“Breakthrough” Power Technologies

<table>
<thead>
<tr>
<th>Now</th>
<th>5-10 Years</th>
<th>15-25 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applications</strong></td>
<td>• LEO/GEO satellites</td>
<td>• Mars Outposts</td>
</tr>
<tr>
<td></td>
<td>• Earth &amp; planetary science missions</td>
<td>• Libration point observatories</td>
</tr>
<tr>
<td></td>
<td>• International Space Station</td>
<td>• Electric propulsion</td>
</tr>
<tr>
<td><strong>Capabilities</strong></td>
<td>• Short duration/low power Mars surface PV</td>
<td>• kW class Mars surface PV</td>
</tr>
<tr>
<td></td>
<td>• 100w class RTGs</td>
<td>• 10-100+kW surface nuclear</td>
</tr>
<tr>
<td></td>
<td>• 10-100kW near-Earth PV</td>
<td>• Higher efficiency/low mass PV for in-space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Multi-MW PV and nuclear dynamic systems for in-space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Robust, high power surface systems</td>
</tr>
</tbody>
</table>

**High Payoff Technology Candidates**

• Thin film and high efficiency PV cells/arrays
• Advanced dynamic and static conversion
• High temp/high strength materials
• High density energy storage
• High efficiency power management/distribution
• Lightweight, deployable structures

**National Benefits:**

Advanced power systems increase the reliability and reduce the mass and cost of NASA, military and commercial satellites and spacecraft
Power System Transition Package Backup Charts
## Power Trade Space

<table>
<thead>
<tr>
<th>Applications</th>
<th>Nuclear</th>
<th>Isotope</th>
<th>PV only</th>
<th>PV/ RFC</th>
<th>PV/ Batt</th>
<th>FC/ RFC</th>
<th>Batt.</th>
<th>Beam</th>
<th>Power Level</th>
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</thead>
<tbody>
<tr>
<td>LEO Fuel Depot</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>~3 MW</td>
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<tr>
<td>BNTR</td>
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<td></td>
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<td></td>
<td></td>
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<td>X</td>
<td>30-50kW</td>
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<tr>
<td>NEP</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30-50kW/ 100kW-MMW</td>
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<tr>
<td>SEP/ Chem</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>20-30kW/ 1-2MW</td>
</tr>
<tr>
<td>Ascent/ Descent/ Re</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>3-5kW</td>
</tr>
<tr>
<td>30 day Mars</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>10-20kW</td>
</tr>
<tr>
<td>500 day Mars</td>
<td>X</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60-100kW</td>
</tr>
<tr>
<td>10 hour rover</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>crewed, 1-3 kW</td>
</tr>
<tr>
<td>Multi-day rover</td>
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<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>crewed, 5-10 kW</td>
</tr>
<tr>
<td>Mars mobile drill</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>1-5 kW</td>
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<tr>
<td>14 day lunar</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2-100kW</td>
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<tr>
<td>45 day Lunar</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>10-100kW</td>
</tr>
<tr>
<td>Lunar S. pole</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>2-100kW</td>
</tr>
<tr>
<td>L2</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>2-10kW</td>
</tr>
</tbody>
</table>

= Preferred concept
Mars Surface Systems Study
Results Overview

• **Short Stay - 30 Days on Surface**
  – Power requirement
    • Entry, descent, landing, ascent (E/D/L/A) = 3.7 kWe
    • Nominal ops = 8.2 kWe (day) / 5.3 kWe (night)
  – System concepts
    • E/D/L/A: regenerative fuel cells
    • Surface ops: small, shielded reactor with CBC engine 100m from hab
    • Could consider PV arrays with RFCs if landing site <15 degrees latitude
  – Landed mass = 3650 kg for all power elements

• **Long Stay ~ 500 days on surface**
  – Power requirement
    • E/D/LA = 3.7 kWe
    • Nominal ops = 18 kWe (no ISRU)
  – System concepts
    • E/D/LA: regenerative fuel cells
    • Surface ops: 2 reactors 2km from hab (any latitude) or PV/RFC if < 15 degrees latitude
  – Landed mass = 6000 kg for either Nuclear or PV (including RFCs and reactants)
Mars Outpost Solar Surface Power for Equatorial Mission

- **Flexible Tent Arrays**
  - Thin, high-η, c-Si solar cells
  - Deployable masts

- **260 A-hr Li Ion Energy Storage**

- **120-VDC PMAD**

- **1400-Day Surface Mission**
  - 2007/2009 Launch Opportunities
  - 1 Great Dust Storm per year
  - 15-37 kW Day time power
  - 2 kW Night time power
  - 0.5 kW Dust storm keep-alive power

- **System Sizing**
  - Power system mass 2360 kg
  - Photovoltaic array area 720 m²
  - Array blanket dimensions 2-m x 43-m
Advanced Space Power Technologies

Candidate Technologies
- Gas-cooled bimodal reactor
- Liquid metal reactor
- Brayton conversion
- Stirling conversion
- K-Rankine conversion
- Thermal control/Radiators
- Advanced PV cells
- PV cell dust mitigation
- Large solar arrays
- Power electronics
- High voltage transmission/conversion
- Energy storage
- High temp/high strength materials
- Environmental protection
- Deployment systems

Key Near-Term Technologies
- Nuclear fission
  - High temp Brayton engine (1300-2000K)
  - High temperature reactor fuel
  - Low mass/low volume radiators (<2kg/m2)
  - High voltage transmission (>5000v)
- Solar photovoltaic
  - High efficiency thin film cells (>20%)
  - Large, low mass array/structure (>500W/kg)
  - Surface and in-space deployment
- High density energy storage (>400Wh/kg)
Solar/Nuclear Pros and Cons

**Solar Pros**
- Avoids political and programmatic issues associated a nuclear development program
- Simplifies the Safety Review & Launch Approval Process
- Leverages current technology development (terrestrial & space)
- Synergistic technology with SEP & large scale Space Solar Power

**Solar Cons**
- Scalability in packaging and deployment of large arrays
- Relatively low insolation at Mars surface due to distance from Sun and atmospheric dust
- Accumulation of dust on array surface
- Sensitivity to diurnal, seasonal and latitude variations
- Requires energy storage for night operation
- Cost and reliability

**Nuclear Pros**
- Constant day/night power at any latitude
- Power production nearly insensitive to planetary environment (e.g. dust, temp)
- Mass and volume scale favorably with power output
- Brayton power conversion heritage - 10kWe/38,000 hours (1970’s)
- Negligible Curies at launch

**Nuclear Cons**
- Public perception/political resistance
- Rigorous safety review process (INSRP)
- Deployment of reactor cart and radiators
- Development of kV power transmission
- Integrated nuclear system testing
- Cost and reliability
Mars In-Situ Power Summary

- In-situ sources, such as wind, areothermal, geothermal and solar have been assessed by the space power community at large and by NASA
- In general these energy sources are low density and require large infrastructures to harvest the energy and convert it to electricity
- The most promising of these sources is solar since it draws upon the technology base of NASA, commercial, and military in-space applications
- Solar energy varies hourly and yearly, but is predictable - except for magnitude and duration of atmospheric dust obscuration of the Sun and power output loss rate of settled dust on the array
- Recent studies show that solar power appears applicable to small (up to 10kW), short duration power needs.
- Analysis, testing, and flight experiments (MATE & DART) have been proposed to develop and verify the ability to mitigate dust accumulation so that long duration missions are feasible using PV arrays
In-situ Power Assessment

• **Aerothermal**
  - Must locate plant near high temperature heat source
  - Have to take power plant and construction equipment to Mars
    • Turbine-generators
    • Heat rejection system
    • Drilling rig
    • Heat exchangers
  - Not a candidate for an initial power system due to massive infrastructure required and limited site possibilities

• **Wind**
  - Typical surface wind speed on Mars is 3-4 m/s (Viking 1 and 2)
  - Wind speed may be greater at distances above the surface
  - Topographic influenced winds and dust storms may reach 20-30 m/s

<table>
<thead>
<tr>
<th>Speed</th>
<th>Wind Energy</th>
<th>Elec. Energy</th>
<th>10 kWe Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 3 m/s</td>
<td>0.225 W/m2</td>
<td>0.08 We/m2</td>
<td>123,000 m2</td>
</tr>
<tr>
<td>@ 10 m/s</td>
<td>8.33 W/m2</td>
<td>3.0 We/m2</td>
<td>3,300 m2</td>
</tr>
<tr>
<td>@ 25 m/s</td>
<td>130 W/m2</td>
<td>47 We/m2</td>
<td>214 m2</td>
</tr>
</tbody>
</table>
  - Not a candidate for initial missions due to uncertainty and variability of winds, large infrastructure and site limitations
Sensitivity of IMLEO to NEP Power & Propulsion System* Specific Mass

- 2018 Human Mars Mission
- Piloted Round Trip Vehicle
- 45 day Mars stay
- Earth flyby return at 13 km/sec
- 25 mt payload, no masses dropped
- 5% tankage fraction
- Fixed 4000 second specific impulse at 60% efficiency
- Consumables mass = 2.6 mt for all cases (based on 330 days)

*Specific Mass (kg/kWe)
(*Power System and Thruster Only - payload, propellant, balance of spacecraft not included)
NEP Power System Specific Mass Trends

Near=LMCR, Brayton, 1300K, 6 kg/m², 200 Vac (Available ~10 yrs)
Mid=LMCR, Brayton, 1500K, 3 kg/m², 1000 Vac (Available ~ 15-20 yrs)
Far=LMCR, Brayton, 2000K, 1.5 kg/m², 5000 Vac (Available ~ 25-30 yrs)
Cargo=Instrument rated shielding, $1.6 \times 10^{15}$ nvt, $1.2 \times 10^8$ rad @ 2 m
Crew=Human rated shielding, 5 rem/yr @ 100 m, 7.5° half angle
Advanced Space Power Development Plan

Years from ATP

2  6  12  Start Mission Set

System Studies
- Pre-Phase A
- Phase A/B

Nuclear
- Bimodal GCR
- LMCR
- Isotope
- Brayton
- Stirling
- Potassium Rankine
- Adv. static; AMTEC

Power Conversion
- Preferred Concepts (Transportation)
- Preferred Concepts (Surface Power)
- Advanced development/demos

Solar Power
- Adv. PV Cells
- Adv. PV Array/Deployment

Energy Storage
- PEM Regen. FC
- Adv. Battery
- Flywheel

Technology down select milestone

May use the same technology to reduce costs.
Nuclear Propulsion and Power Roadmap

System Studies
- Fuel, Rx, Engine
- Power Conversion/Reactor Optimization

Fuels
- Nuclear Fuel Characterization and Dev.
- Early Mission Fuel Selection
- Advanced Fuel Available (MMW and NTR)

Power Reactor
- Surface and Low Power NEP
- Low Power Design, Surface/NEP
- Phase C/D Surf/LP NEP
- High Power Design, MMW NEP

Testing & Safety
- Public Perception and Test Facility Dev./INSRP
- Characterization and Life Tests
- Low Power Tests
- High Power MMW Tests

Propulsion
- TPA, Nozzles, EP, ICHM, Mat’ls & Structures
- Increase Component Life-- e.g., EP Thruster Power, Eff., & Life

Power
- Dynamic Conv, radiators, PMAD, HT materials
- High Power PMAD, Radiators, Etc.
- 100 kWe Class Hall/Ion Thruster
- 500-1000 kWe Class EP Thrusters (Ion, MPD)
- BNTR, 1 MWe Hybrid, 10 MWe NEP
- HT 2 kWe Brayton
- HT 25 kWe Brayton Multi-kWe Stirling
- 100-200 kWe Surface Power
- 100-500 kWe Brayton
- 5-10 MWe Brayton/K Rankine