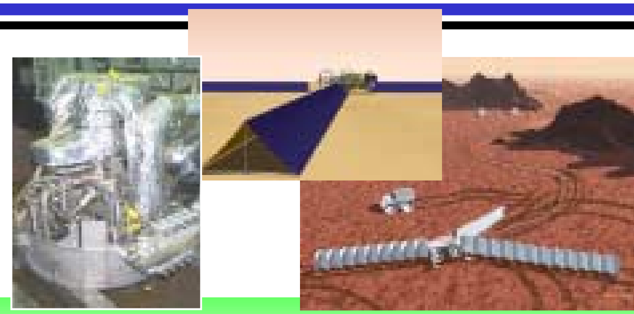
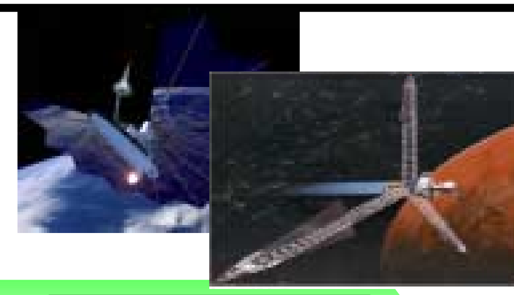
“Breakthrough” Power Technologies





Now	5-10 Years	15-25 Years

Applications

Now:
- LEO/GEO satellites
- Earth & planetary science missions
- International Space Station

5-10 Years:
- Mars Outposts
- Libration point observatories
- Electric propulsion

15-25 Years:
- Human missions far from Earth
- High power electric propulsion

Capabilities

Now:
- Short duration/low power Mars surface PV
- 100w class RTGs
- 10-100kW near-Earth PV

5-10 Years:
- kW class Mars surface PV
- 10-100+kW surface nuclear
- Higher efficiency/low mass PV for in-space

15-25 Years:
- Multi-MW PV and nuclear dynamic systems for in-space
- Robust, high power surface systems

High Payoff Technology Candidates

- Thin film and high efficiency PV cells/arrays
- Advanced dyanmic 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

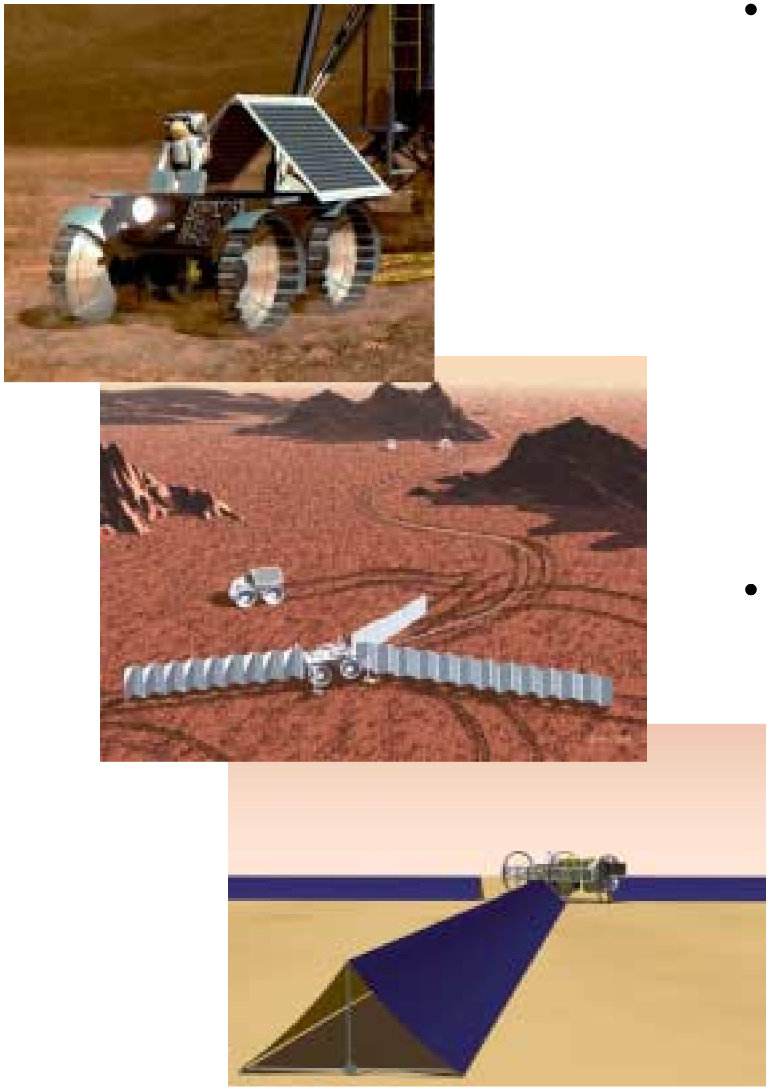
Power System
Transition Package Backup Charts

Power Trade Space

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

= Preferred concept

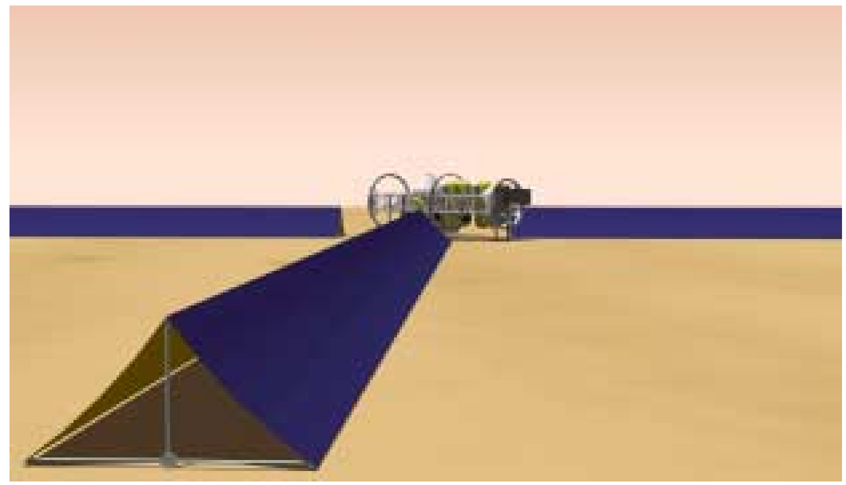
Mars Surface Systems Study
Results Overview

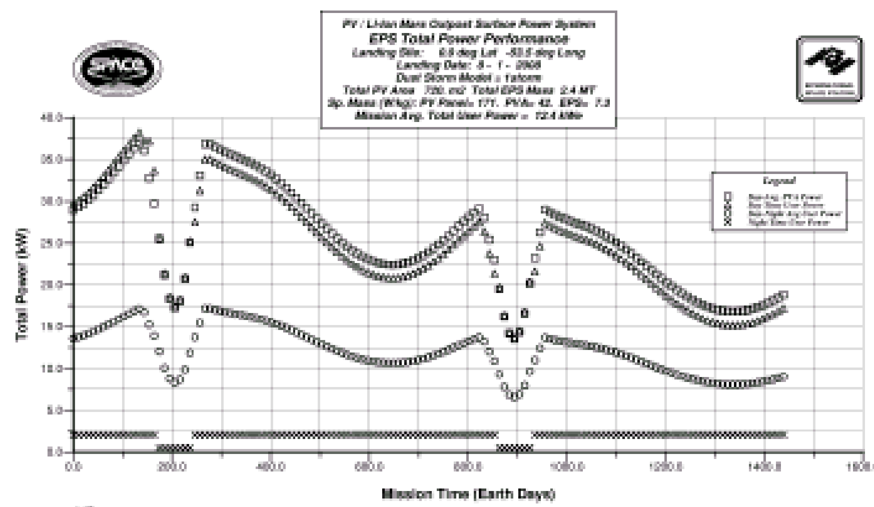


- **Short Stay - 30 Days on Surface**
  - Power requirement
    - Entry, descent, landing, ascent (E/D/L/A) = 3.7 kWe
    - Nominal ops = 8.2 kWe (day) / 5.3 kWe (night)
  - System concepts
    - E/D/L/A: regenerative fuel cells
    - Surface ops: small, shielded reactor with CBC engine 100m from hab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

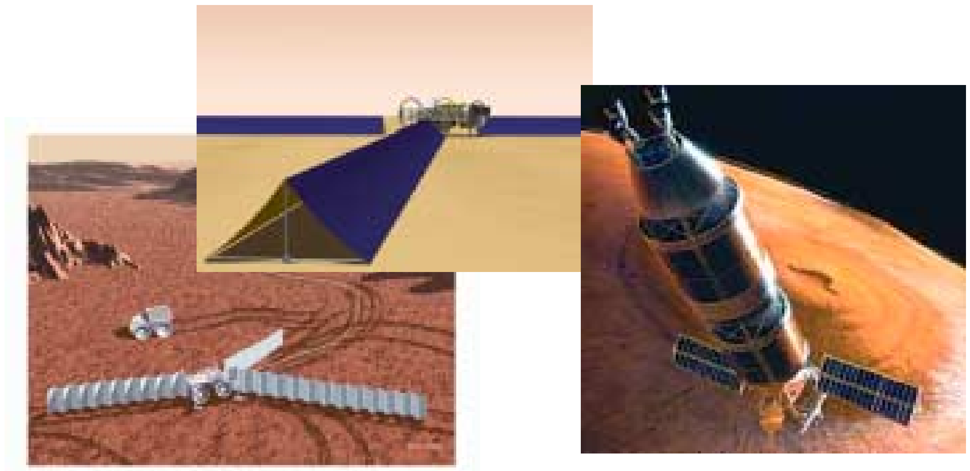
Mars Outpost Solar Surface Power for Equatorial Mission

- **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



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)

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

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 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

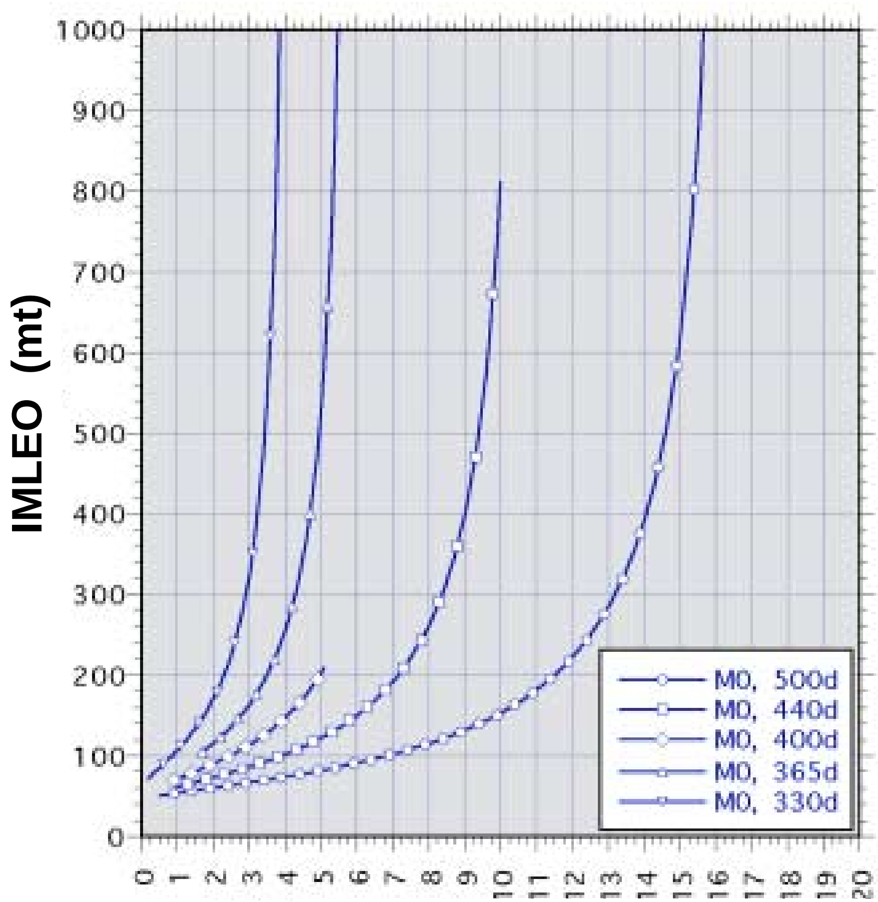
- **Aerothermal**
  - Must locate plant near high temperature heat source
  - Have to take power plant and construction equipment to Mars
    - Turbine-generators
    - Heat rejection system
    - Drilling rig
    - Heat exchangers
  - Not a candidate for an initial power system due to massive infrastructure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

Speed	Wind Energy	Elec. Energy	10 kWe Area
@ 3 m/s	0.225 W/m2	0.08 We/m2	123,000 m2
@ 10m/s	8.33 W/m2	3.0 We/m2	3,300 m2
@ 25 m/s	130 W/m2	47 We/m2	214 m2

  - 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

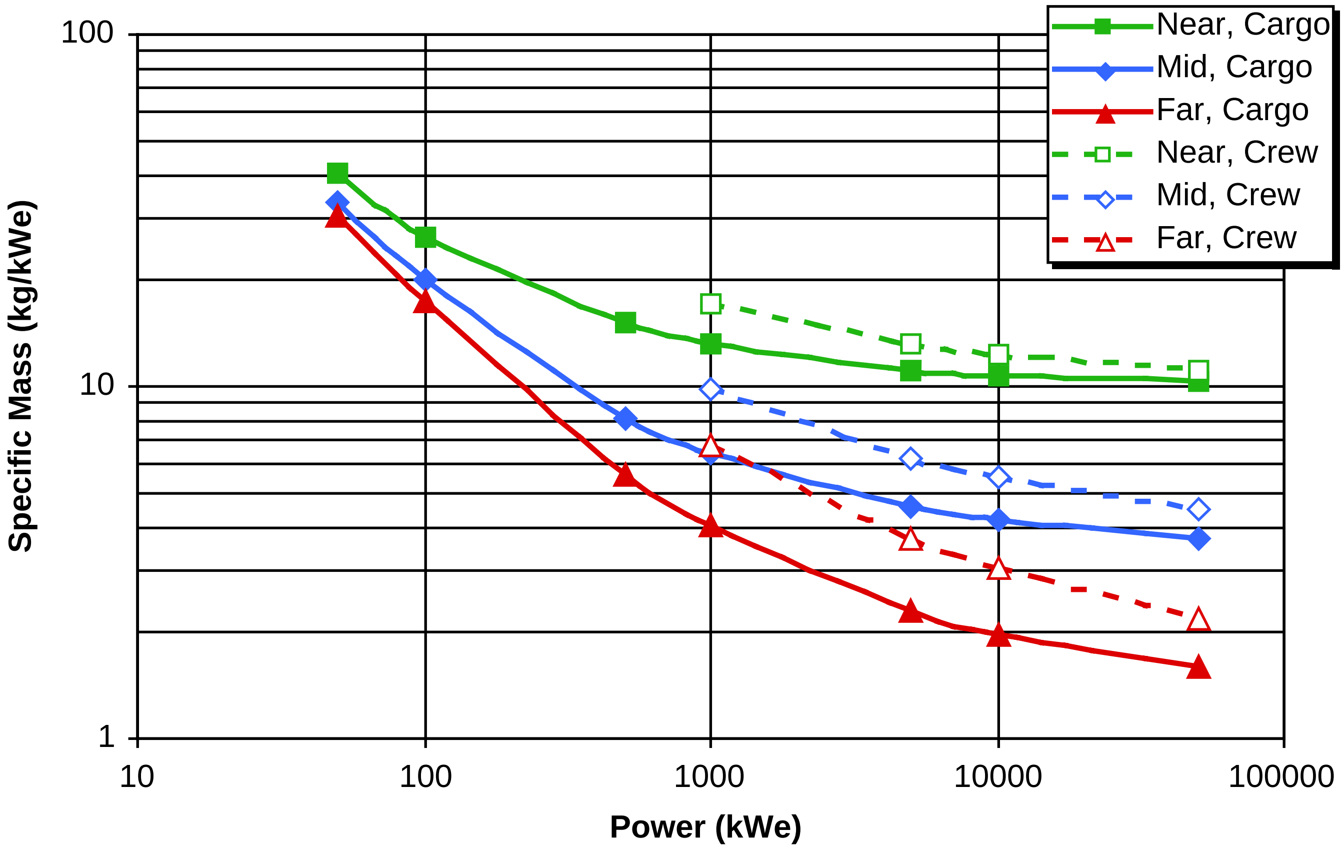


***Specific Mass (kg/kWe)**
(*Power System and Thruster Only - payload, propellant, balance of spacecraft not included)

- 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)

Extreme IMLEO sensitivity to power system and thruster specific masses

NEP Power System Specific Mass Trends



Near=LMCR, Brayton, 1300K, 6 kg/m2, 200 Vac (Available ~10 yrs)

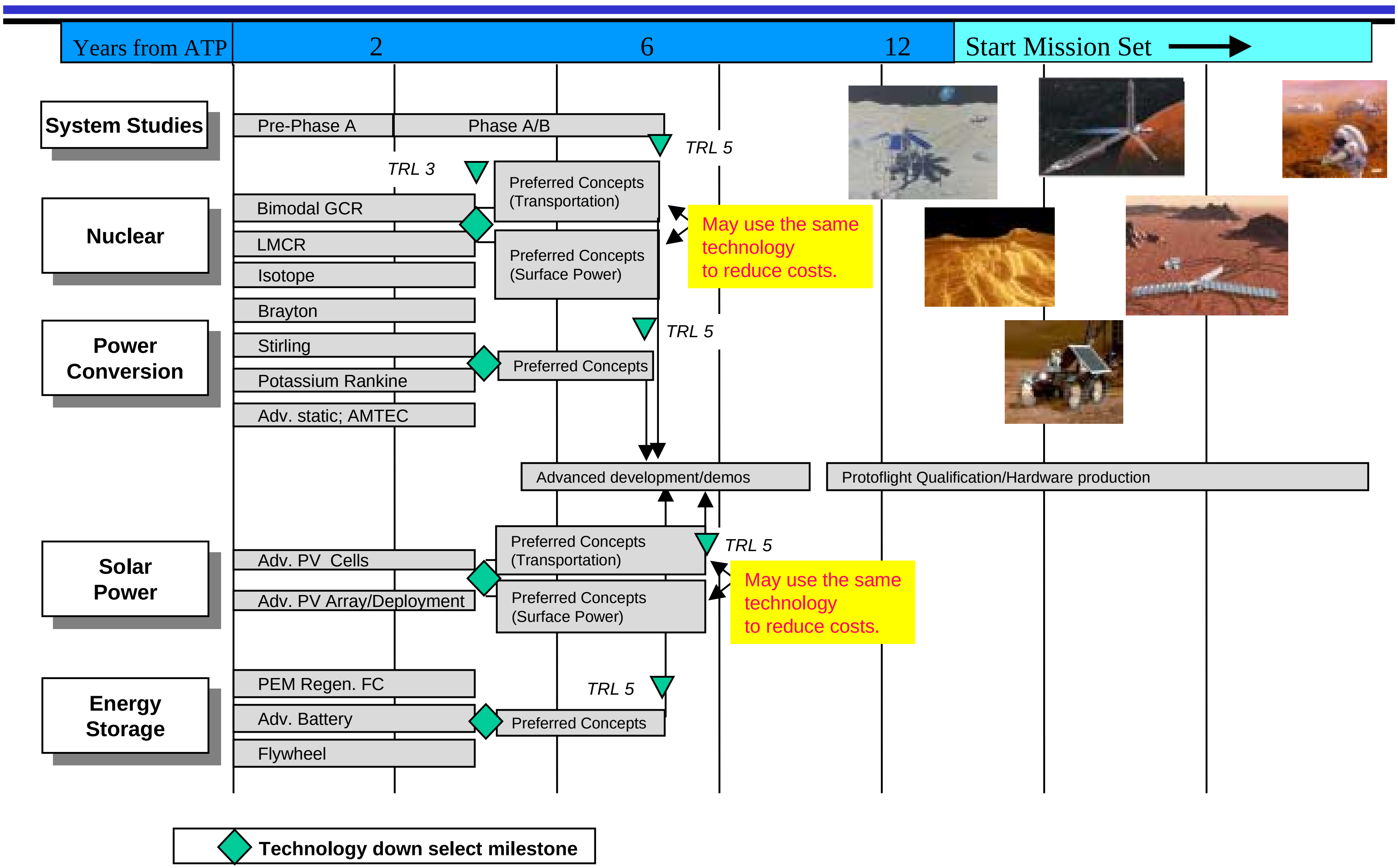
Mid=LMCR, Brayton, 1500K, 3 kg/m2, 1000 Vac (Available ~ 15-20 yrs)

Far=LMCR, Brayton, 2000K, 1.5 kg/m2, 5000 Vac (Available ~ 25-30 yrs)

Cargo=Instrument rated shielding, 1.6×10^{15} nvt, 1.2×10^{8} rad @ 2 m

Crew=Human rated shielding, 5 rem/yr @ 100 m, 7.5° half angle

Advanced Space Power Development Plan



Nuclear Propulsion and Power Roadmap