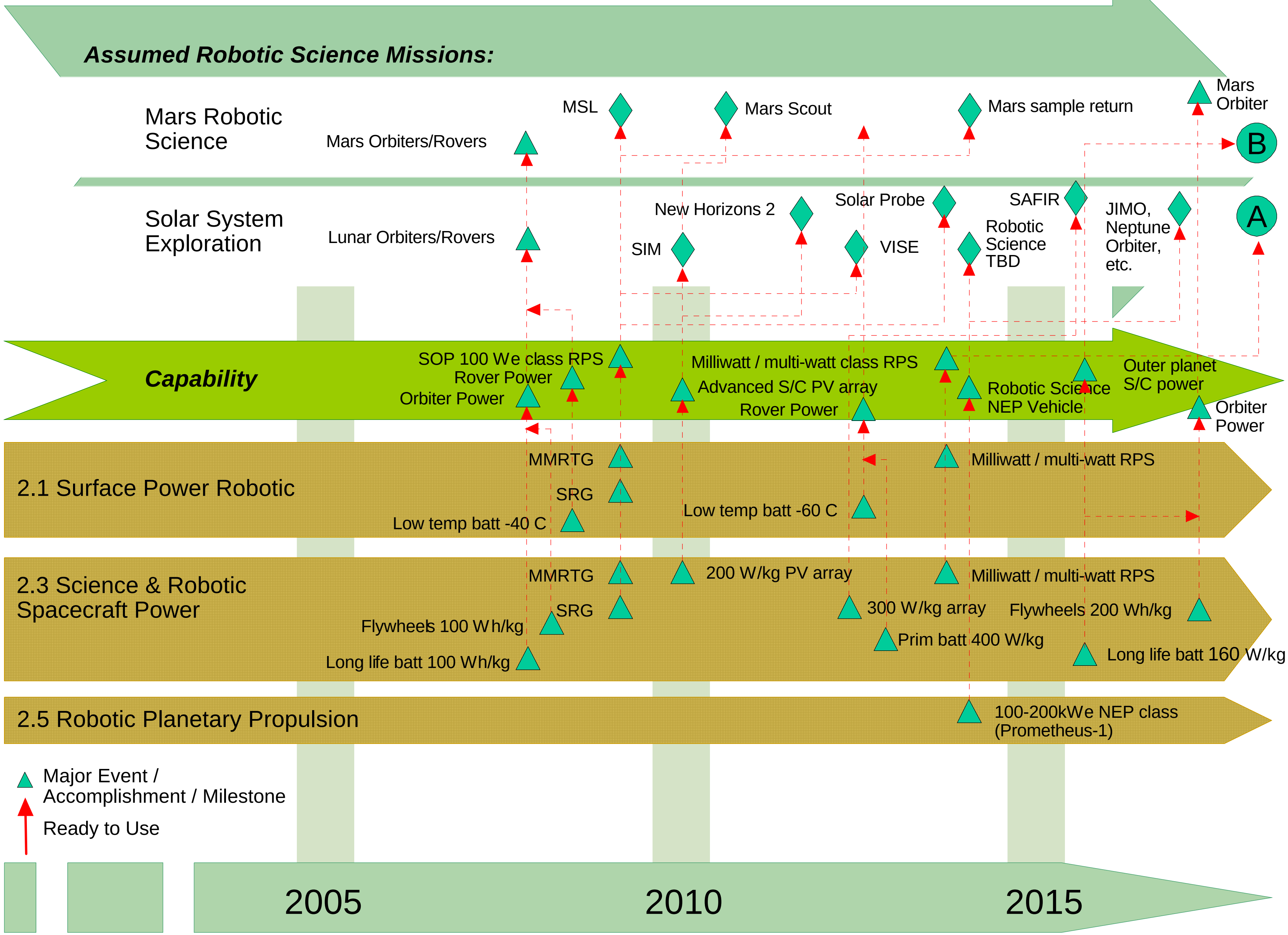
Concluding Charts

Joseph J. Nainiger, NASA Glenn Research Center, Chair

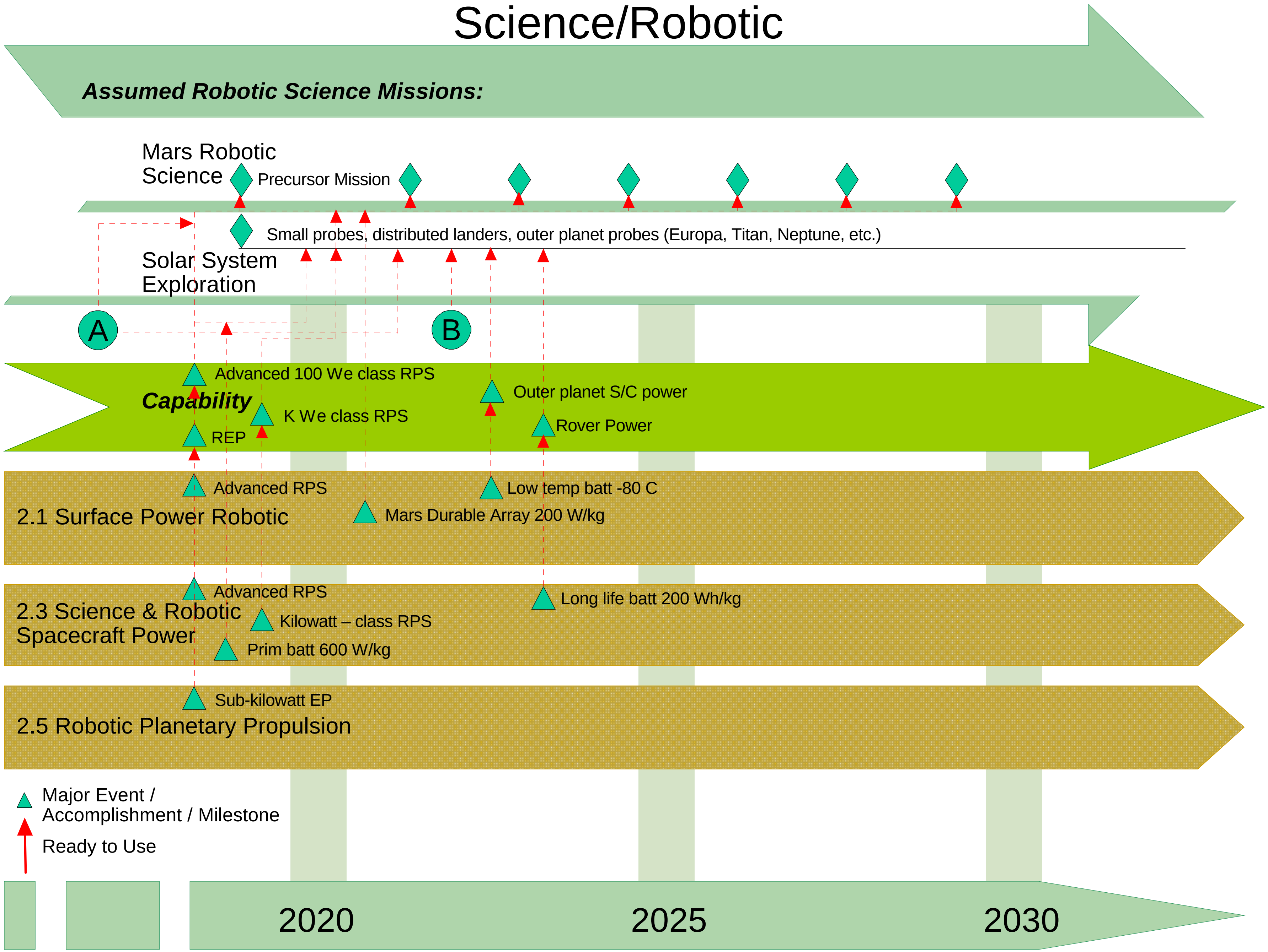
Disclaimer:
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 Team members, and is not the official view of NASA or DOE.

Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

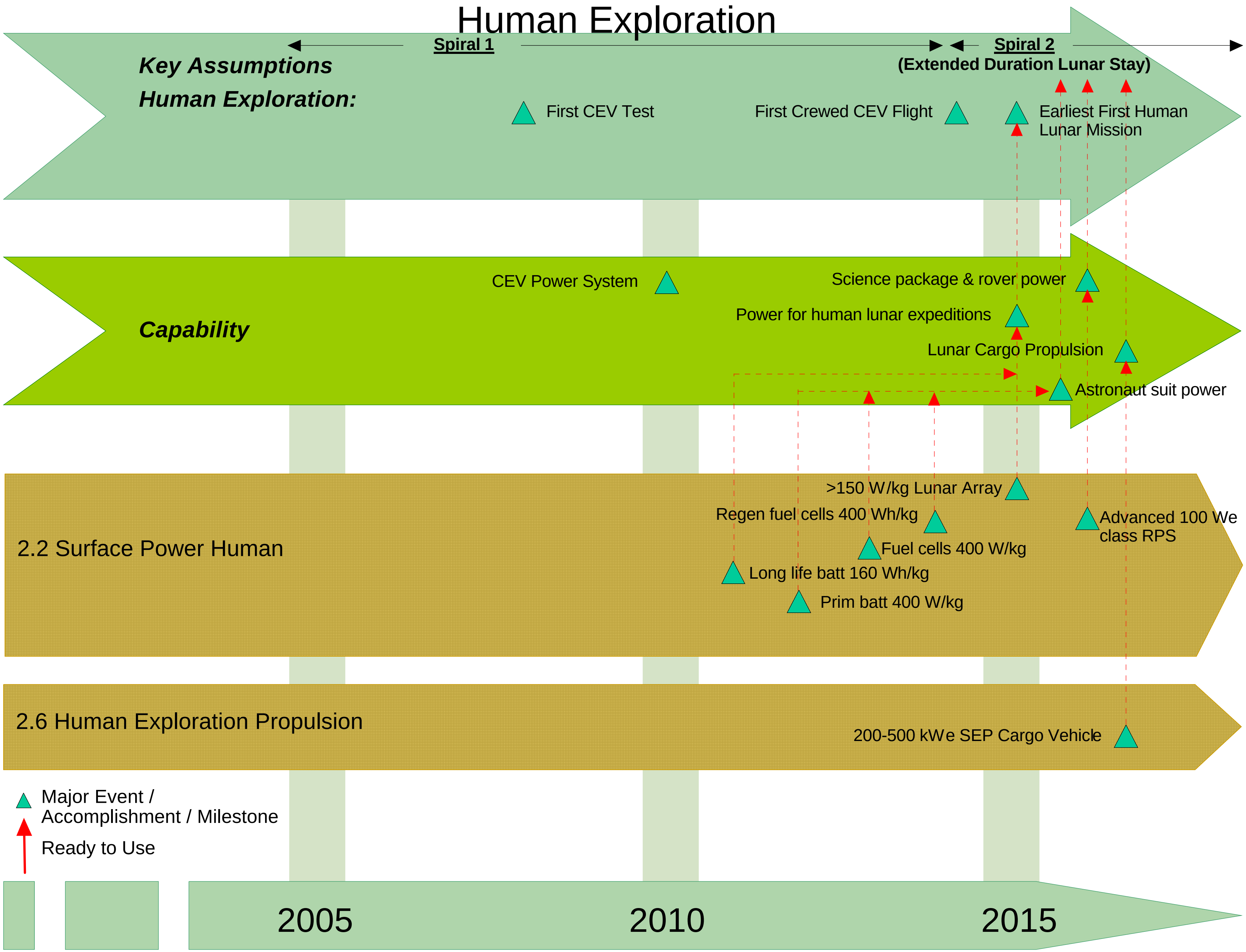
Science/Robotic



Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

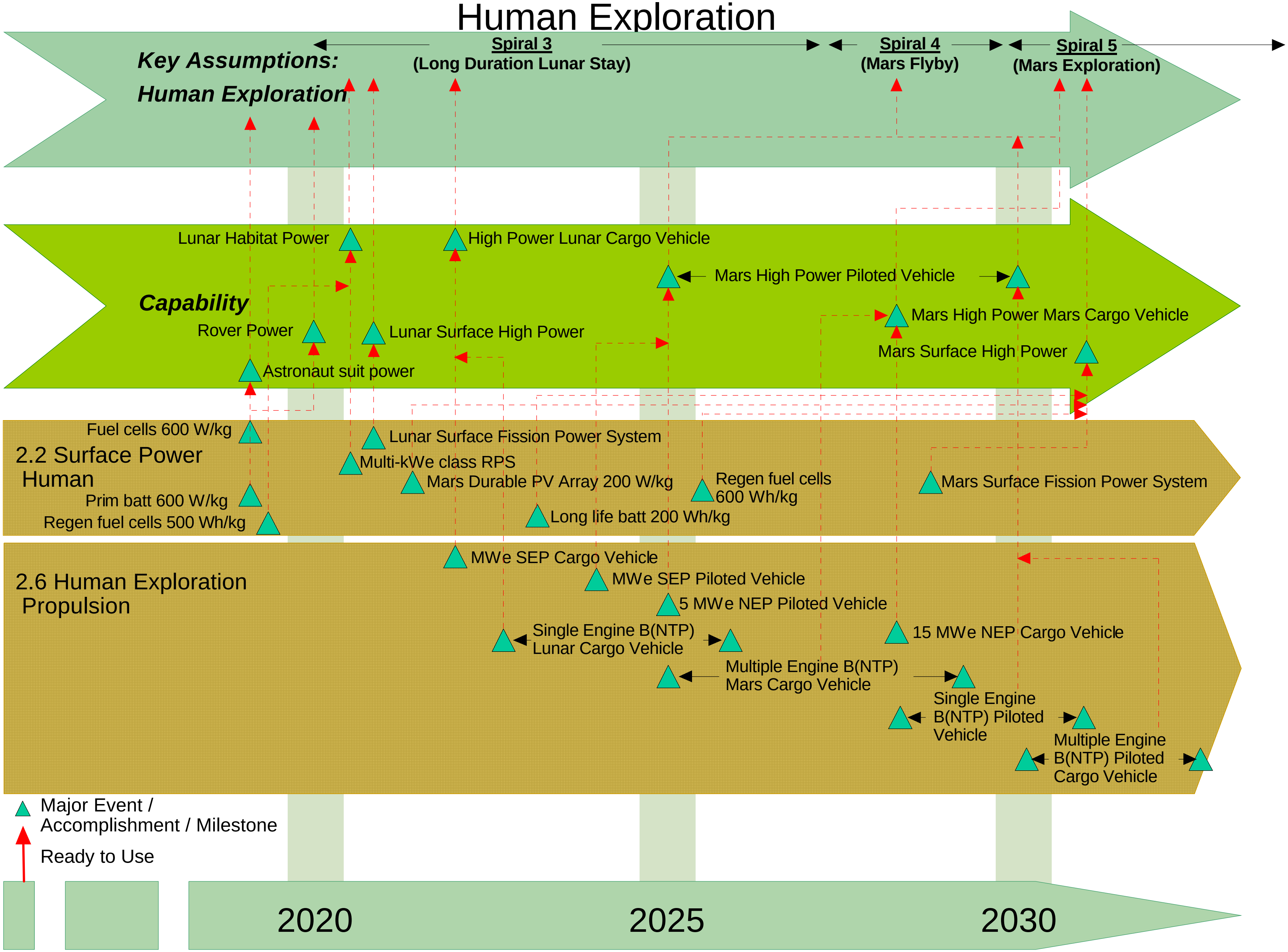


Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap



Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

Human Exploration



HEP & P Capability Technical Challenges

- Fission Systems
  - Infrastructure reestablishment (separate chart)
  - Technology capture (i.e., Rover, Nerva, SP-100…)
  - High temperature fuels and materials
  - Shielding
  - Autonomous control
  - Lifetime
  - Dynamic power conversion
  - Heat rejection
  - PMAD
  - High power thruster technology
  - Ground Testing (subsystems and systems)
- Radioisotope systems
  - Lightweight components (power conversion, heat rejection, PMAD)
  - High efficiency power conversion (reduce PU-238 cost)
  - Sub-kW electric propulsion sub-system
  - Infrastructure (separate chart)
- Solar Systems
  - Very large (100s of kWe to MWe), high specific power (300 to 500 W/Kg) solar arrays
  - Ground testing of very large, deployable arrays
  - Radiation resistant solar cells
  - High power thruster technology
- Energy Storage
  - Fuel Cells: Medium power PEM Fuel Cells, Regenerative fuel cells, Small fuel cells
  - Primary Batteries: High specfic energy, RAD hard Low temperature batteries
  - Secondary Batteries: High Specfic energy, Long Life, RAD Hard, Low Temp. Batteries
  - Fly wheels:

Infrastructure/Facility Needs

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- Fission Systems
  - Fuels and materials fabrication
  - Fuels & materials irradiation facilities
  - Physics criticals facilities
  - Ground test facilities
  - Fast-spectrum Test Reactors
  - Large EP thruster test facilities
  - Vehicle integration facilities
  - Launch site facilities
  - Fuel & reactor shipping & transportation facilities
  - Hot hydrogen test facilities
- Radioisotope Systems
  - Domestic production of Pu-238 (5 kg/year)
  - Increase purchase quantity of Russian PU-238 to supplement
  - Increase capabilities to assemble larger RPSs
- Solar Systems
  - Testing of large photovoltaic arrays
  - Large EP thruster test facilities
- Energy Storage Systems

HEP & P Capability Crosswalk

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	2. High-energy power and propulsion	3. In-space transportation	4. Advanced telescopes and observatories	5.Communication & Navigation	6. Robotic access to planetary surfaces	7. Human planetary landing systems	8. Human health and support systems	9. Human exploration systems and mobility	10. Autonomous systems and robotics	11. Transformational spaceport/range technologies	12. Scientific instruments and sensors	13. *In situ* resource utilization	14. Advanced modeling, simulation, analysis	15. Systems engineering cost/risk analysis	16. Nanotechnology
2. High-energy power and propulsion	Same element	Moderate	Moderate	Moderate	Critical	Critical	Critical	Critical	No Relationship	Moderate	No Relationship	Critical	Moderate	Moderate	Moderate
3. In-space transportation		Same element													
4. Advanced telescopes and observatories			Same element												
5. Communication & Navigation				Same element											
6. Robotic access to planetary surfaces					Same element										
7. Human planetary landing systems						Same element									
8. Human health and support systems							Same element								
9. Human exploration systems and mobility								Same element							
10. Autonomous systems and robotics									Same element						
11. Transformational spaceport/range technologies										Same element					
12. Scientific instruments and sensors											Same element				
13. *In situ* resource utilization												Same element			
14. Advanced modeling, simulation, analysis													Same element		
15. Systems engineering cost/risk analysis														Same element	
16. Nanotechnology															Same element

Legend:

- Same element
- Critical Relationship (dependent, synergistic, enabling)
- Moderate Relationship (enhancing, limited impact, Limited Synergy)
- No Relationship

Concluding Remarks

- The High Energy Power and Propulsion (HEP & P) Roadmap Team has been pleased to present to the NRC panel our interim roadmap results to date
- We have addressed the four questions given to this panel for evaluation, i.e.,
  - Do the capability roadmaps provide a clear pathway to (or process for) technology and capability development?
  - Do the capability roadmaps have connection points to each other when appropriate?
  - Are technology maturity levels accurately conveyed and used?
  - Are proper metrics for measuring the

Summary/ Forward Work

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- Adjust roadmaps as appropriate based on verbal feedback from NRC review
- Initiate more interaction with other Capability Roadmap Teams to exchange capability requirements and data
- Receive the draft Strategic Roadmaps
- Review and assess all applicable Strategic Roadmaps and their requirements for HEP & P capability
- Adjust HEP & P roadmaps as appropriate to ensure consistency with Strategic Roadmaps requirements
- Develop rough order of magnitude cost estimates for the HEP & P Capability Roadmap
- Prepare for 2^{nd} NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Backup Slides for Introduction and Conclusion For CR-2

Click to add subtitle

HEP & P Capability Roadmap Process and Approach – Initial Requirements

- **Each sub-team has been given the same set of initial requirements from which more detailed requirements will be determined**
    - Lunar Roadmap Framework: Short Stay
    - Lunar Roadmap Framework: Long Stay
    - Lunar DRM TP2001
    - Lunar Robotic Science DRM
    - Mars Roadmap Framework
    - Mars FY03 NEP Architecture
    - Mars NASA SP2
    - Mars NASA SP-6107
    - Mars TP 2002
    - Mars Robotic Science DRM
    - Outer Solar System Science DRM

HEP & P Relevance

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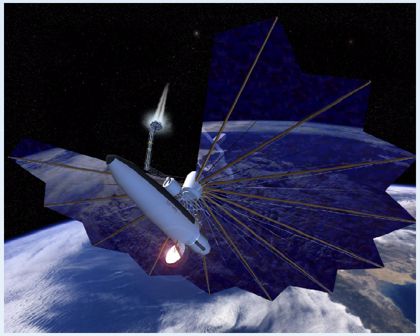
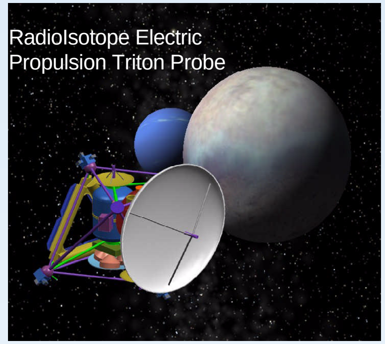
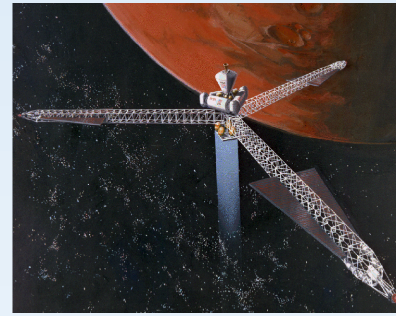
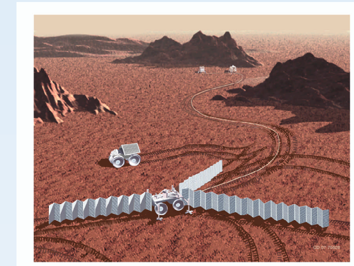


SEP/Chemical Mars Transport Stage



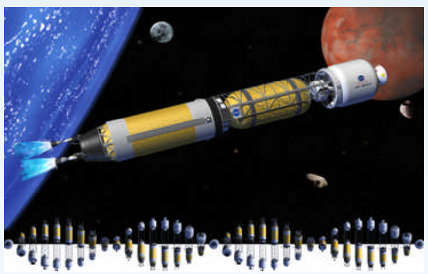


15 MWe NEP Mars Piloted Vehicle

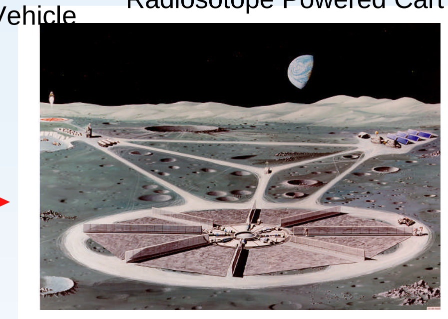


Nuclear Fission Mars Power Systen
Radiosotope Powered Cart

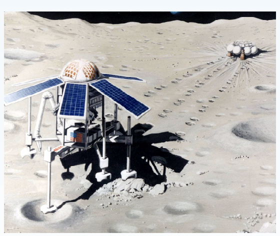
High Energy Power & Propulsion



Nuclear Thermal Propulsion Piloted Vehicle

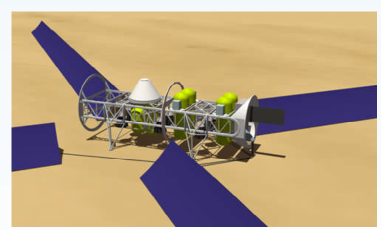


Nuclear Fission Lunar Power System

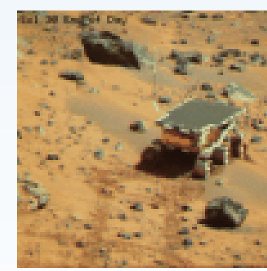


Photovoltaic Powered Robotic Lunar Lander

Radioisotope Powered Deep Space Probe



Photovoltaic Mars Power System

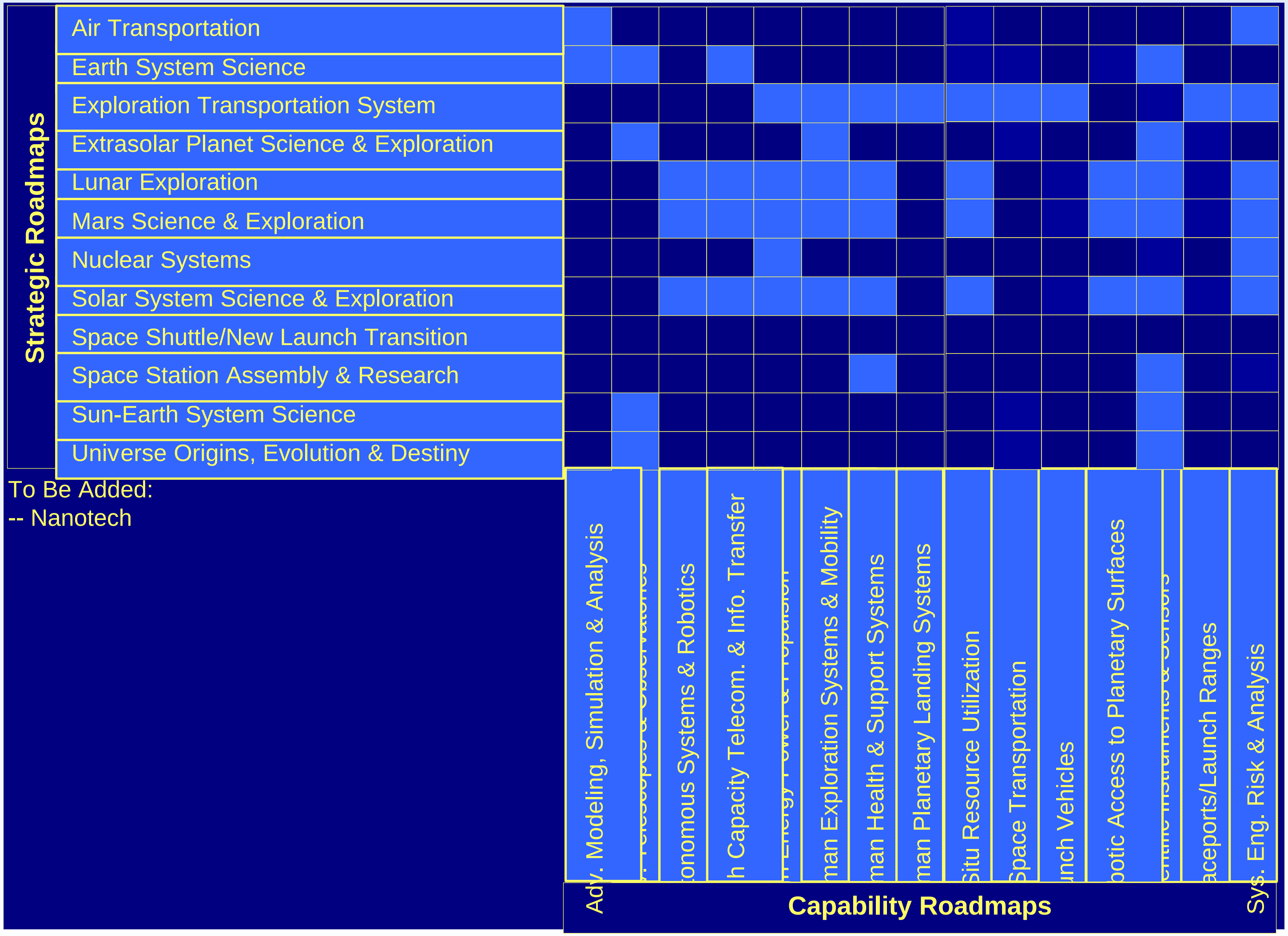


Photovoltaic Powered Mars Rove

Additional Assumptions

- The Spiral definitions given by ESMD were used as a basis for implied power and propulsion requirements/needs for human exploration
- Develop a human-rated lunar fission power system that is extensible to Mars for long-duration missions
- The current NASA Prometheus Nuclear Program has initiated preliminary technology development in advanced power conversion and electric propulsion
- Roadmap activity will highlight the need for capability choices/decisions without actually making those decisions
- Although cognizant of cost/budget issues, the team has not yet prioritized developments based on budget
- Multi-hundred kW to MW size space solar arrays are achievable

Strategic/Capability Relationship Example



HEP & P Connection Points with Other Capability Roadmaps

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High Energy Power and Propulsion	Capability Flow and Criticaltiy	Related Roadmap	Nature of Relat
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
		Human Exploration Systems &	
Surface Power (PV/Radioisotope)	→	Crew Mobility/Surface rovers	Power sources requ crew surface rovers
Surface Power (PV/nuclear fission)	→	In-Space Assembly Large & Intermediate Scale Assy	High Power neede cranes, tools, etc.
Component Technologies/PMAD	→	In-Space System Deployment Electrical & Data Interconnects	Power managemer distribution equipm
		In Situ Resource Utilization	
Surface Power (PV/nuclear fission)	→	Resource Extraction; excavation, drilling, etc. Resource Processing; consumable(O2), fuel, feedstock, etc. production In situ manufacturing	All of these ISRU pr will depend upon hi power/enegry sourc
		Human Health & Support Systems	
Component Technologies; Batteries, PMAD	→	Life Support & Habitation; EVA(Portable Life Support Systems)	Advanced batteries power supplies
Surface Power(PV/nuclear fission)	→	Life Support & Habitation; Advanced life support, habitats	High power system needed to support h activities
		In-Space Transportation	
Component Technologies: Fuel tanks & ancillary components, guidance & nav, avionics, vehicle health management	→	All Human & Robotic Earth, lunar, and planetary ascent and descent stages	Advanced technolo components will enh may enable In-Spac Transportation capa
		Nanotechnology	
Component Technologies	←	Advanced Nano-Scale Materials & Concepts for Nano-Scale Devices; Nano-to-Micro Systems Integration	Battery electrode m quantum dot PV, etc

HEP & P Connection Points with Other Capability Roadmaps (continued)

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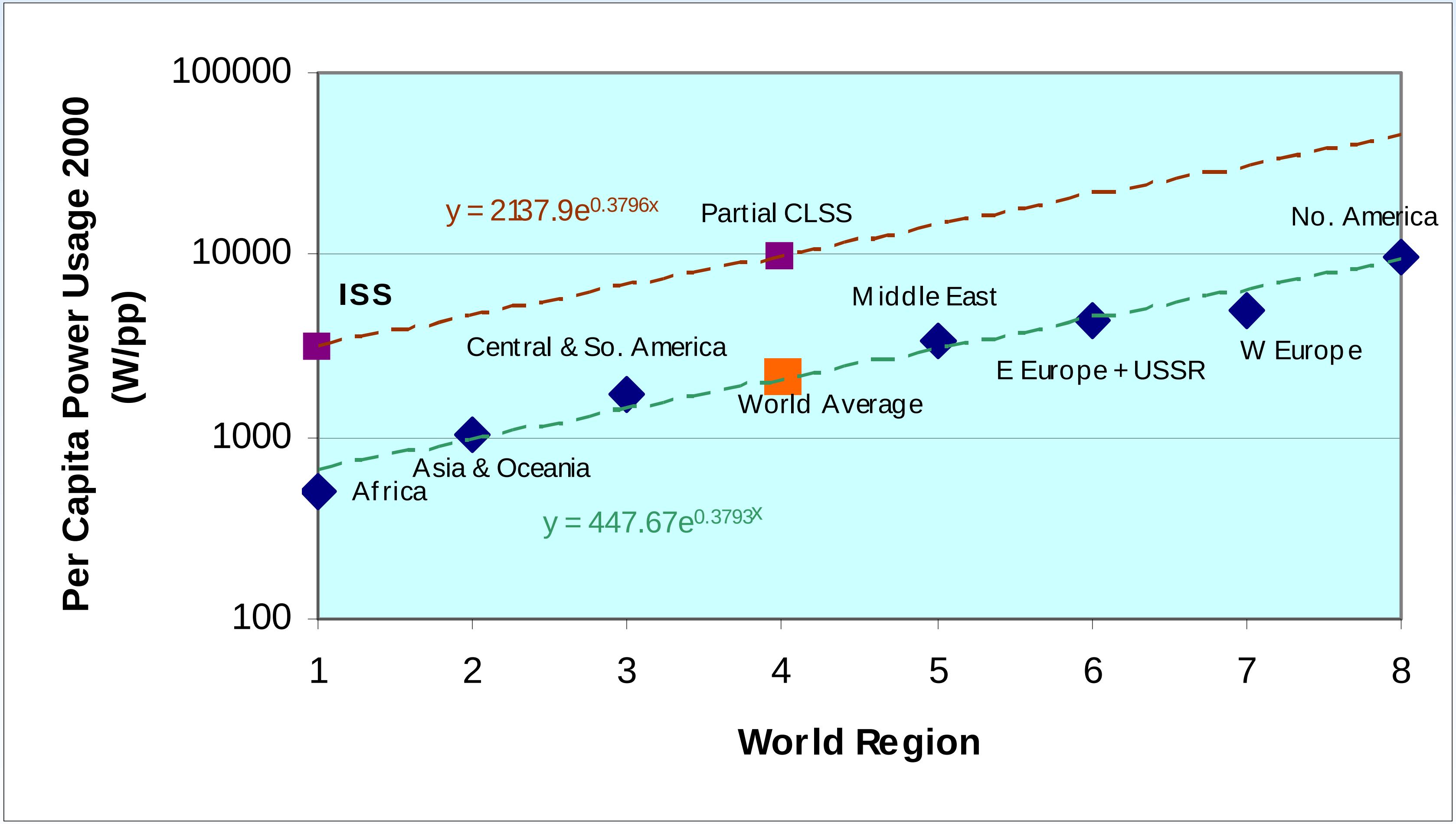
		Robotic Access to Planetary	
Surface Power (PV/Radioisotope)	→ (red)	Surface Access: Mobility	Power sources requ surface rovers, clim
Surface Power (PV/Radioisotope)	→ (red)	Surface Material Access and Processing	Power for drilling, c sample acquisition, transfer.
Component Technologies (PV, GPHS, batteries, PMAD)	→ (red)	Aerial Systems	Power for planes, g balloons, etc.
		System Engineering Cost/Risk	
All Sub-topics in High Energy Power & Propulsion	← (blue)	All system engineering sub-topics.	All elements of syst engineering can be to conceptual decis design, developme cost & risk analyses
		Communications & Navigation	
Component Technologies/PMAD	→ (blue)	All communications systems types; power supplies	High efficiency pow are often needed fo performance comm
High Eneryg Propulsion Systems/Guidance & Nav	← (red)	Comm/navigation	Comm system play in nav.
		Advanced Telescopes &	
Component Technologies (solar cells, photovoltaic arrays, energy storage,thermal heat rejection, power management and distribution, material and structures, guidance and Nav, avionics...)	→ (blue)	Filled aperture systems, interferometers, formation flying, microwave systems, gravity wave observatories	All advanced telesc observatories requi component technolo described. Future v systems will require power capabilities. technologies in thes would be enhancing
		Transformaitonal Spaceport/Range Technologies	
Surface Nuclear Fission Power Systems High Energy Nuclear Electric & Nuclear Thermal Propulsion Systems	↔ (blue)	Vehicle-Independent Spaceport System Capabilities; Advanced Servicing Systems, Rapid Transportation, Handling & Assembly, Inspection & System Verification Integrated Space- & Ground-based Range System Capabilities; Decision	New/large nuclear s may require new sp capabilities.
Red – Critical			
Blue – Moderate			

Backup Charts For Solar Systems

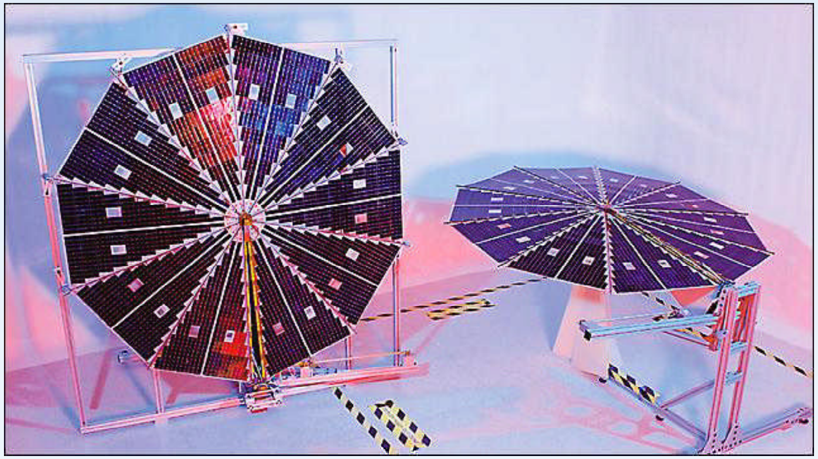
Power Needs for Humans in Space

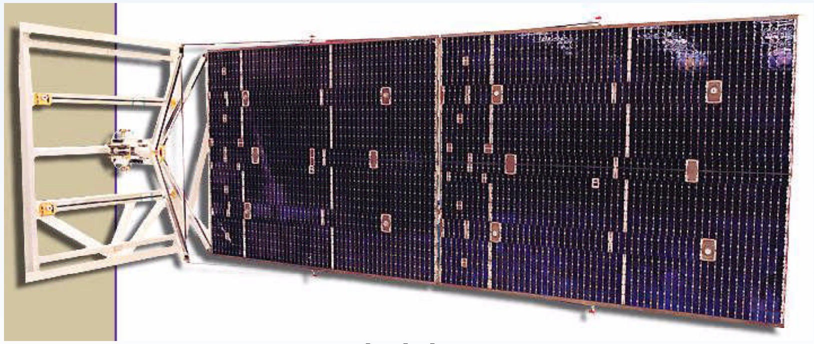


Solar arrays

Teledesic Solar Array

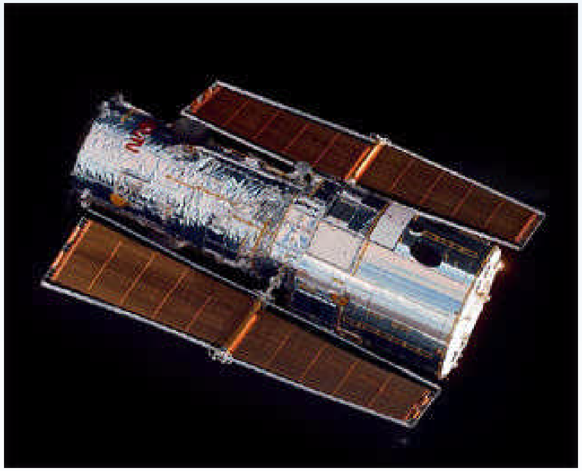
Ultraflex Array





PUMA rigid array

Hubble Space Telescope



Capability for Exploration Propulsion

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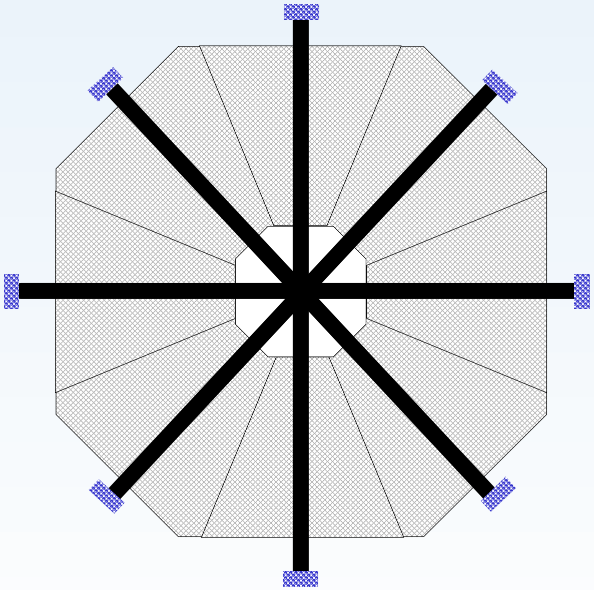
- **SEP Lunar Cargo Vehicles**
  - 0.1 - 1 MWe Spacecraft power (dependent on payload mass)
  - 50 - 100 kW versions of SOA thruster concepts (Hall/Ion)
  - Near term solar arrays (500 W/kg)
  - 200 kW advanced array comparable in size to ISS arrays
  - • 1 year round trip, reusable

- **SEP Mars Transportation Vehicles**
  - 2 - 10 MWe envisioned for Lunar/Mars Applications
  - 500 kW - MW thrusters (Hall/Ion/Advanced)
  - Advanced solar arrays (1000 W/kg)
  - Large, lightweight deployable structures
  - ~ 2 year trip time, possible reuse

0.5 MWe SEP Mars Cargo (1999)*



5 MWe SEP concept (1990) 30,000 m^2*

Not to Scale

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Backup Charts for Energy Storage Systems

Future Mission Requirements for Capability Area: Energy storage

Category	Mission Type	Driving Requirements	SOP Capability	Challenge
Human Exploration Missions	Lunar/Mars Surface Mission: Habitat/Outposts	Very High (MWh) energy Storage Capability & High Specific Energy (>500 Wh/kG)	Hundreds of Kwh 30-90 Wh/kg	10X Energy storage capability 5-10 X Higher Specific Energy
Human Exploration Missions	EVA: Suit, Astronaut Equipment	Very High Specific Energy Rechargeable Battery/Fuel Cell (> 300 Wh/kg) with Long Life	100 Wh/kg with six month operational life	3x Higher specific energy Longer life
Human Exploration Missions	Crew Transportation Vehicle: CEV	High power (5-30 kW), Low Mass (> 200 W/kg) and Low Maintenance Fuel Cells, 5000 hours Operating life	10 kW, 90 W/kg alkaline fuel cells that require periodic maintenance(2600 hours)	2-3 X Hgher specific power Long Life
Robotic and Human Exploration Missions	Solar powered surface missions: Rovers, Landers	High Specific Energy (>200 Wh/kg) rechargeable batteries with low temperature operational capability (<-80 C)	-20 C rechargeable batteries (70 Wh/kg)	2X Higher specific energy Very low temperature operation
Robotic Exploration Missions	Outer Planetary Probes and sensor networks	Low mass and compact primary batteries(500 Wh/kg) with low temperature operational capability (<-80 C)	-20 C primary batteries (150 Wh/kg)	2-3 X Higher specific energy Long life, Very low temperature operation
Robotic Exploration Missions	Orbital Spacecraft: Earth Orbiters. Planetary Orbiters	Low mass (> 100 Wh/kg) rechargeable batteries with Long Life Capability (>20 years), •Radiation resistance (5-20 M Rads)	30 Wh/kg with > 15 year life	2-3 X Higher specific energy Long life Rad hard
Robotic Exploration Missions	Inner Planetary Probes	High Temperature Primary and Rechargeable Batteries (400 C)	0-60 C	High Temperature operation

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Candidate Advanced Storage Systems and Capability Readiness Levels of SOA Systems

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Mission Type	Driving Capability Requirements	Candidate Adv. Technology	Current CRL	Required Date for CRL3
Lunar/Mars Surface Missions: Habitat /Out Posts	MWh energy Storage Capability	Regenerative Fuel Cells Fly Wheels	2	2015
EVA: Suit, Astronaut Equipment	Low mass and compact rechargeable energy storage system (> 300 Wh/kg)	Adv Rechargeable Batteries Small Fuel cells	2	2015
Crew Transportation Vehicle: CEV	High power (20-40 kW) Low Mass (> 200 W/kg) Low Maintenance Fuel Cells	PEM Fuel Cells and Advanced Hydrogen and Oxygen Storage	2	2010
Solar powered surface missions: Rovers, Landers	Low mass(>150 Wh/kg) rechargeable batteries with low temperature capability (<-80 C)	Adv Li rechargeable Batteries	2	2012, 2015
Outer Planetary Probes and sensors	Low mass (> 500 Wh/kg) and compact primary batteries with low temperature operational capability (<-80 C)	Advanced Li rimary batteries	2	2010, 2015
Orbital spacecraft: Earth orbiters, Lunar Orbiters, Planetary Orbiters	Low mass (> 150 Wh/kg) rechargeable batteries with Long Life Capability (>20 years), •Radiation resistance (5-20 M Rads)	Adv. Li-Ion/Li-Polymer Rechargeable Batteries	2	2010-2015
Inner Planetary Probes	High Temperature Primary and Rechargeable Batteries (400 C)	High Temperature Na/Li Batteries	1	

Summary of Energy Storage Technology Needs of Robotic Science Missions

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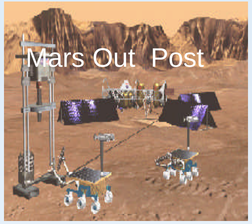
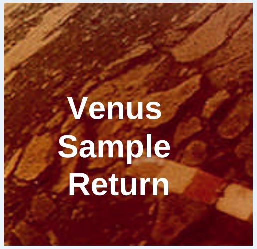
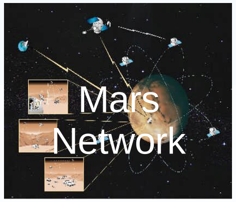
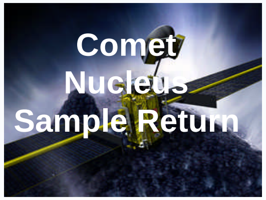
- Low temperature primary(<-100°C) and rechargeable (<-60°C) batteries for planetary probes and mars surface missions
- High temperature batteries (> 475 °C) for inner planetary missions
- Long calendar life (>15 years), high specific energy (>120 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions
- Long cycle life (>30,000 cycles) and high specific energy (>120 Wh/kg) rechargeable batteries for Mars and earth orbital SEC, SEU & origins missions
- High specific energy primary batteries (>500 Wh/kg) for comet/asteroid probes









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°C)
- Radiation tolerance poorly understood
- Voltage delay

Characteristics of SOA Primary Batteries

Type	Application	Voltage (a)	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Specific Power, W/kg (c)	Operating Temp. Range, °C	Capacity Loss % Per Year	Mission Life (yrs)	Manufacturer	Configuration
Ag-Zn	Cell	1.61	200	550	1100	0-55	60	1	Yardney	Prismatic
	Typical Launch Vehicle	28	119	283	118	5 to 40	60	1	Eagle Picher	Manually Activated
$Li\text{-}SO_2$	Cell	2.9	238	375	682	-40 to 70	<2.5			Cylindrical
	Galileo Probe Battery	38	91	147	261	-15 to 60	<2.5	9	Alliant Tech	Three 13 cell batteries
	Genesis Battery	24	142	127	402	-20 to +30	<2.5	6	SAFT	Two 8 cell batteries
	MER	30	136	388	390	0 to 60	<2.5	5	SAFT	Five 12 cell batteries
	Stardust	20	192	182	519	-26 to +50	<2.5	10	SAFT	Two 8 cell batteries
$Li\text{-}SOCl_2$	Cell	3.2	390	878	139	-30 to- 60	<1			Cylindrical
	Sojourner	9	245	514	102	-20 to 30	<1	5	SAFT	Three 3 cell batteries
	Deep Impact	33	221	380	106	-20 to +30	<1	4	SAFT	Three 13 cell batteries
	DS-2	14	128	339	64	-80 to +30	<1	4	Yardney	Two 4 cell batteries
	Centaur Launch batteries	30	200	517	83	-20 to +30	<1	6	Yardney	One 9 cell batteries
Li- BCX	Cell	3.4	414	933	148	-40 to 70	<2		Wilson GB	Cylindrical
	Astronaut Equipment	6	185	211	115	-40 to +72	<2	3	Wilson GB	2 cell radio batteries
$Li\text{-}CF_x$	Cell	2.6	614	1051	15	-20 to 60	<1		Eagle Picher	Cylindrical DD
	Range Safety battery	39	167	149	14	-20 to 60	<1		Eagle Picher	15 Cell Battery

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 Rechargeable Batteries

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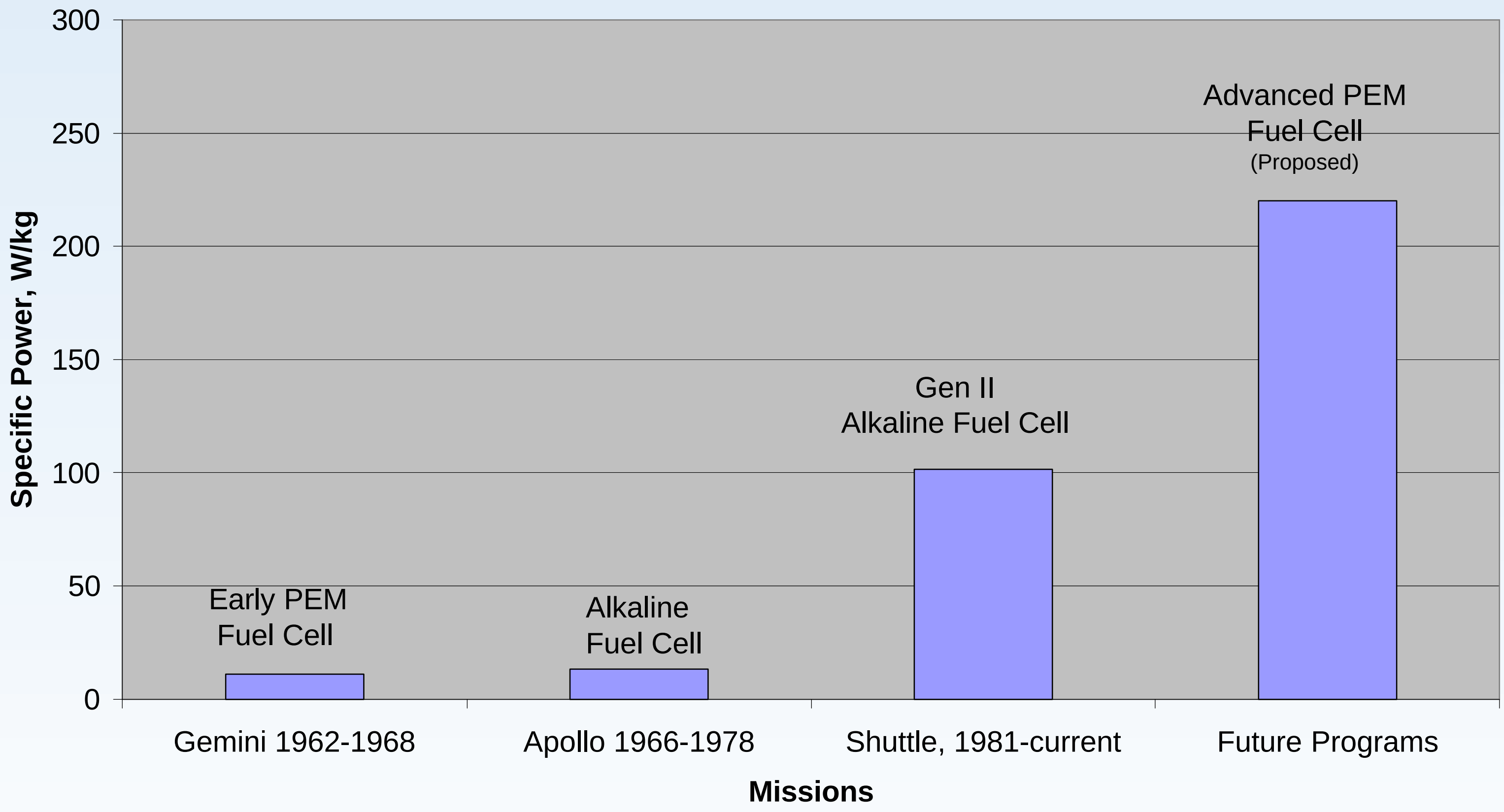
Technology	Use	No of Batteries / Cells in Bat	Ah Rated/actual	Operating Voltage	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life to Date	Manufacturer
Ag-Zn	Cell	1	40/58	1.5	128	248	-20 to 25			BST
	Pathfinder Lander	1/18	40/58	27	100	191	-20 t0 25	2	100	Yardney
Ni-Cd	Standard 50 Ah	1	50/62	1.25	37	111	-20 to 25	3		Gates
	Landsat	3/22	50 /60	22-36	34	53	-20 to 26	3	25K	MDAC
	TOPEX	3/22	50/60	22-36	34	53	-10 to 30	3 to 5	40K	MDAC
Super Ni-Cd	9 Ah Cell	1	9/12	1.25	31	93	-20 to 30	15		EPI
	50 Ah Cell	1	50/63	1.25	32	100	-20 to 30	15		EPI
	Sampex Battery	1 /22	9/12	28	28	72	-20 to 30	5	58K	EPI
	Image	1/ 22	21/24	28	33	71	-20 to 30	5	14K	
IPV Ni-H_2	IPV Cell	1	98/83	1.25	48	71	-10 to 30		10	EPI
	Space Station	6/76	81/93	48	24	8.5	-10 to 30	6.5	11K	Boeing
	HST	6/22	80/85	28	8	4	-10 to 30	5	65K	EPI
	Landsat 7	2/17	50 / 61.7	24			-10 to 30	5	>50K	LMAC
CPV Ni-H_2	CPV Cell	2	16/17.5	2.50	43.4	77	-10 to 30	10		EPI
	MIDEX MAP	1/11	16/17.5	28	36	21	-10 to 30	5	50K	
	Odyssey	2/11	16/17.5	28	36	21.1	-3 to 8	10 to 14	1K	LMAC
	Mars 98	1/11	16/17.5	29	37	41	5-10	3		LMAC
	MGS	2/16	20/23	20	35	25	5-10	1 Mars Yr	50K	LMAC
	EOS Terra	2/54	50/	67		21	-5 to 10	5		
	Stardust	1/11	16/17.5	28	36	21	-5 to 11	7	1135 days	LMAC
SPV Ni-H_2	SAR 10065	1/12	50/60	28	54.6	59.3	-10 o 30	10		JCI/EPI
	Clementine	1/22	15/18	28	54.8	78	-10 to 30	200 cycles	200 cycles	JCI/NRL
	Iridium	1/22	60/70	28	53.4	67.7	-20 to 30	3 - 5	50K	JCI/ EPI
Li-Ion	Cell	1	8.6/10	4.0	133	321	-20 to 30	1		Yardney
	MER-Rover	2/8	16-20	28	90	250	20 to 30	1	n/a	Yardney

Characteristics of Fuel Cells



Fuel Cells In Space

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Type	Gemini	Apollo	Shuttle
No. Flights	7 (#5 -12)	All	All
Manufacturer	General Electric	Pratt & Whitney	United Technologies
Type	PEMFC	AFC	AFC
Fuel Cell Modules	3 - 350 W	3	3
Peak Power	1 kW	2.3 kW	36 kW
Power Module (continuous)	500 -620 W	1.5 kW	14 kW
Cell temperature (°C)	40 to 60	200 -250	83 - 105
Voltage	23.3 - 26.5V	26 - 31 V	26.5 - 32.5V
Fuel Cell Stack Mass	31	110	91
H_2 Storage pressure	210 to 250 psi	245 psi	290 -290 psi
O_2 Storage pressure	800 psi	900 psi	850 -950 psi
Electrolyte	Sulfonated polystyrene	85% KOH	30 - 40 % KOH
Efficiency	50 – 60%	60%	61.8% @6 kW
Service life	400 - 800 Hrs@ 0.5kW	400 -1500 Hrs@ 1kW	2000 Hrs@ 4.5 kW
Time in Space	840 Hrs	1995 Hrs	Serviced 2000Hrs

Characteristics of SOA Alkaline Fuel Cells

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Characteristic	Alkaline Fuel Cell
Specific Power, Watts/kg Power Density, Watts/liter	90 155
Efficiency	70%
Maintenance frequency	Every 2600 h
Differential Pressure Limit	41 kPa
Operating Temperature	90^{o}C
Failure Mechanisms	Attack of epoxy frames and Noryl insulator plates by KOH.

Li-Ion Batteries

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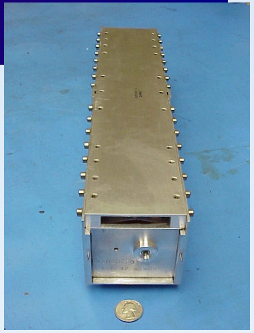
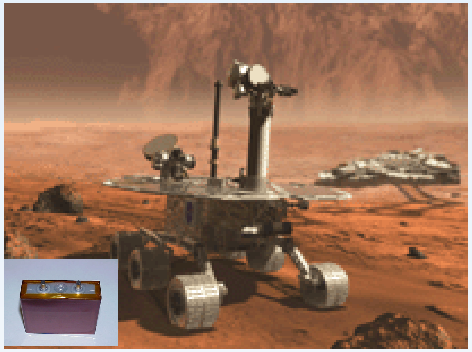


Technology Status

- **Small capacity cells & batteries are being used in several commercial applications(> 100 Wh/kg, <500 cycles)**
- **Work in progress to develop cells and batteries for aerospace & DoD applications**
  - **Low temperature (-20 C) & limited cycle life (1000 cycles) batteries developed and qualified for Mars surface missions (TRL 8-9)**
  - **Technology infused to Mars surface missions (Spirit and Opportunity rovers)**
  - **Batteries under qualification for aircraft applications**
- **TRL: Long life batteries (3-4), -60 C batteries (2-3)**



Mission Benefits

- **Enabled MER (3-4 X mass and volume savings, -20 C)**
- **Outer planetary orbiters/fly-by (Mass and volume)**
- **Mars/Earth orbiters (Mass and volume)**
- **Mars surface missions(Low temp.operation)**

Technical Issues

- **Limited Cycle Life**
- **Limited Calendar Life**
- **Safety**

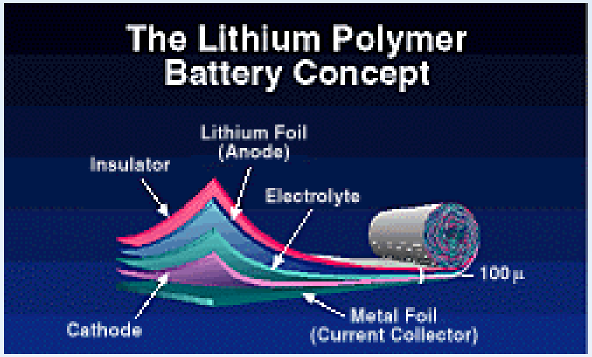
Potential Capabilities

Battery Level:	SOA Li -Ion	Adv. Li-Ion
Specific Energy (wh/kg)	90	200
Energy Density (wh/l)	180	400
Cycle Life (30% DOD)	15 K	> 30 K
Calendar Life (years)	3	> 15
Operating Temperature	-20 to 30	-60 C to 60 C

Li-Polymer Batteries

Technology Status

- **Two types: Gel Electrolyte, Solid Polymer**
- **Gel polymer electrolyte batteries in use in commercial applications(> 120 Wh/kg, <500 cycles). Similar to Li-Ion batteries**
- **True solid polymer electrolytes under development**
  - **SOA electrolytes: 10^{-5} S/cm (Goal : 10^{-3} S/cm)**
  - **TRL: (1-2)**



Advantages

- **Mass and volume savings (4-5 X Vs SOP)**
- **Long Life (> 15 years)**

Mission Benefits

- **Outer planetary orbiters/fly-by (mass & volume)**
- **Mars/Earth orbiters (mass & volume)**

Technical Issues

- **Poor electrolyte conductivity**
- **Hermetic sealing of cells**
- **Life**

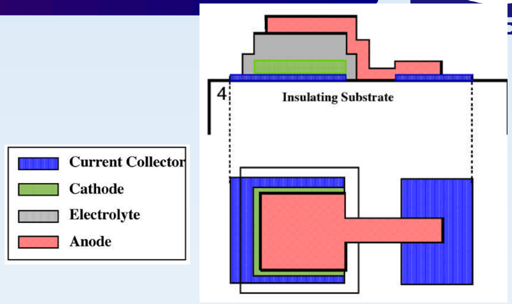
Potential Capabilities

Battery Level:	SOA (Gel)	Adv. Polymer
Specific Energy (wh/kg)	100	150
Energy Density (wh/l)	200	300
Cycle Life (30% DOD)	5k	> 30 K
Calendar Life (years)	2	15

Li-Solid Electrolyte Batteries

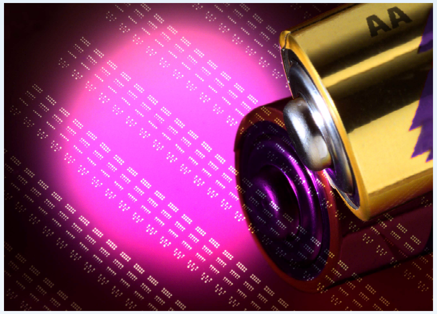
Technology Status

- Micro-batteries, with 70 microAh/cm^2 have been developed for memory back-up and low-power MEMS applications.
- Long cycle life (> 20 K) demonstrated
- TRL: 1-2



Advantages

- Mass and volume savings (4-5 X Vs SOP)
- Long Life (> 20 years



Mission Benefits

- Outer planetary orbiters/fly-by (mass & volume)
- Mars/Earth orbiters (mass & volume)

Technical Issues

- Poor electrolyte conductivity
- Low area-specific capacity
- Scale up to large capacity cells

Potential Capabilities

Battery Level:	SOA	Adv. Solid State
Specific Energy (wh/kg)	n/a	>200
Energy Density (wh/l)	n/a	>300
Cycle Life (30% DOD)	20 K	100 K
Calendar Life (years)	> 3Y	20
Operating Temperature	0 to 40^{o}C	0 to 100 ^{o}C

PEM Fuel Cells

Technology Status

- > 30 kW PEM fuel cell systems developed for EV applications
- 50-500 W Hydrogen-air systems are under development for DOD applications
- 5-10 kW PEM fuel system is being developed for RLV applications
- TRL: 4

Technical Issues

- **H2 & O2 storage**
- **System complexity**
- **Life validation**

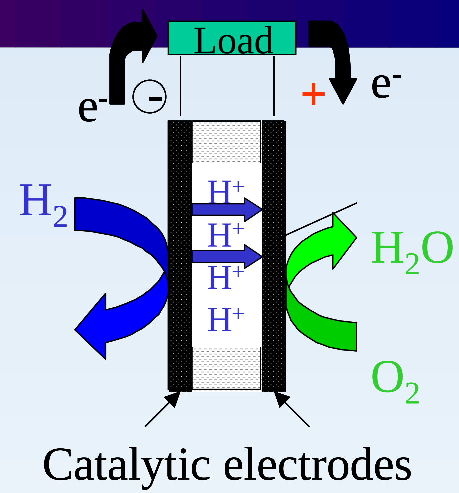
Advantages

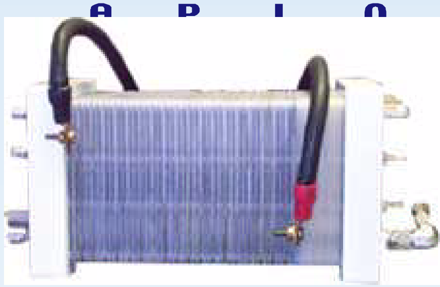
- **High specific energy (500 Wh/kg)**

- Mission Benefits
  - **Crew Exploration Vehicles**
  - **Human Lunar Exploration Missions**
  - **Human Mars Exploration Missions**

Current programs

DOE EV program
NASA RLV Program

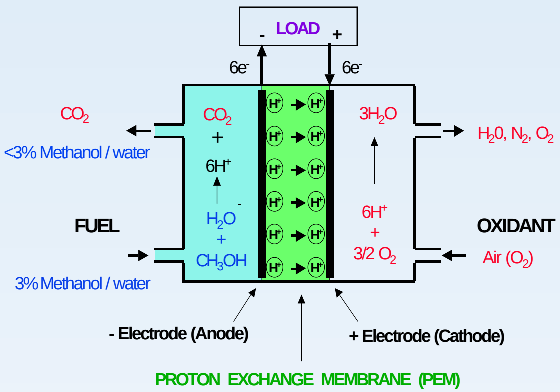




Potential Capabilities

Advanced Fuel Cell Technology-NASA

Primary Fuel Cells



Description

- Provides high specific energy & energy density compared to SOA primary batteries
- Consists of PEM Fuel Cell, fuel & O2 Storage Tanks
- Suitable for missions requiring >5 kWh
- Provides 2-3 X mass savings compared to primary batteries

Technology Status

- Prototypes fabricated & tested
- 300 Wh/kg
- TRL: 4-6 (01)

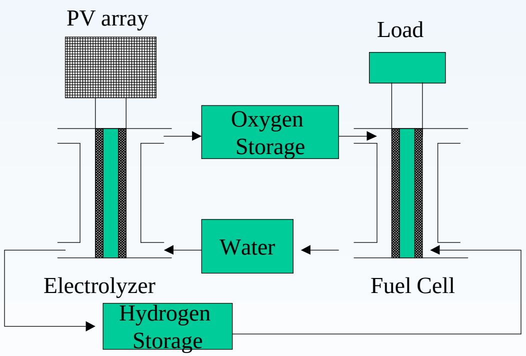
Future Development

- Improve to 500 Wh/kg
- Improve H2 & O2 storage capability
- Optimize system design to reduce mass and volume
- Demo tech readiness for missions

Technical Issues

- H2 & O2 storage
- Safety

Regenerative Fuel Cells



Description

- Provides high specific energy & energy density compared to SOA rechargeable batteries
- Consists of Electrolyzer, Fuel Cell, fuel & O2 Storage Tanks
- Attractive for high energy storage applications (>5 kWh)

Technology Status

- Prototypes fabricated & tested
- 100-200 - Wh/kg
- TRL: 4-6 (01)

Future Development

- Improve Specific Energy to 200-300 Wh/kg
- Improve charge/discharge efficiency to 70%
- Improve H2 and O2 storage capability
- Optimize system design to reduce mass & volume
- Demo tech readiness for surface rovers, orbiters, sample return missions

Technical Issues

- Charge/discharge eff.
- H2 & O2 storage
- Safety

Fly Wheels

Technology Status

- Two Types:
  - Fixed-Axis Energy-Only System
  - Fixed-Axis Energy/Momentum System
- Engineering model units fabricated and tested (25-30 Wh/kg)
- TRL: 3

Advantages

- High usable Specific energy (> 75 Wh/kg)
- Long cycle Life (> 50,K Cycles @ high DoD)
- Wider operating temperature range (-40 C to 100 C)
- Probable radiation tolerance (> 5 Mrads)

Mission Benefits

LEO/GEO missions

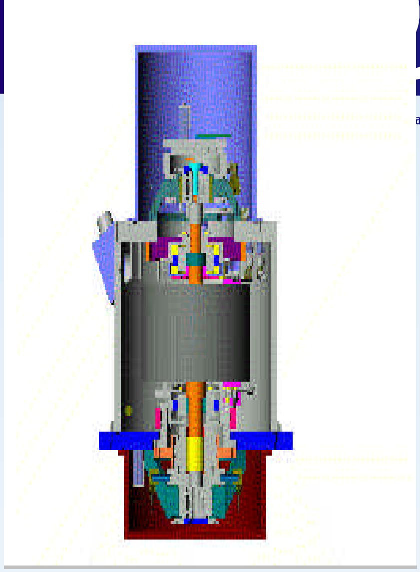
Space Station

Technical Issues:

- Miniaturization
- Safety
- Reliability

Current programs

- NASA Code-R Program
- AFRL FACETS Program



Fixed-Axis Energy-Only System

Potential Capabilities

Characteristics of Advanced Rechargeable Batteries

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Characteristic	SOP Ni-H_2	Li-Ion with liquid electrolyte	Li-Solid Polymer Electrolyte*	Li-Solid Inorganic Electrolyte*
Technology Readiness Level	10	5-9	3	1-2
Specific energy (Wh/kg)	30-40	100-150	>200	> 200
Energy density (Wh/l)	40-50	200-300	300-450	> 300
Cycle life	60, 000	1500	1500	>10,000
	(at 30% DOD)	(at 100% DOD)	(at 100% DOD)	at 100% DOD
Operating temperature	-5-30 C	-60 to 80 C	0-80 C	0-80 C
Self discharge rate		1% / month	0.25% / month	0.1% month
Shape factor /packing eff	Poor	Good	Excellent	Excellent

Long Life Rechargeable Battery Performance Targets

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	Ni-H2	Lithium Technology		
Characteristics	Present State of Practice	Present State of Practice	Goal 5 years	Goal 10 years
Specific Energy (Wh/kg)	30	100	120	200
Energy Density (Wh/liter)	10	200	200	400
Cycle Life at 30% DOD *	50,000	10-15,000	30,000	50,000
Calendar Life (years)	15	3	10	15

* DOD = Depth-of-discharge

Low Temperature Primary Battery Performance Targets

Primary Energy Storage Characteristics	Present State of Practice	Goal (5 years)	Goal (10 years)
Specific Energy at 0°C (Wh/kg)	250	400	600
Specific Energy at –40°C (Wh/kg)	100	200	300
Specific energy at –80°C (Wh/kg)	50	100	200
Discharge rate (hrs)	> 20	> 20	> 20

Low Temperature Rechargeable Battery Performance Targets

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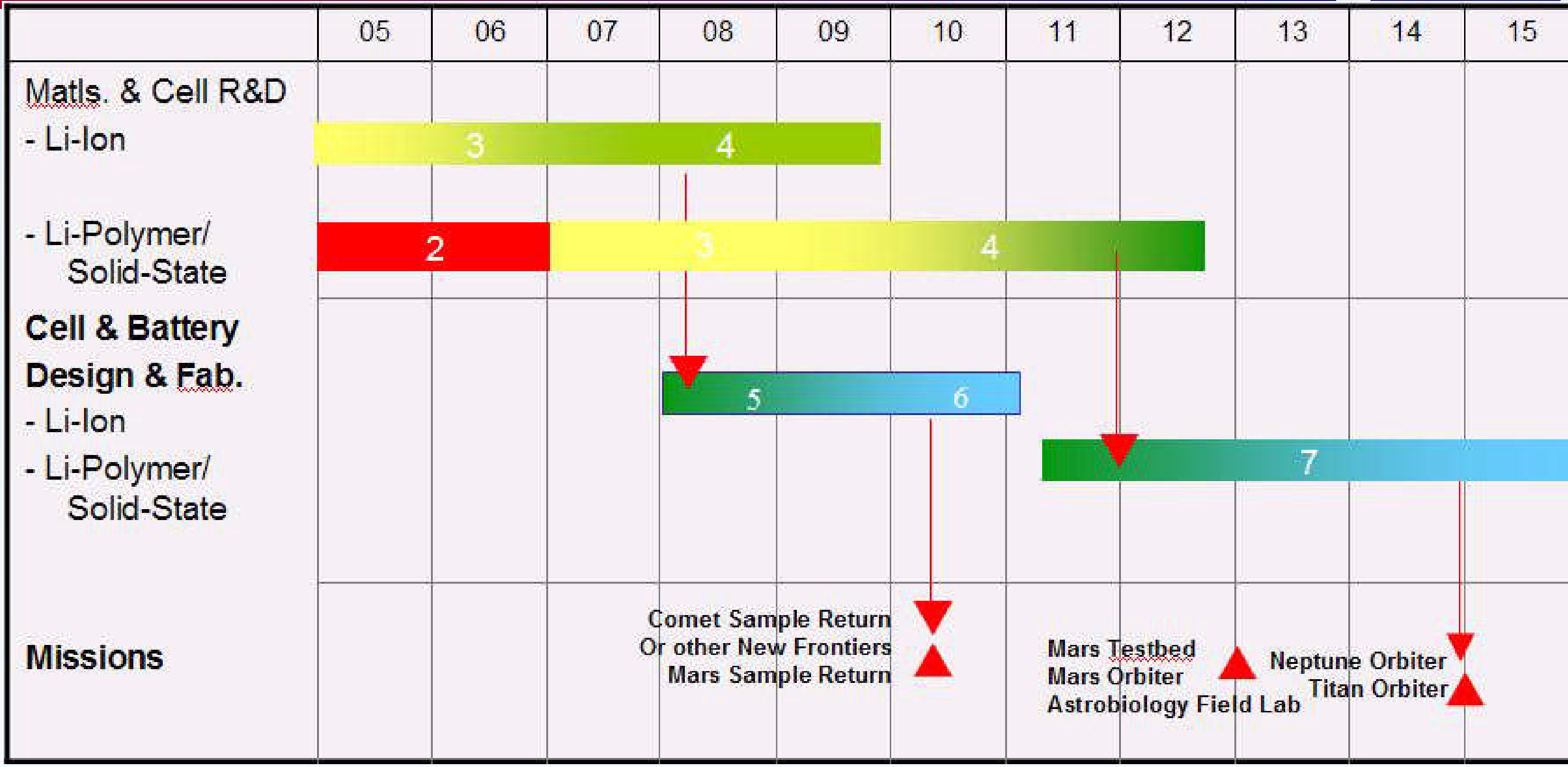
	Lithium Ion Technology		
Characteristics	Present State-of-Practice	5 years	10 years
Specific energy at $0^{o}C$ (Wh/kg)	100	120	200
Life Time (yrs)	5 yrs	10yrs	15 yrs
Cycle Life (# of cycles) (80%DOD)	> 500	> 500	> 500
Low Temperature Performance			
Specific Energy at $-20^{o}C$	70	100	160
Specific Energy at $-40^{o}C$	40	80	140
Specific Energy at $-60^{o}C$	0	65	120
Specific Energy at $-80^{o}C$	0	40	80
Discharge rate (hours)	>10	> 10	> 10

Projected Capabilities of Fly Wheels

Advanced Planning & Integration Office

	Current Values			Post-2013	
Parameter	NiH2	Li ion	Flywheels (6)	Li-Ion	Flywheels
energy density	35	35	44	150	70
orbit time	100	100	100	100	100
eclipse time	35	35	35	35	35
DOD	0.35	0.35	0.89	0.35	0.89
RT efficiency	0.8	0.8	0.95	0.93	0.95
charge/discharge efficiency	0.9	0.9	0.95	0.9	0.95
delivered energy	2900	2900	2900	2900	2900
stored energy	9206	9206	3430	9206	3430
required energy	4475	4475	3382	3850	3382
spacecraft power	5524	5524	5233	5524	5233
battery replenish	4131	4131	3122	3554	3122
% energy before taper		70	N/A	70	N/A
% insolation time before taper		55	N/A	55	N/A
P1		4674		4523	
P2		223		215	
Total Array Power	9655	9655	8355	10047	8355
storage mass (1)	263.0	263.0	78.0	61.4	49.0
electronics mass (2)	27.6	27.6	included	27.6	included
Subtotal	290.7	119.7	78.0	89.0	49.0
array mass (4)	50.8	50.8	44.0	52.9	44.0
Subtotal	341.5	173.4	122.0	141.9	93.0
attitude control sys mass (3	47.4	47.4	N/A	47.4	N/A
Total System Mass	388.9	388.9	122.0	189.3	93.0
array power density (5)	190				
battery electronics density	200				

Long Life Rechargeable Battery Technology Development Roadmap

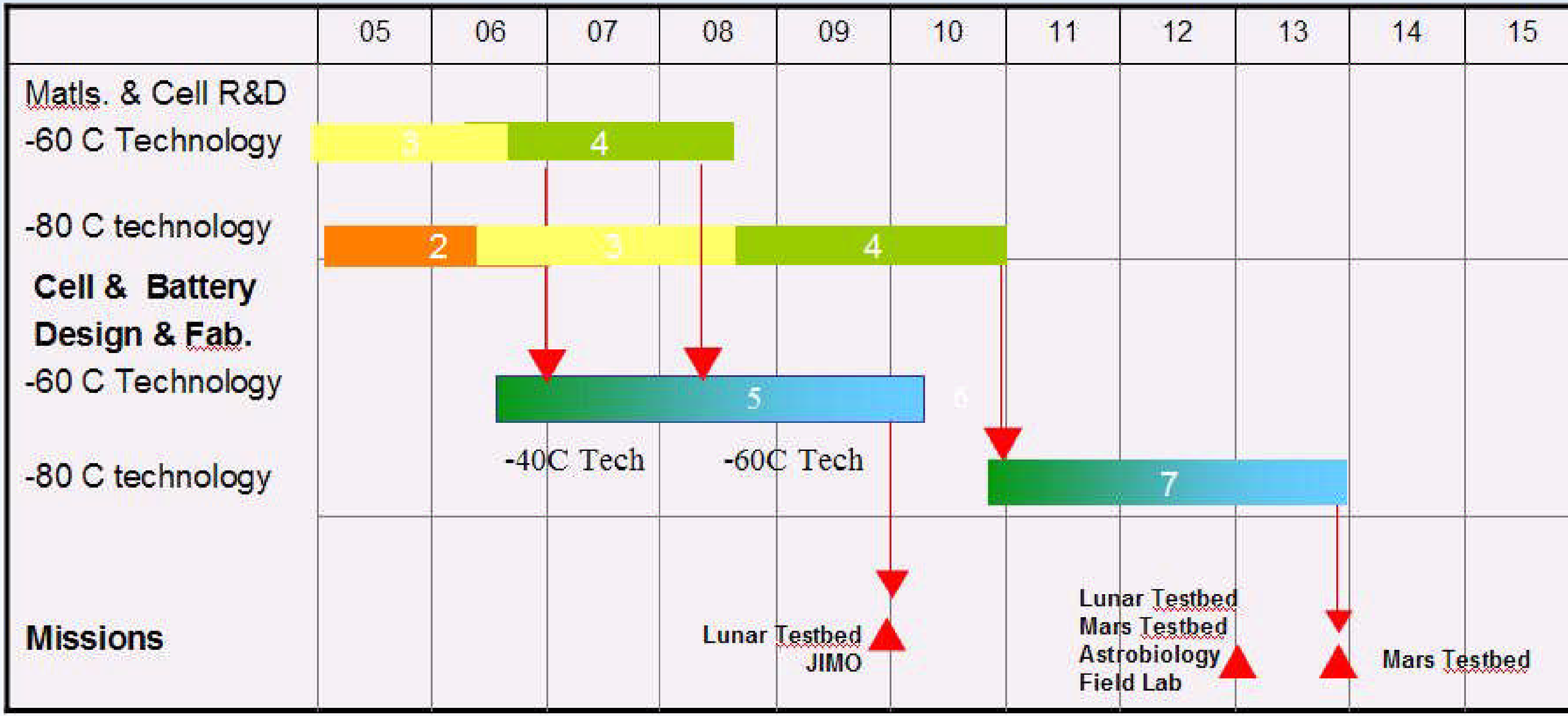


Rough Estimated Cost for the Development Long life Rechargeable Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Materials & Cell R&D (TRL 1-3)												
Li Ion Technology-1	1	1	1	1	1							5
Li Polymer/SolidstateTechnology-2	2	2	2	2	2	2	2	1				15
Tech Maturaration TRL(4 to 6)			2	2	2	2	2	2	2	2	2	18
Total Development Cost	3	3	5	5	5	4	4	3	2	2	2	38
DOD Cost Share for Tech Maturation			1	1	1	1	1	1	1	1	1	9
NASA Cost Share	3	3	4	4	4	3	3	2	1	1	1	29

Low Temperature Rechargeable Battery Technology Development Roadmap

Advanced Planning & Integration Office



Rough Estimated Cost for the Development Low Temperature Rechargeable Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Materials & Cell R&D (TRL 1-3)										
Li Technology-1	0.6	0.6	0.6	0.6						2.4
Li Technology-2	0.8	0.8	0.8	1.2	1.2	1.2				6
Tech Maturaration TRL(4 to 6)			1	1	1	1.5	1.5	1.5	1.5	9
Total Cost	1.4	1.4	2.4	2.8	2.2	2.7	1.5	1.5	1.5	17.4

Low Temperature Primary Battery Technology Development Roadmap

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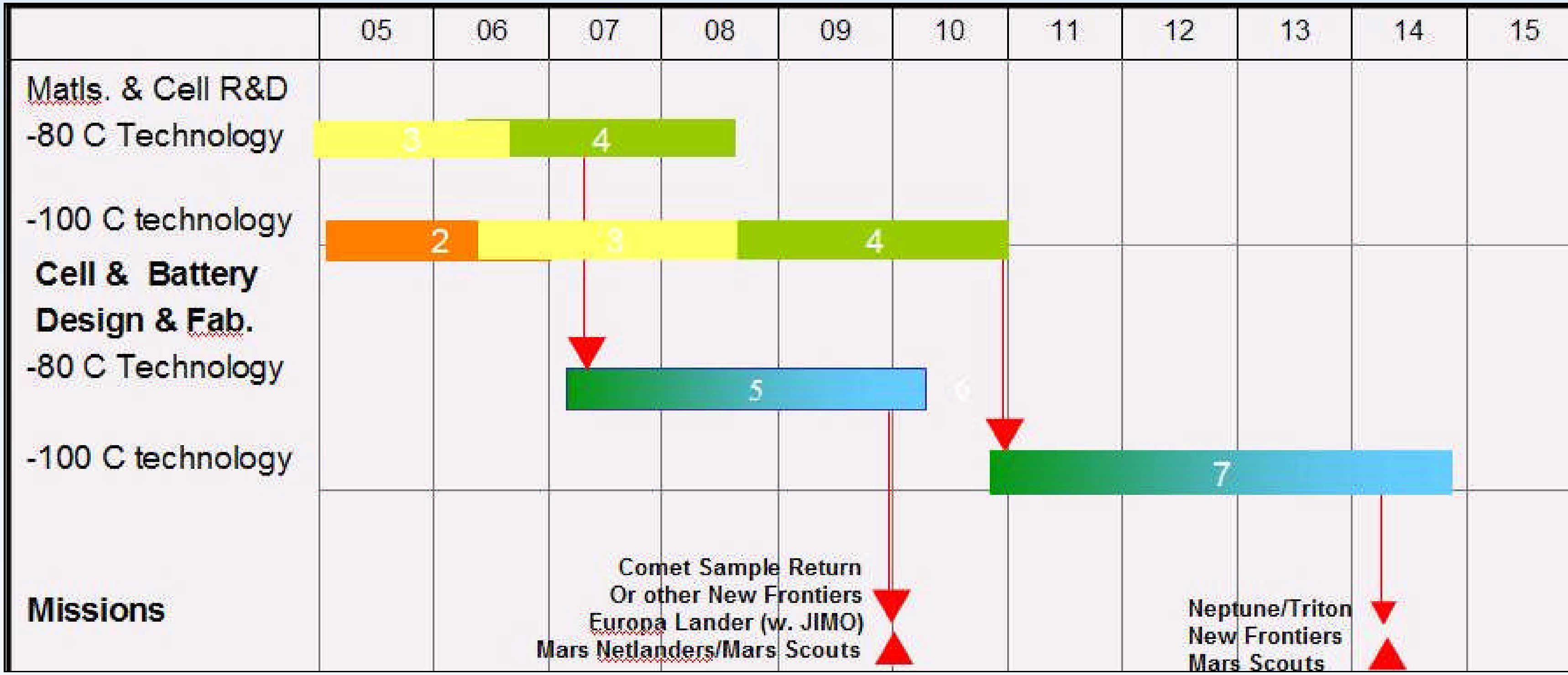
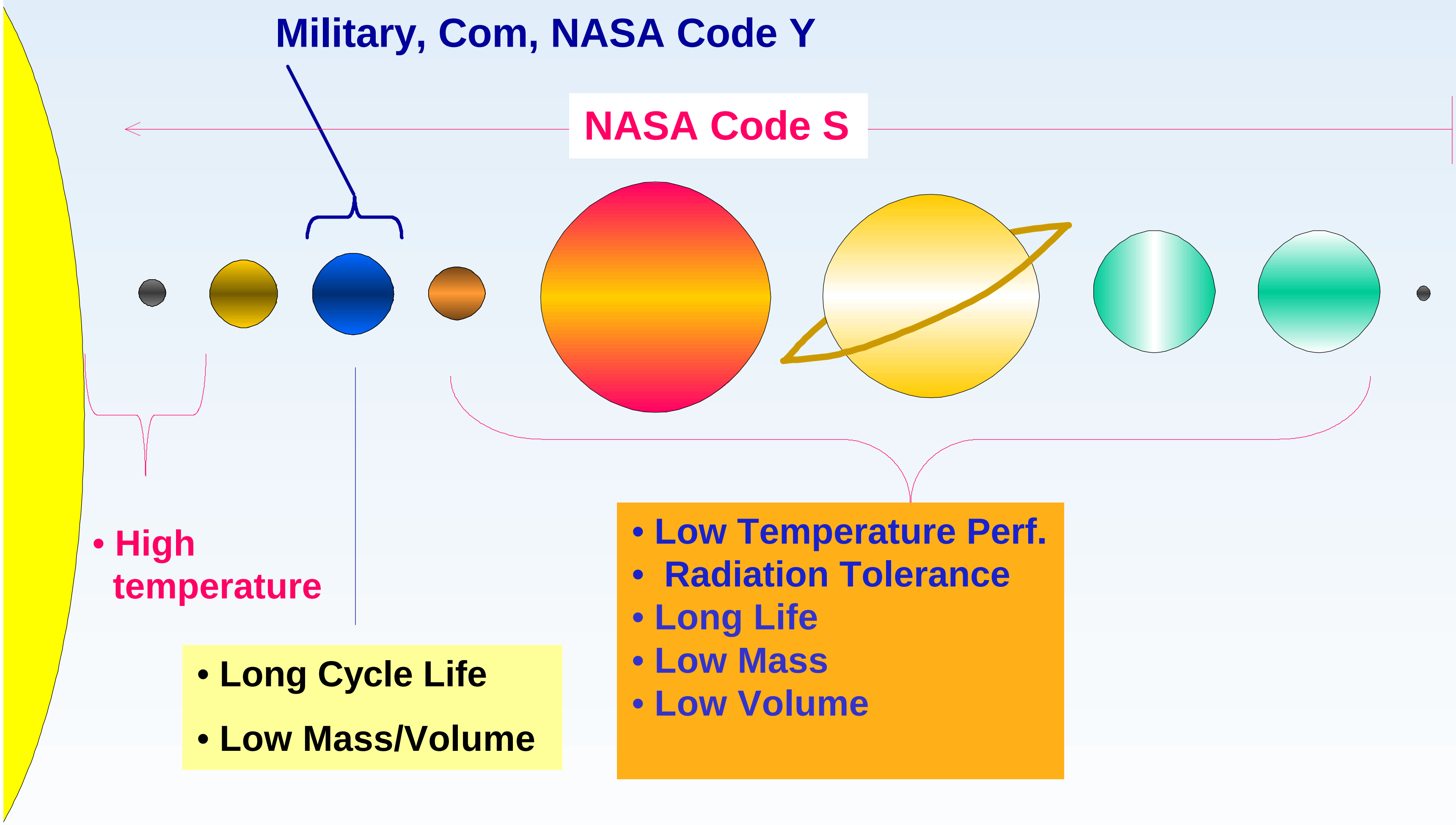


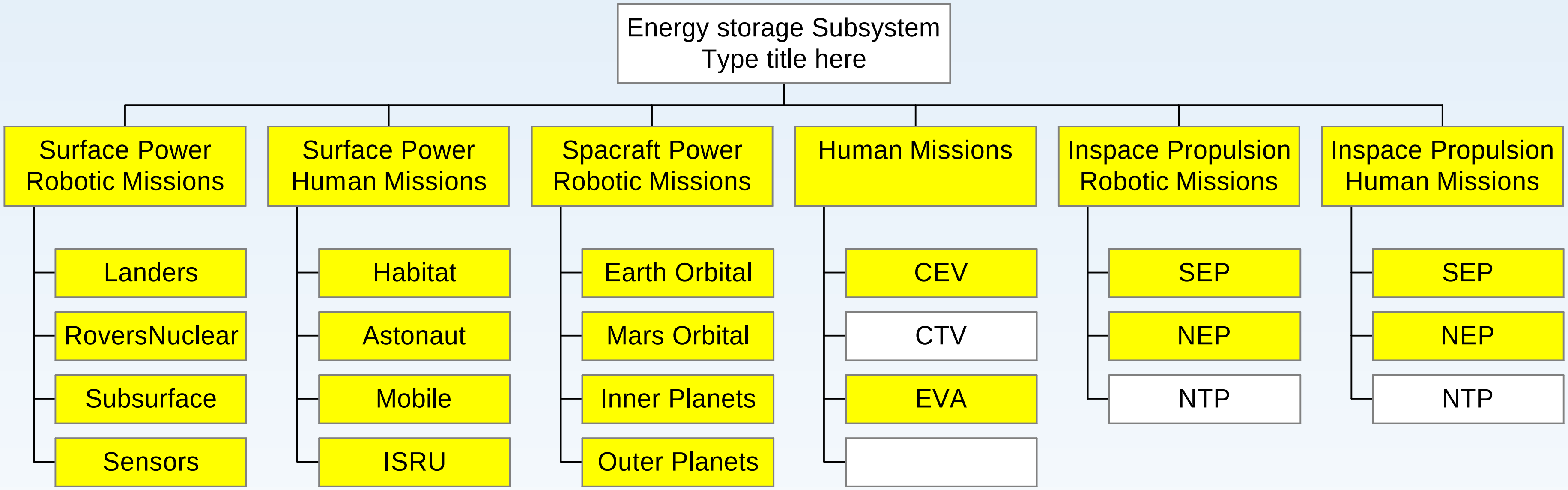
Rough Estimated Cost for the Development Low Temperature Primary Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Materials & Cell R&D (TRL 1-3)											
Li Technology-1	0.6	0.6	0.6								1.8
Li Technology-2	0.6	0.6	0.6	0.6	0.6	0.6					3.6
Tech Maturaration TRL(4 to 6)			1	1	1	1	1	1	1	1	8
Total Cost	1.2	1.2	2.2	1.6	1.6	1.6	1	1	1	1	13.4

Energy Storage Needs of Code S Missions



CBS-Energy Storage Subsystem



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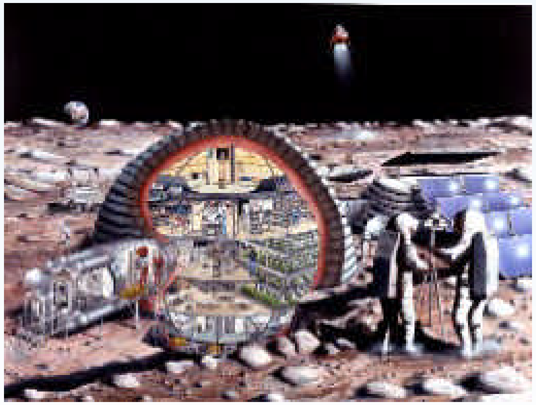

Radioisotope Power System (RPS) Capability Roadmap Status

Backup Charts

Disclaimer: This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 XXX Sub-Team members, and is not the official view of NASA or DOE.

Classes of RPS

- Small RPS (milliwatt/multiwatt) class
  - Small probe and distributed lander applications
  - System design to begin in 2006
- 100 We class
  - Multiple Mars/solar system Science missions + Spiral 1-2 landers/rovers
  - State-of-the-art multi-mission generators
    - Multi-mission RTG (MMRTG under development)
    - Stirling Radioisotope Generator (SRG under development)
  - Advanced (lower mass than SOA + enables REP)
    - No system development planned
    - Low-mass, high-efficiency power conversion under NASA's Radioisotope Power Conversion Technology (RPCT) program
- Kilowatt class (1-2 kWe)
  - Flagship Science missions, REP, Spiral 2-5
  - No system development planned
- Multikilowatt class (5 kWe module)
  - Power/heat option for Spiral 3-5
  - No system development planned

State-of-the-Practice Light Weight Radioisotope Heater Unit (LWRHU)

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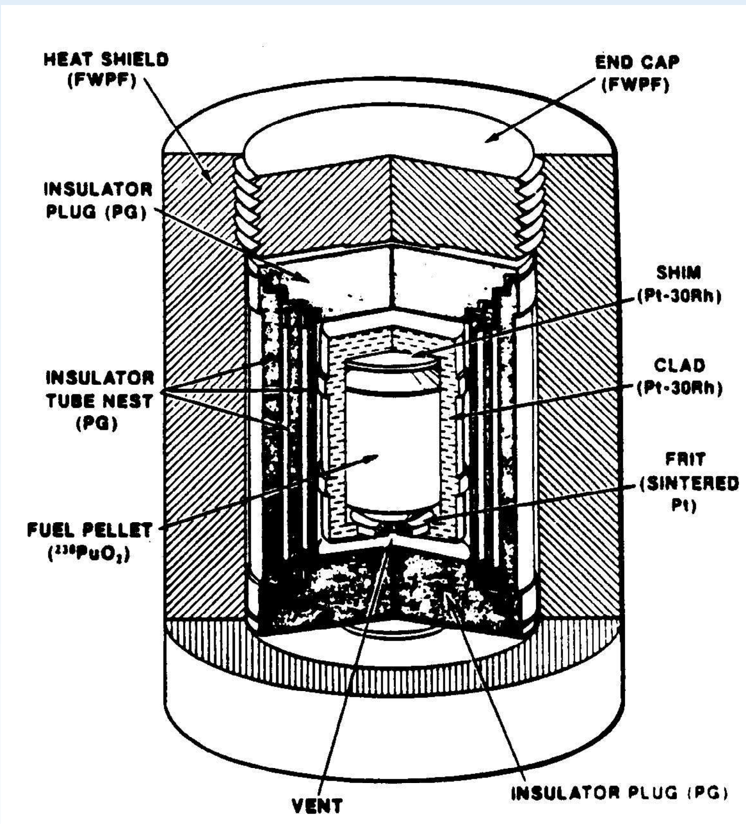

- Recent uses for thermal control
  - MER 03 - 16
  - Mars Pathfinder (Sojourner) - 3
  - Cassini - 117
  - Galileo - 120
- ~ 70 LWRHUs stored at Los Alamos

DOE's Current RPS Production Infrastructure

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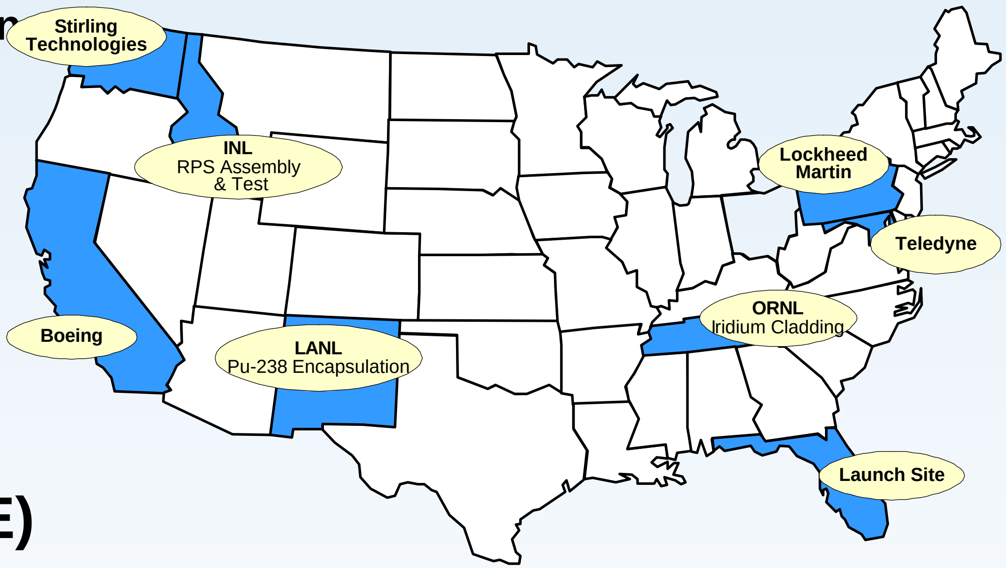
- **DOE maintains infrastructure**
  - Nuclear facilities
    - LANL and INL
  - Heat source hardware production
    - ORNL
  - Safety analyses
  - Pu-238 supply
    - Storing neptunium-237 (Np-237) at INL
    - Interim Russian purchase (using NASA funds)
- **NASA funds (through DOE) mission-specific development**
  - System design/development
  - Flight hardware
  - Production/acquisition cost of Pu-238



Proposed Consolidated Nuclear Infrastructure Capabilities

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- Consolidation would be complete and operational in late 2010 or 2011
- Storage of Np-237
- Domestic production of 5 kg/year of Pu-238
- Heat source production
  - Purification of Pu-238 for pellet fabrication
  - Encapsulation of pellets in Ir
- GPHS module assembly
- RPS assembly and testing
- RPS delivery to NASA
- Non-nuclear heat source hardware production

Enhanced Infrastructure to Support Expanded Exploration Missions

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- Increase quantity purchase of Russian Pu-238 to supplement the 5 kg/year domestic production
- Increased purification and encapsulation production rates
- Increased capabilities to assemble larger RPSs
- With appropriate planning and commitment of resources, RPS infrastructure could support expanded exploration missions

SUMMARY OF RADIOISOTOPE THERMOELECTRIC GENERATORS SUCCESSFULLY LAUNCHED BY THE UNITED STATES (1961 - 2003)

Launch Date	Spacecraft	Mission Type	User	Type of RTG	# of RTGs	Initial Average RTG Power (W)	Total Initial Spacecraft Power (W)
6/29/61	Transit 4A	Navigational	USN / APL	SNAP-3B7	1	2.7	2.7
11/15/61	Transit 4B	Navigational	USN / APL	SNAP-3B8	1	2.7	2.7
9/28/63	Transit 5BN-1	Navigational	USN / APL	SNAP-9A	1	>25.2	25.2
12/5/63	Transit 5BN-2	Navigational	USN / APL	SNAP-9A	1	26.8	26.8
4/14/69	Nimbus III	Meteorological	NASA / Goddard	SNAP-19B3	2	28.2	56.4
11/14/69	Apollo 12	Lunar	NASA / Johnson	SNAP-27	1	73.6	73.6
1/31/71	Apollo 14	Lunar	NASA / Johnson	SNAP-27	1	72.5	72.5
7/26/71	Apollo 15	Lunar	NASA / Johnson	SNAP-27	1	74.7	74.7
3/2/72	Pioneer 10	Outer Planets	NASA / Ames	SNAP-19	4	40.7	162.8
4/16/72	Apollo 16	Lunar	NASA / Johnson	SNAP-27	1	70.9	70.9
9/2/72	Triad	Navigational	USN / APL	Transit-RTG	1	35.6	35.6
12/7/72	Apollo 17	Lunar	NASA / Johnson	SNAP-27	1	75.4	75.4
4/5/73	Pioneer 11	Outer Planets	NASA / Ames	SNAP-19	4	39.9	159.6
8/20/75	Viking 1	Mars Lander	NASA / Langley	SNAP-19	2	42.3	84.6
9/9/75	Viking 2	Mars Lander	NASA / Langley	SNAP-19	2	43.1	86.2
3/14/76	LES-8*	Communications	USAF / Lincoln Labs	MHW-RTG	2	153.7	307.4
3/14/76	LES-9*	Communications	USAF / Lincoln Labs	MHW-RTG	2	154.2	308.4
8/20/77	Voyager 2	Outer Planets	NASA / JPL	MHW-RTG	3	159.2	477.6
9/5/77	Voyager 1	Outer Planets	NASA / JPL	MHW-RTG	3	156.7	470.1
10/18/89	Galileo	Jupiter System	NASA / JPL	GPHS-RTG	2	288.4	576.8
10/6/90	Ulysses	Solar Polar	NASA / JPL	GPHS-RTG	1	283	283
10/15/97	Cassini	Saturn System	NASA / JPL	GPHS-RTG	3	295.7	887

* Two Spacecraft on one Launch

RTGs = 21 Successful Launches with 22 Spacecraft containing 40 RTGs

		Aborted	Launches (All	Launch Vehicle	Problems)		
4/21/64	Transit 5BN-3	Navigation	USN / APL	SNAP-9A	1	25	25
5/18/68	Nimbus B-1	Meteorology	NASA / Goddard	SNAP-19B2	2	28	56
4/11/70	Apollo 13	Lunar	NASA / Johnson	SNAP-27	1	73	73

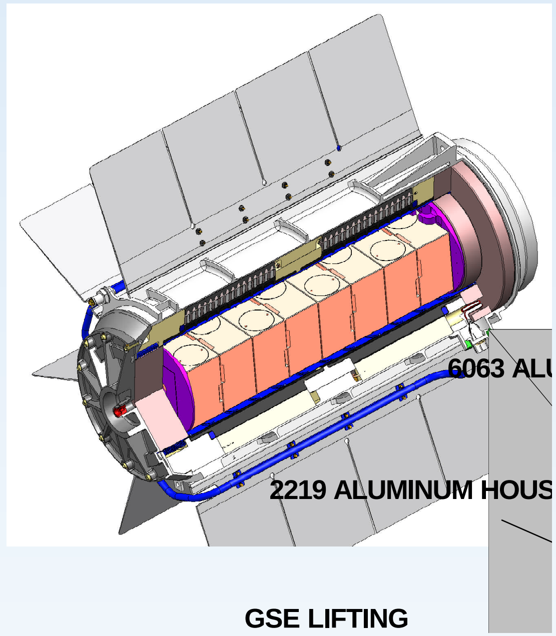
3 Aborted Launches / 3 Spacecraft / 4 RTGs – 1heat source burned up as designed (Pu metal), 2 heat sources recovered (fuel reused), 1heat source with graphite impact case on ocean floor

RHUs = Galileo (101in FSAR) , Cassini (117), Apollo 11 (2 – 15W RHUs), Mars Pathfinder (3), MER03A (8), MER03B (8)

"Multi-Mission" RTGs

	MMRTG	SNAP-19	
		Viking	Pioneer
Beginning of life (BOL) power (We)	123	42.5	41.2
Voltage (volts)	28	4.4	4.0
Mass (kg)	43	15.2	13.6
Envelope (cm)	66 L x 64 D	40 L x 59 D	28 L x 51 D
BOL specific power (We/kg)	2.9	2.8	3.0
BOL thermal inventory (Wt)	2000	683	648
BOL system efficiency (%)	6.2	6.2	6.3
BOL T_{HJ}/T_{CJ} (ºC)	535/208	546/174	512/167
Number of couples	768	90	90
Couple dimensions (cm)			
N leg	0.589 D x 1.26 L PbTe	0.985 D x 1.27 L PbTe	
P leg	0.467 D x 0.531 L PbSnTe	0.686 D x 0.254 L SnTe	
	0.467 D x 0.711 L TAGS	0.686 D x 1.016 L TAGS	

Multi-Mission RTG



DESIGN METRICS

- Design Life: 14 Years + Storage

	Mars Noon	Deep Space
Projected power		
– BOM (2000 Wt)	124 We	126 We
– BOM + 14 yrs	99 We	101 We

- Mass: 43.5 kg
- Size: 26” (66 cm) L x 25” (64 cm) D fin tip-to-tip

A

Eig

GPHS (Step 2)

768

thermocouples in 16 modules

PbTe

TAGS/PbSnTe

Ful

power at launch

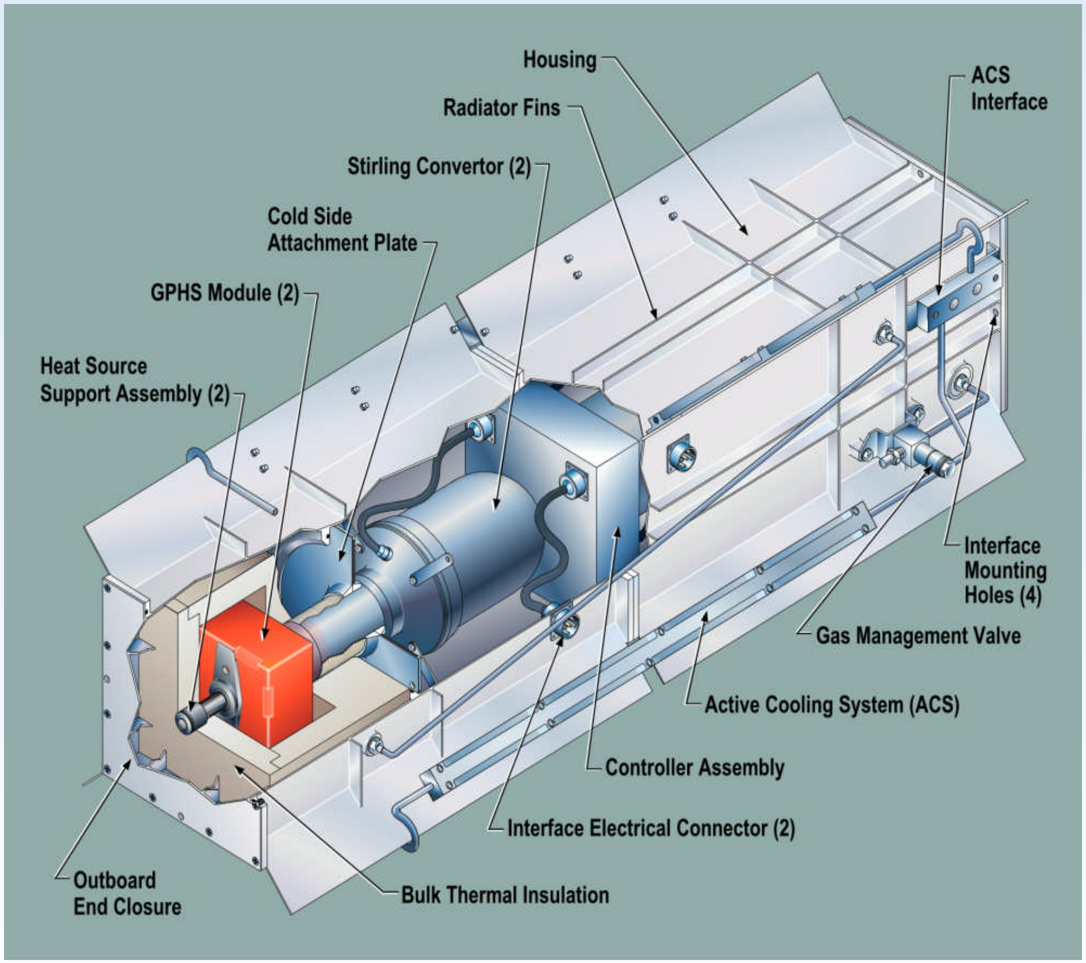
Arg

helium cover gas

Alu

external housing

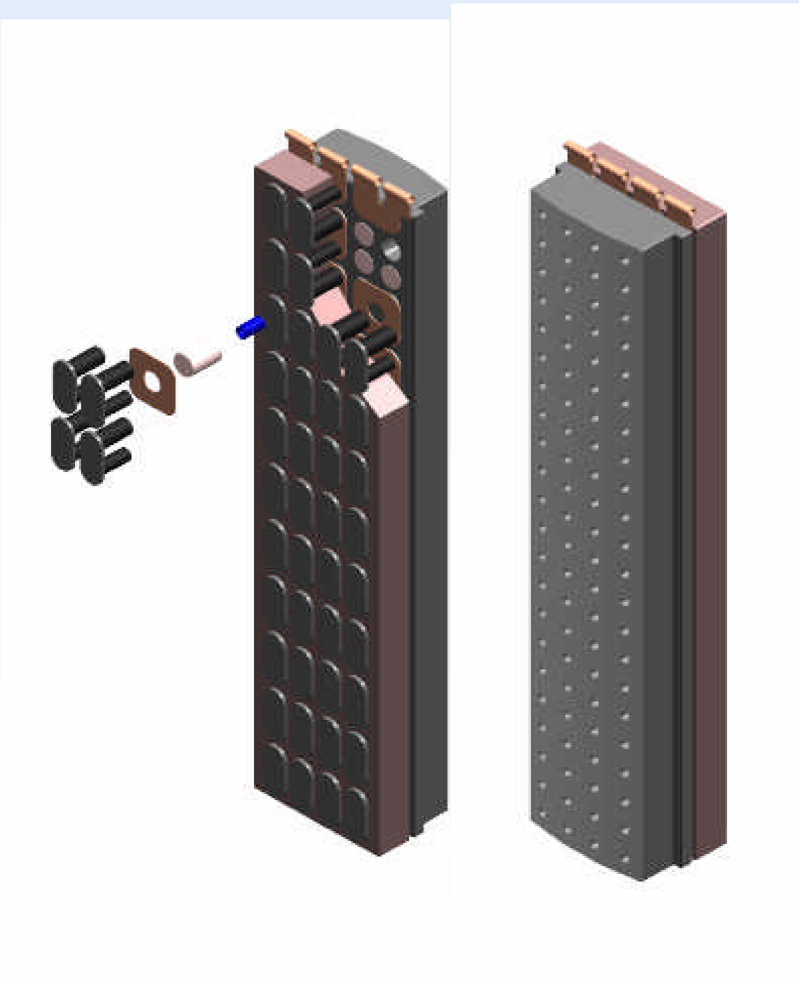
Stirling Radioisotope Generator (SRG110)

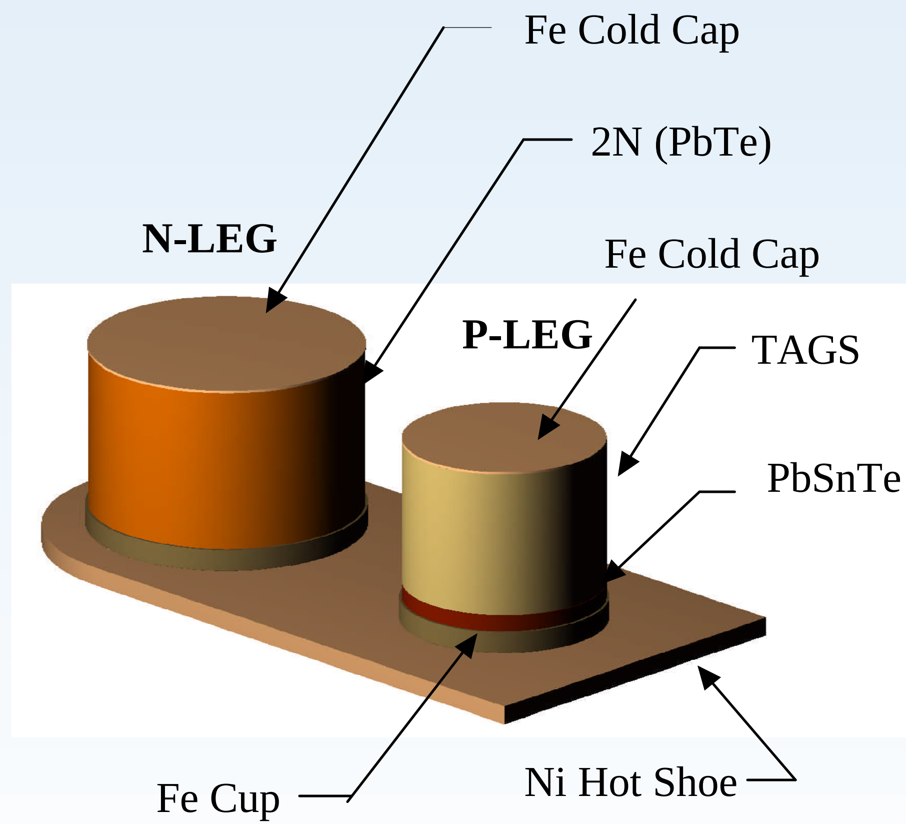


Projected power
- BOM 112 We
- 14 years 94 We

- Mass 34 kg
- Length 89 cm
- Diameter 27 cm
- Hot junction 650 •C
- Cold junction 80 •C
- Voltage 28 Volts dc
- Frequency 80 Hz
- Mean pressure 370 psia
- Design lifetime 14 years

PbTe/TAGS Thermoelectrics





Major SCA Components and Functions

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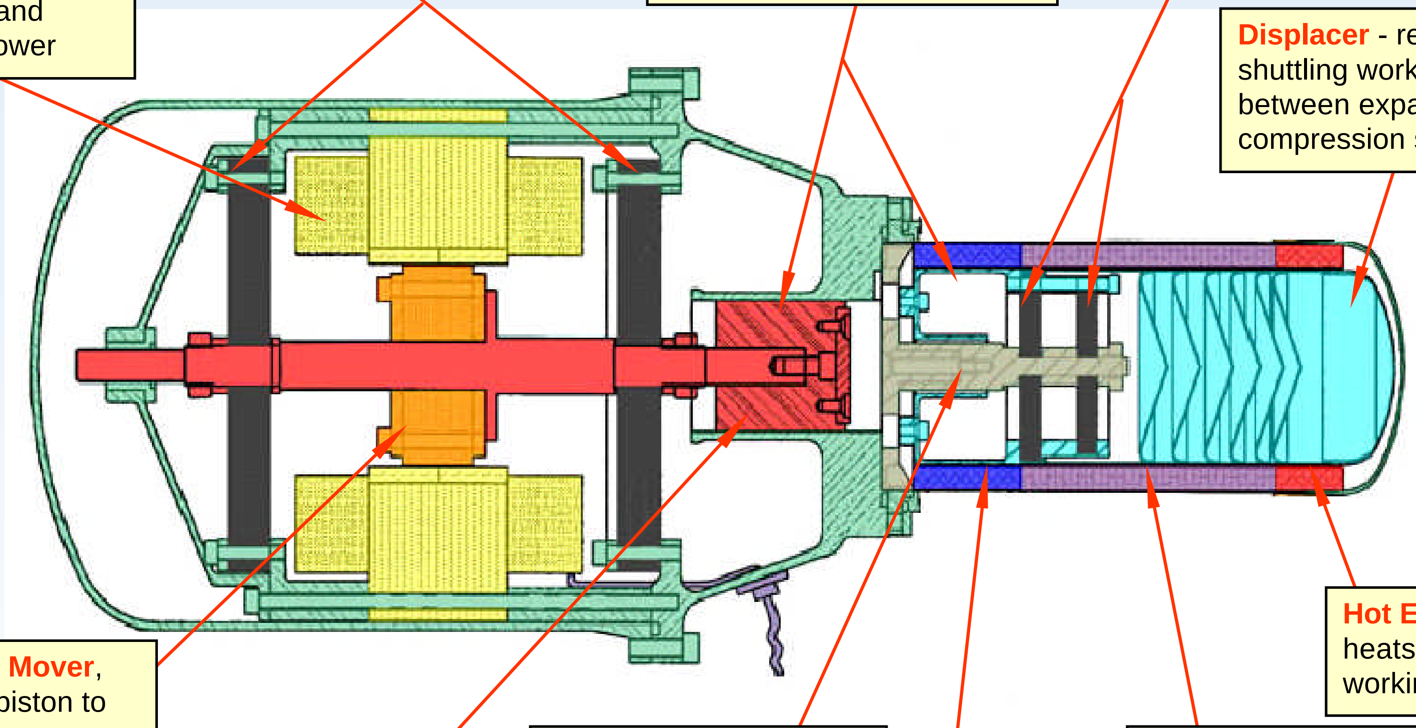
Linear Alternator Magnets, Stator & Coils - remain stationary and produce electric power

Piston Flexures - support and spring Piston /Alternator assembly

Close Clearance Seals - isolates gas working spaces

Displacer Flexures - support and spring the displacer

Displacer - reciprocates, shuttling working fluid between expansion and compression spaces



Linear Alternator Mover, reciprocates with piston to produce power

Power Piston - reciprocates and drives the alternator

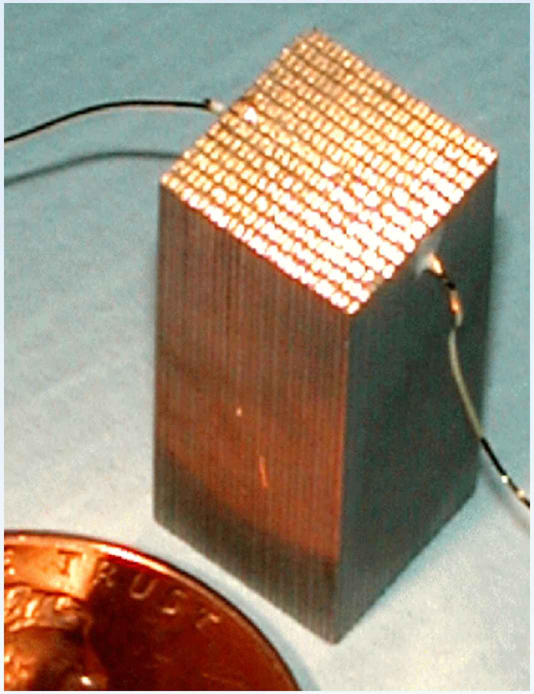
Displacer Rod - drives the displacer

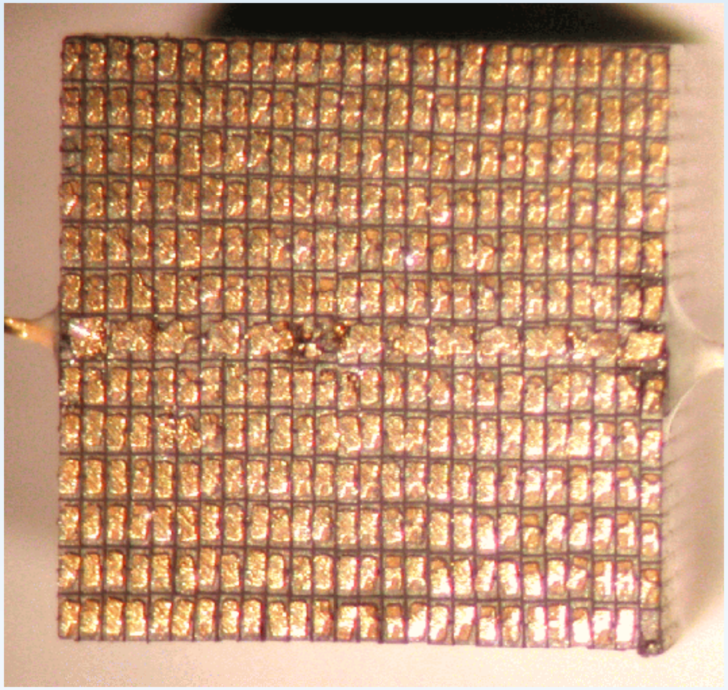
Cold End Hx - rejects heat from the working gas

Regenerator - improves engine cycle efficiency

Hot End Hx - heats the working gas

Hi-Z 676 Element Series-Parallel BiTe Module





Cold side showing series-parallel interconnects

- **26 x 26 elements, 0.010” x 0.010” cross section**
- **Module size 0.29” x 0.29” x 0.9”**
- **Welded interconnects**
- **Series/parallel design**

NASA Radioisotope Power Conversion Technology Program

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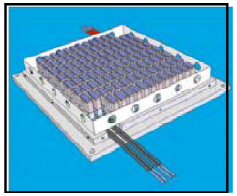
Development Projects

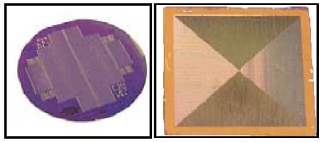
– Breadboard (TRL 5) demos funded at several $M/year

TE	Teledyne	Improve performance and manufacturability of segmented Bi-Te with PbTe, PbSnTe and TAGS unicouples. Demonstrate 10-12% efficiencies and >5 W/kg specific powers.
TPV	Creare	Demonstrate selective emitter-based TPV power generator with simulated radioisotope thermal source. Target 15-20% converter efficiency and ~15 W/kg specific power.
TPV	Edtek	Demonstrate TPV power generator employing improvements in GaSb PV cell, Frequency Selective

TE



TPV

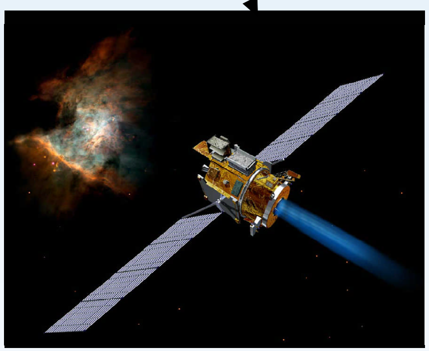


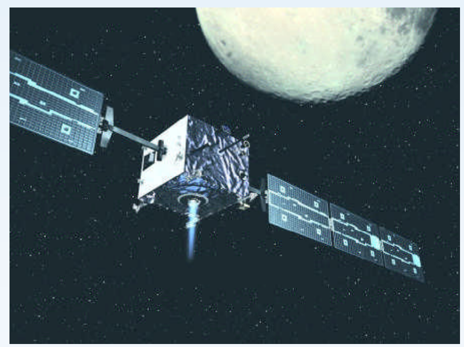
Stirling

Discontinued afte

State-of-the-Practice Electric Propulsion for REP

- **Missions:**
  - Routine use on US and foreign COMSATS (stationkeeping and final insertion)
  - Increasing use for planetary missions
    - Asia (HAYABUSA)
    - Europe (BELI-COLOMBO, SMART-1)
    - USA (DEEP SPACE-1, DAWN)

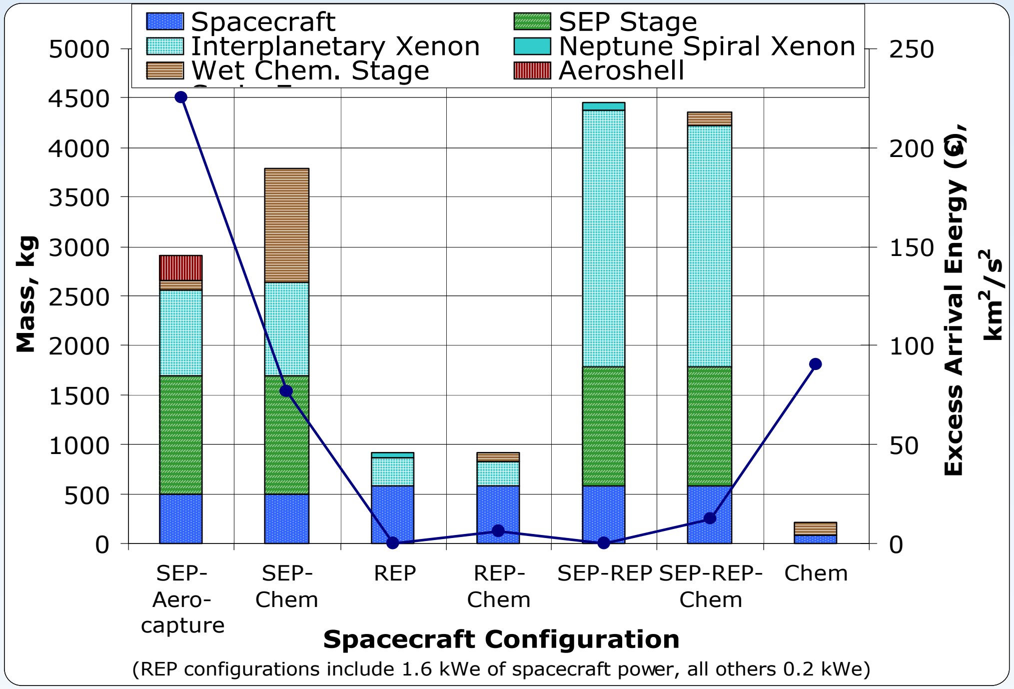




- **Systems (single string)**
  - Hall thrusters for Isp less than ~2500 sec
  - Ion thrusters for Isp greater than ~2500 to 3300 sec
  - Powers • 2.5 kWe
  - Efficiencies (thruster + PPU) • 60%
  - Specific masses (thruster + gimbal + PPU + cabling) • 15 kg/kWe

REP Performance – Total Spacecraft Mass

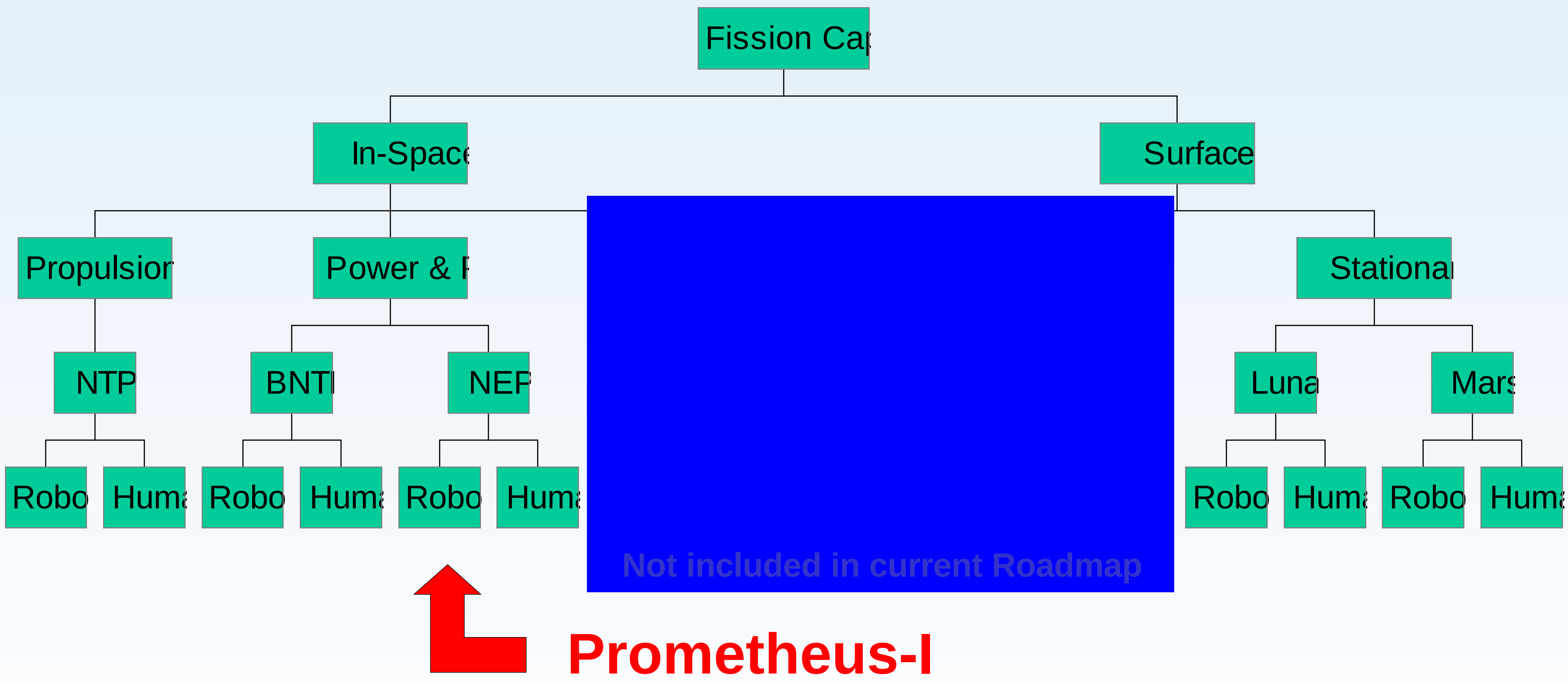
- Neptune Orbiter Mission
- ~ 500 kg spacecraft to Neptune Orbit (depending on power level)
  - Except for all-Chem (could only deliver 80 kg)
  - REP includes 1.6 kWe spacecraft power, all others 0.2 kWe
- Launch on Delta IV M+(4,2)



REP allows lowest total spacecraft mass

Backup Charts for Fission Systems

VSE Could Utilize A Diverse Set of Fission Power and Propulsion Systems



Exploration Spirals

- Spiral 1 (2008-2014)
  - **Provide precursor robotic exploration of lunar environment**
  - **Deliver a lunar capable human transportation system for test and checkout in LEO**
- Spiral 2 (2015-2020)
  - **Execute extended duration human lunar exploration missions**
  - **Extend precursor robotic exploration of Mars environment**
- Spiral 3 (2020+)
  - **Execute a long-duration human lunar exploration campaign using the Moon as a testbed to demonstrate systems (e.g., lander, habitation, surface power) for future deployment at Mars**
- Spiral 4 (~2025+)
  - **Execute human missions to vicinity of Mars**
- Spiral 5 (~2030+)
  - **Execute initial human Mars surface exploration mission**

Space Fission Systems Have Many Developmental Milestones (Demos)

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- All Fission Power and Propulsion Systems
  - Fuel performance
  - Mass, Power, temperature, lifetime, reliability
  - Radiation tolerance
  - Water- and sand-immersion kinetics (Safety Requirements)
  - Startup, power control, transient behavior
  - Shield performance
- NEP
  - PMAD / PPU
  - Thruster performance
- Surface Power
  - Landing
  - Environmental compatibility
  - PMAD
- NTP
  - Engine clustering (if small engine)
- BNTP
  - Bi-modal operation

Partial List

NASA Technology Readiness Levels

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TRL Level	Definition
9	Actual system “flight proven” through successful mission operations
8	Actual system completed and “flight qualified” through test and demonstration (ground or flight
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

NASA Capability Readiness Levels

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7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

NTR Reduces IMLEO by ~50% Compared To Chemical / Aerobrake & ~200-300% Compared To "All Chemical"

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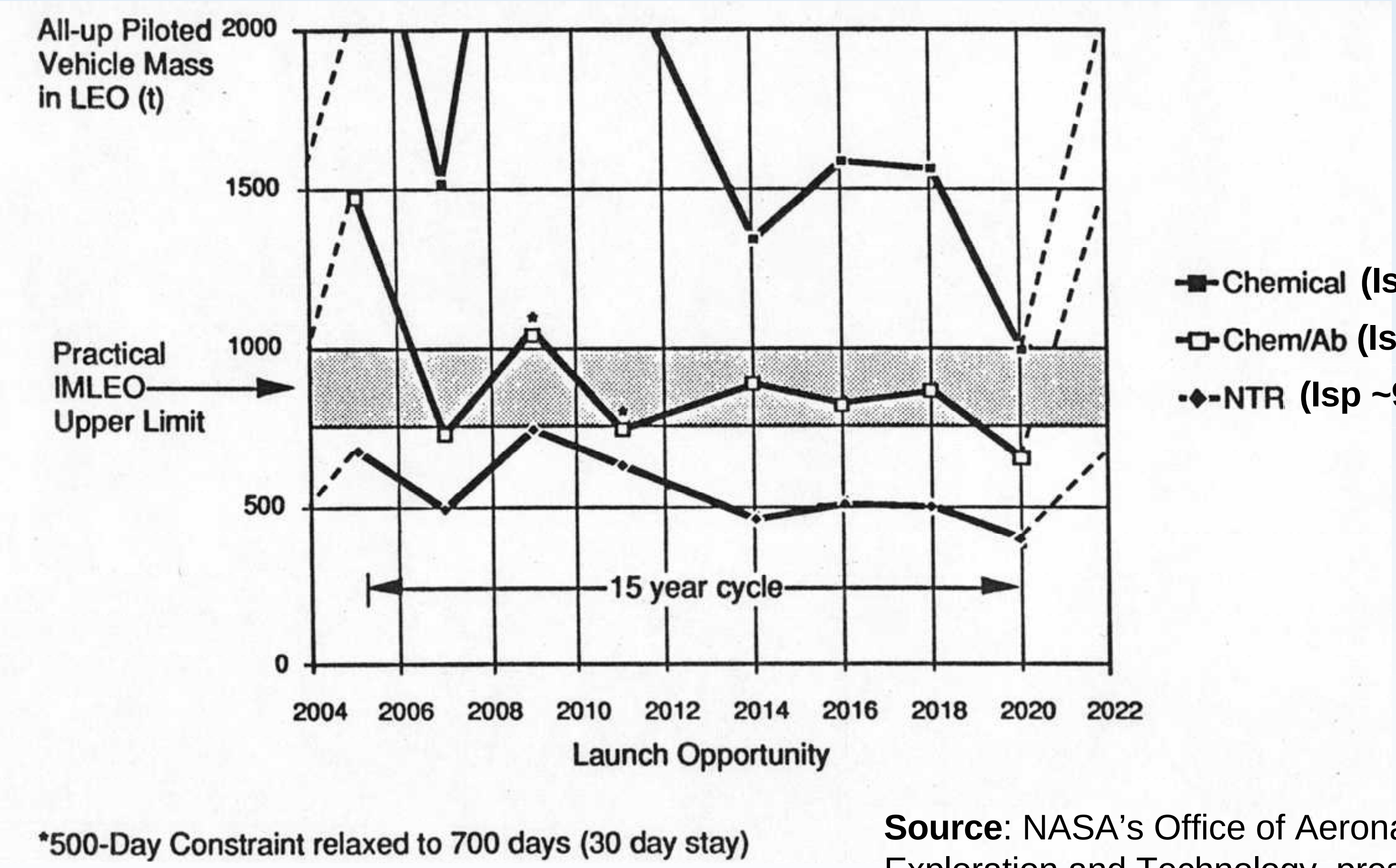
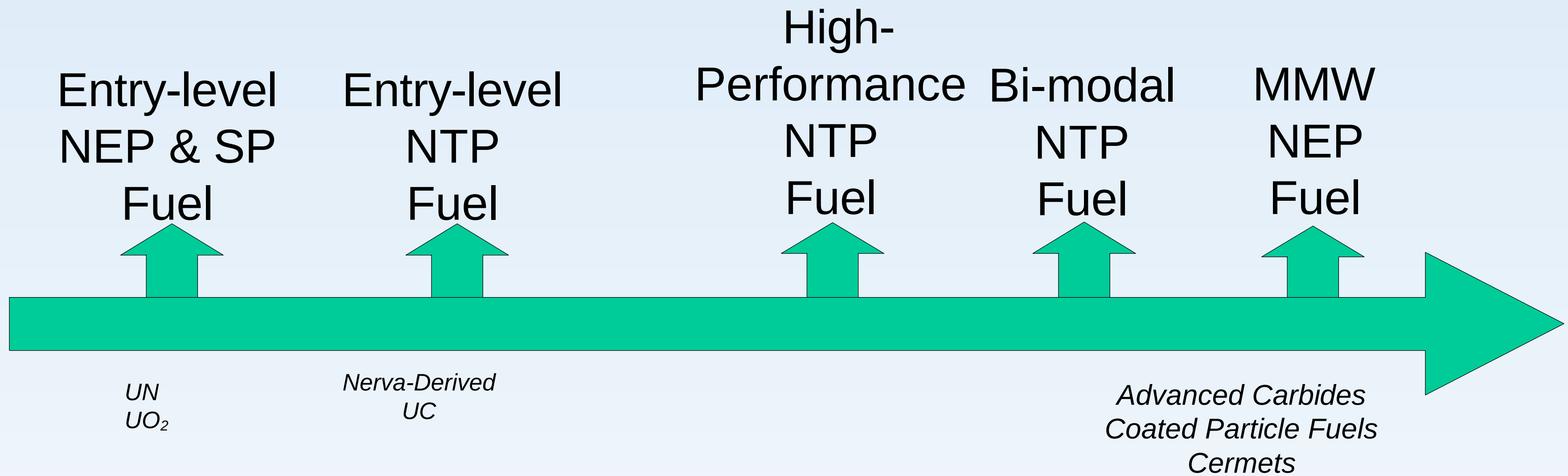
IMLEO Requirements for Mars "Opposition-class" Short Round-Trip Missions



- Chemical (Isp ~475 s)
- Chem/Ab (Isp ~475 s)
- NTR (Isp ~925 s)

Source: NASA's Office of Aeronautics, Exploration and Technology, presented to Stafford Synthesis Team in 1991

Opportunities Exist To Leverage Technology Investments – Example



•Limited commonality of entry-level NEP and NTP fuels

•Potential for common Hi-Po NTP, BNTP, and MMW fuels

Bimodal NTP
- 2500 - 2700(?) K Fuel Temp
- Low burn-up (~ few %)
- Short Operation (< 2 hr) @ high power (330 - 550 MW_{th})
- Medium Operation (< 3 yr) @ low power (~125 kW_{th})

Entry-Level NEP & SP
- 1000 - 1500 K Fuel Temp
- Low burn-up (~ few %)
- Long Operation (5-15 yr)
- 100 kW_{th} - ~ 1 MW_{th}

NTP
- 2500 - 2700(?) K Fuel Temp
- Low burn-up (< 1 %)
- Short Operation (< 2 hr)
- 330 - 550 MW_{th}

MMW-NEP
- 1500 - 2000K Fuel Temp
- High burn-up (~ few %)
- Medium Operation (< 3 yr)
- 10 - 100 MW_{th}