Nuclear Power Options for Mars Polar Robotic Outpost

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Outline

- **Summary of Previous Polar Base Work**
- **Modification to Solar Power module for mid-latitude operations**
- **Power System Options & Potential R&D Directions**
  - Solar Array
  - Radio Isotope
  - Nuclear Reactor
- **Comparison of Power Systems**
- **Conclusions and Recommendations**

Nuking the Polar Base Summary

Objective

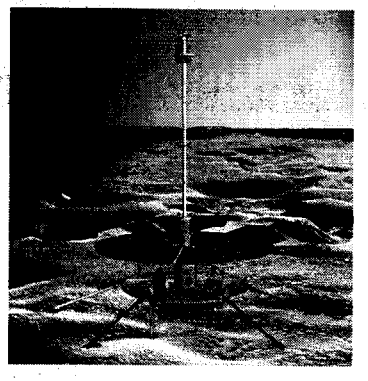
- Investigate impacts of replacing solar power with nuclear power for polar robotic outpost

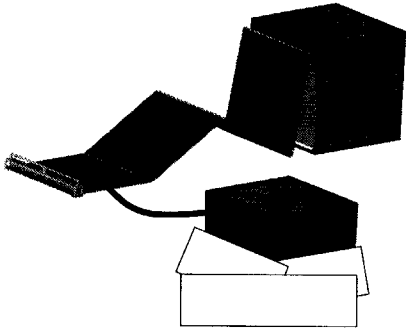
Background

- Previous robotic polar outpost study utilized ~3 KW of solar power
- Near polar location provided 220 sols of continuous sunlight in Martian year
- Majority of polar base was shut down during winter eclipse period

Approach

- Assume 3 KW power requirement and Near polar base location
- Assess impacts of moving outpost to mid-latitudes
- Investigate operational feasibility of solar, RTG, and nuclear reactors
- Use HOMER design as initial basis for outpost reactor





Status

- Nuclear power enables continuous operation of polar base
  - RTG & Reactor have roughly same mass for 3 KWe
  - RTGs provides lowest technical risk provided Plutonium challenges (cost/production/perception) are overcome
  - Nuclear power has significantly higher power weight efficiency (kw-hr/Martian yr/kg) than solar power
- Solar power is optimized for summer daylight only operations

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Summary of Previous Polar Base Work

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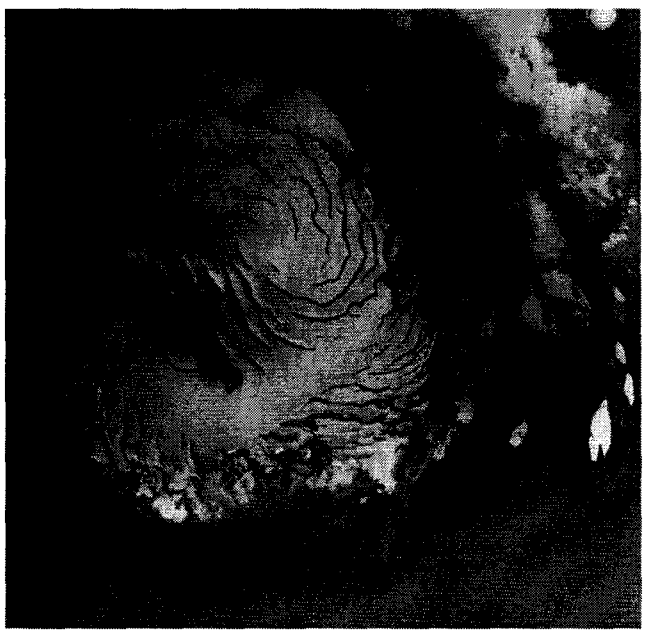
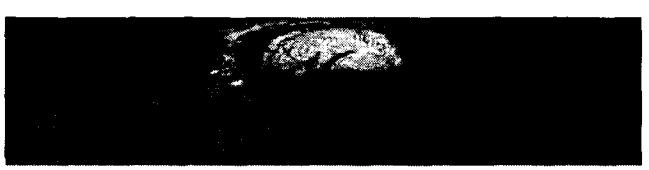
Why Pick the North Pole?



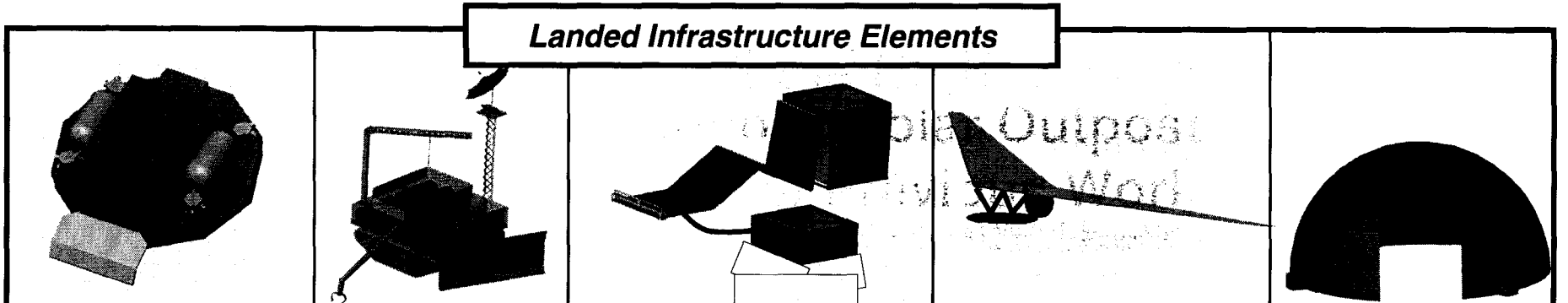


- **Interesting temporal and spatial variations**
  - Steeper temp, pressure, wind gradients than the rest of Mars; Reduced winds and dust;
  - More seasonal frost growth than the rest of Mars (Science, 12/7/01)
- **Possible ancient sea-bed**
  - Ideal region to search for underground water
  - Ideal region to search for fossilized/existing life
  - Low elevation much better for aircraft
- **Smoother terrain than southern hemisphere**
  - Safer rover traverses and aircraft landings
  - Better terrain for base construction
  - Very smooth terrain by terrestrial standards
- **Only area of Mars known to contain water**
  - Possible site for future fuel production
- **Constant summer sunlight (220 sols) and temperature for solar array**
  - More tranquil weather, reduced winds and dust, more imagery, and time to erect the base and achieve IOC

Mars Robotic Polar Outpost
Summary of Previous Work

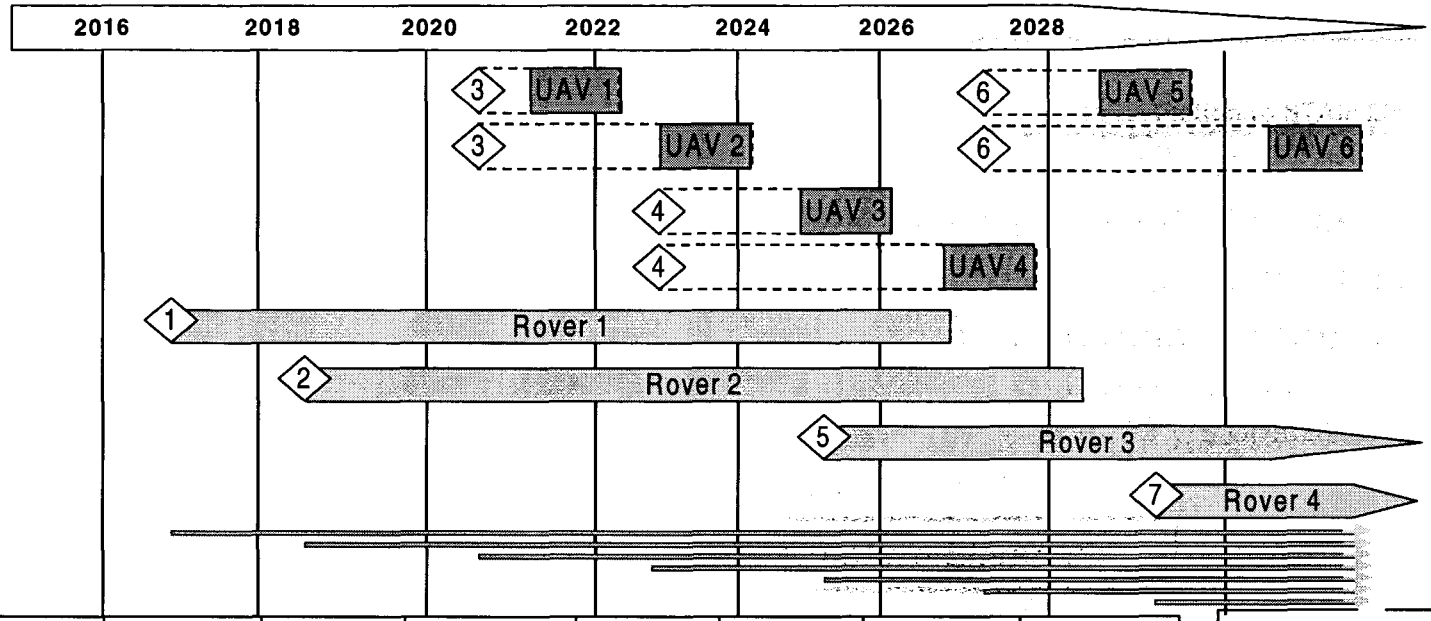
- **Funded by**
  - JPL Mars Advanced Studies Program
  - NASA Exploration Team (NEXT)
- **Team members**
  - Led by The Aerospace Corporation, with involvement from JPL, JSC, Glenn, KSC
  - Team X defined communication orbiter and sized surface solar power station
- **Outcome**
  - Strategy for a permanent robotic outpost on Mars
  - Study addressed launches over period 2016-2028
  - Total cost of $11.35 Billion over 18 yrs (3 yrs development/15 yrs operations)
  - Architecture adaptable to new discoveries or failures

Landed Infrastructure Elements



Landers	Rovers	Power Modules	Flyers	Shelters

Mars Robotic Polar Outpost Buildup



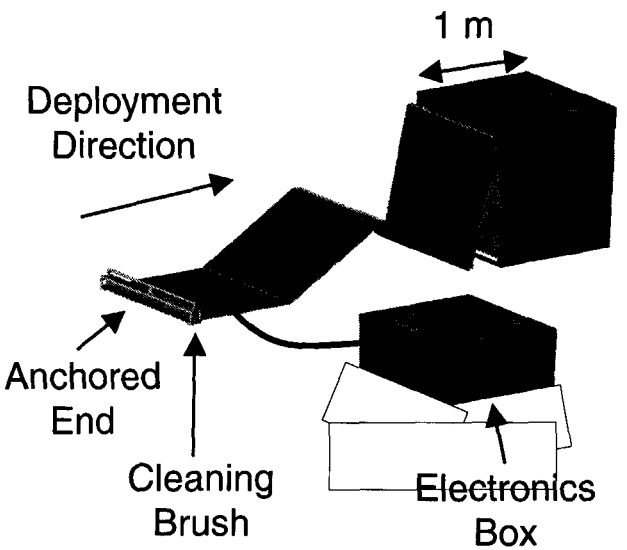
Launch Opportunity	2016	2018	2020	2022	2024	2026	2028
Cruise Stage/Orbiter	Weather	Weather	Remote Sensing	Remote Sensing	Weather	Weather	Remote Sensing
Lander 1	Rover	Rover	2 UAVs	Rover	2 UAVs	Rover	2 UAVs
Lander 2	10 m boom; EVA Demo1; Weather Stations; Power Station; Plow	Sample Analysis Lab; Shelter	200m drill; Rover Science; Radio telescope	Spare parts; Plant facility; Seismic Stations	ISPP demo; EVA Demo2; Weather stations	Spare parts; EVA Demo3; ISRU demo; Cryobots	Mid L/D demo; Spare parts

Note: Diamonds indicate arrival dates; Numbers indicate launch opportunity;
Dashed empty boxes indicate UAVs are unassembled and in storage on Mars
One lander carries a vehicle payload on each launch opportunity (1 rover or 2 UAVs)
Each red line represents 1000kg of landed science, power or comm infrastructure

Power System Options

Mars Polar Outpost
Original Concept for Power Infrastructure

Power Station Solar Array



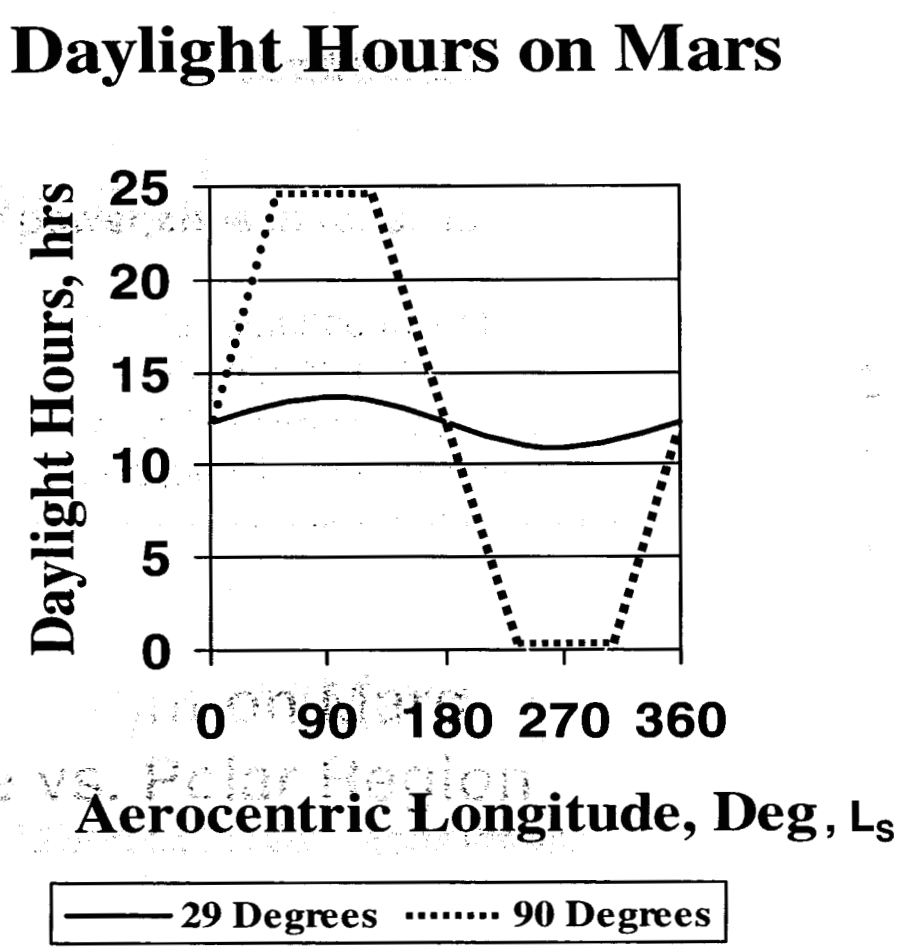
$46 M (1st unit)
$28 M (2nd unit)
3 kW, 100V unregulated,
363 kg, 1.3 m^3, per unit
including redundant power
electronics

- **Polar site (75°N) leads to extreme seasonal variations**
  - Summer: Continuous sunlight (over 220 sols)
  - Winter: Long eclipse periods
  - RPS used for rovers and distributed science network sensors
- **Solar power chosen for seasonal activities at base**
  - UAV flights, Science investigations (furnaces, vacuum chambers, etc.)
  - Power station site smoothed by rover-mounted plow before array deployment
  - Arrays only exposed during continuous sunlight months (220 sol) and cleaned weekly
    - Arrays never retracted after deployment
    - Arrays covered in place with thermal blanket and electronics warmed with RHUs
  - Lifetime of 15 years with some radiation/dust degradation

Days of Sunlight on Mars
Mid-Latitude vs. Polar Region

Investigate impact of moving Team-X designed Polar Power Module to Mid-Latitudes and providing continuous power

- Summer on Mars has 24+ hours of daylight at Pole
- Summer at 29 degrees latitude has only 13.5 hours
- Winter at 29 Degrees has about 11 hours of daylight
- Lower incident sunlight on arrays in winter
  - 45% intensity of summer sunlight
  - Arrays don't track sun
- Winter daylight hours and "power" of available sunlight will size array and batteries for mid-latitude polar base



29-deg N. latitude chosen because of low seasonal variation in daylight hours

Solar Power for Mars Robotic Outposts
Polar versus Mid-Latitude

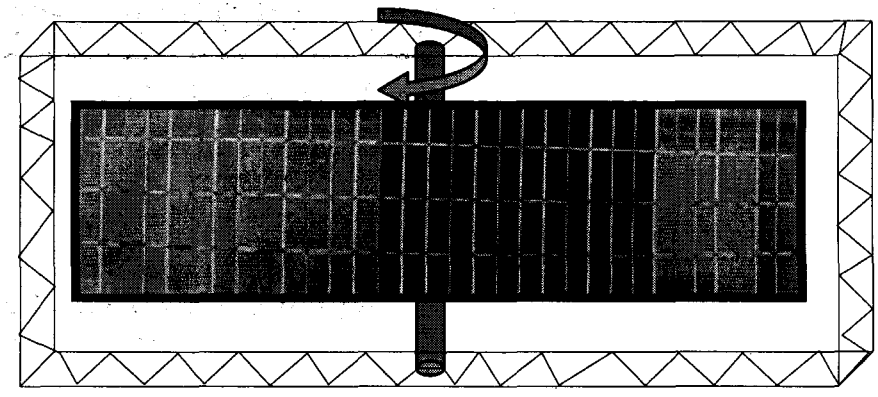
	Polar Outpost	Mid-Latitude (sleep mode)	Mid-Latitude (continuous Power)
Location	75-deg N	29-deg N	29-deg N
Daylight Load (100 V system)	3 kWe	3 kWe	3 kWe
Night Time Load	0	0.250 Kwe 12 V system	3 kWe 100 V system
Array Mass (Generate 3kWe)	216	777 kg	777 kg
Array Mass (charge batteries)	0	85 kg	855 kg
Batteries	0	12 kg	25 kg
Hinges	34 kg	124 kg	210 kg
Power Electronics	113 kg	179 kg	228 kg
Total Mass	363 kg	1,177 kg	2,095 kg

- *Mid-latitude Requirement for 3kWe power in winter months over-sizes arrays in summer months*
- *Mid-latitude Power Electronics mass assumes excess solar cell banks are switched off in summer months*

Solar Power System
Possible Improvements to Polar Array

Standout solar array design issues/options

- Utilize highest efficiency cells: GaAs triple junction, heavier than thinned crystalline silicon, but smaller array acreage
- Efficiency improved by custom triple junction to suit Mars spectrum
- Polar location calls for vertical array (low sun angle unacceptable)
- Polar location calls for tracking (single axis is OK)
- Array substrate options: rigid panel or inflation deployable
  - Backbone bend stiffness truss required for wind
  - Ability to "hunker down" against excessive wind required
- Heaters essential for maintenance and condensation removal
- Dust control essential for long op life (design impact)



Gravity helps suspend the array vertically
Elevation above ground avoids saltation

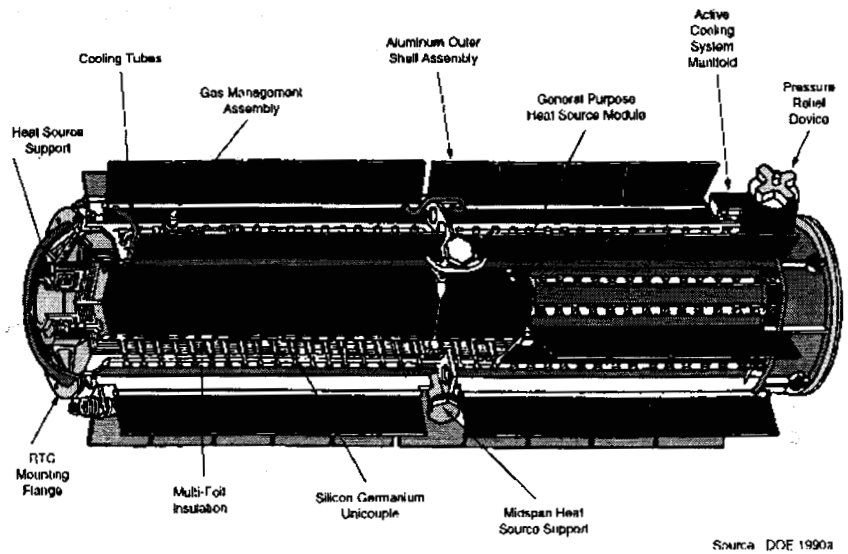
Sojourner Dust Accumulation Control Experiment
Glass cover disk over solar cell - rotated away each day

Solar Power System
Possible R&D Directions

- **Spectrum-customized multi–junction crystalline cell technology - thinned silicon and GaAs**
- **Design studies of hard panel array vs flexible substrate in stretch frame**
  - Designs for light weight backbone
- **Mars Dust management methods**
  - array heaters (condensation and frosting)
  - reorientation and vibration
  - brush array cleaner (windshield wipers)
  - corona glow discharge (electrostatic)
  - low pressure fans
  - concentrated pressurized jets (hose down)

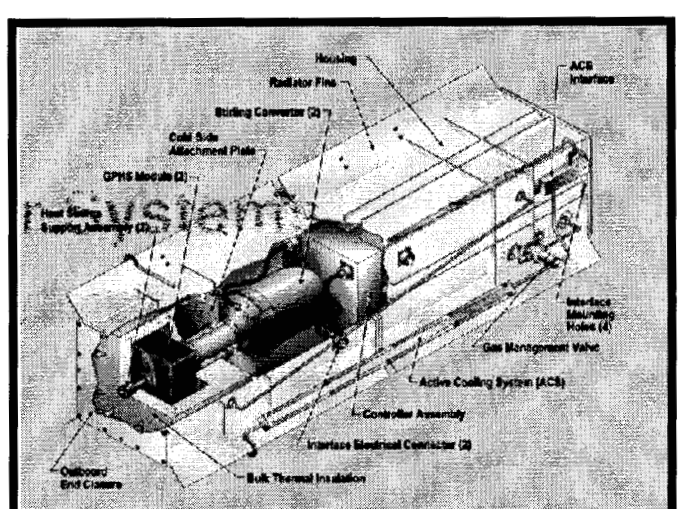
Radio Isotope Power Systems

- **RPS Types**
  - RHU radio-isotope heating units
  - RTG radio-isotope thermoelectric Generator
  - GPHS General Purpose Heating System
  - SRG Stirling Radio-isotope Generator
  - MMRTG Multi-mission RTG
- **RTG Characteristics**
  - Fuel: Plutonium 238 (not weapons material)
    - Very expensive and scarce
  - Specific Power: 25 w/kg Plutonium
  - Specific RTG system Power: 3-5 w/kg
  - RTG well proven in space missions
    - 44 RTGs have powered 24 spacecraft
  - Cassini used 3 GPHS for ≈ 870 watt



Source: DOE 1990a

GPHS-RTG (on Cassini)



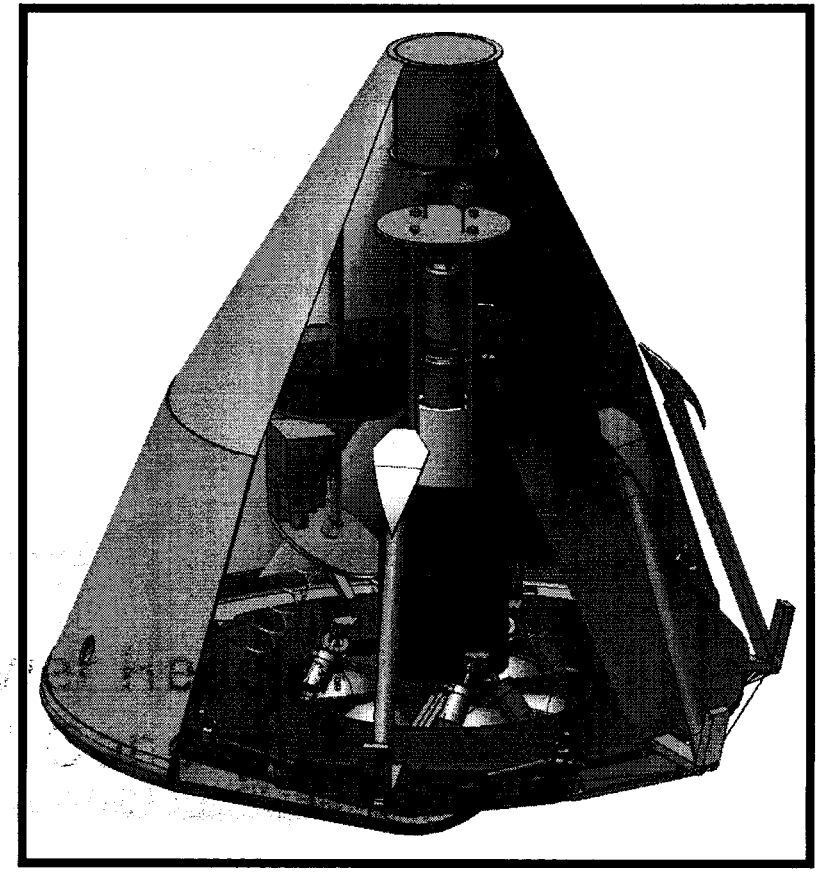
Stirling Radioisotope Generator (SRG)

Radio Isotope Power System
Possible R&D Directions

- **Prospects for Future Availability of Plutonium 238**
  - The US production line for Plutonium 238 is now being reinvigorated
  - Procurement from Russia should continue until US production comes on line (ca 2010)
  - Availability of Plutonium 238 benefits deep space missions and the HEDS road map for man on Mars
  - The convenience, reliability and specific weight of RTGs is decisively attractive
- **Pursue continuous improvement of conversion efficiency**
  - Thermoelectric conversion
  - Dynamic conversion (Stirling engine)
  - Lighter refractory materials
  - Lighter structural materials

Space Power Reactor HOMER* Concept

- **Government Design study for Mars power**
  - 15 kwt 3 kwe
  - Dimensions: 2.5 m diam x 2.4 m length (12 cum)
  - Mass of Fissile Material: 73 kg (5 kg/kwt 24 kg/kwe)
  - HOMER Total Power System Volume: 48 cum
  - HOMER Reactor Mass: 214 kg
  - HOMER Total Power System Mass: 775 kg
  - Sodium Heat pipe cooled reactor
  - Stirling engine energy conversion
  - Specific Reactor tPower: 70 wt/kg
  - Specific System ePower: 3.8 we/kg
  - HOMER Specific Power-Volume: 0.25 kwe/cum



From Elliott et al "Mission Concept for a Nuclear Reactor Powered Mars Cryobot Lander", STAIF 173, 2002;

***HOMER = Heat pipe Operated Mars Exploration Reactor**

Space Power Reactor
Possible R&D Directions

- **Reduce weight (but not shielding effectiveness)**
- **Address reentry shield for launch abort**
  - Jettison when well on the way
- **Prometheus is focal point for space power reactors**
  - Advocate for surface reactor development
- **Exploit space nuclear reactors in Mars orbit to support power intensive science, HEDS and Prometheus**

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Comparison of Power Systems

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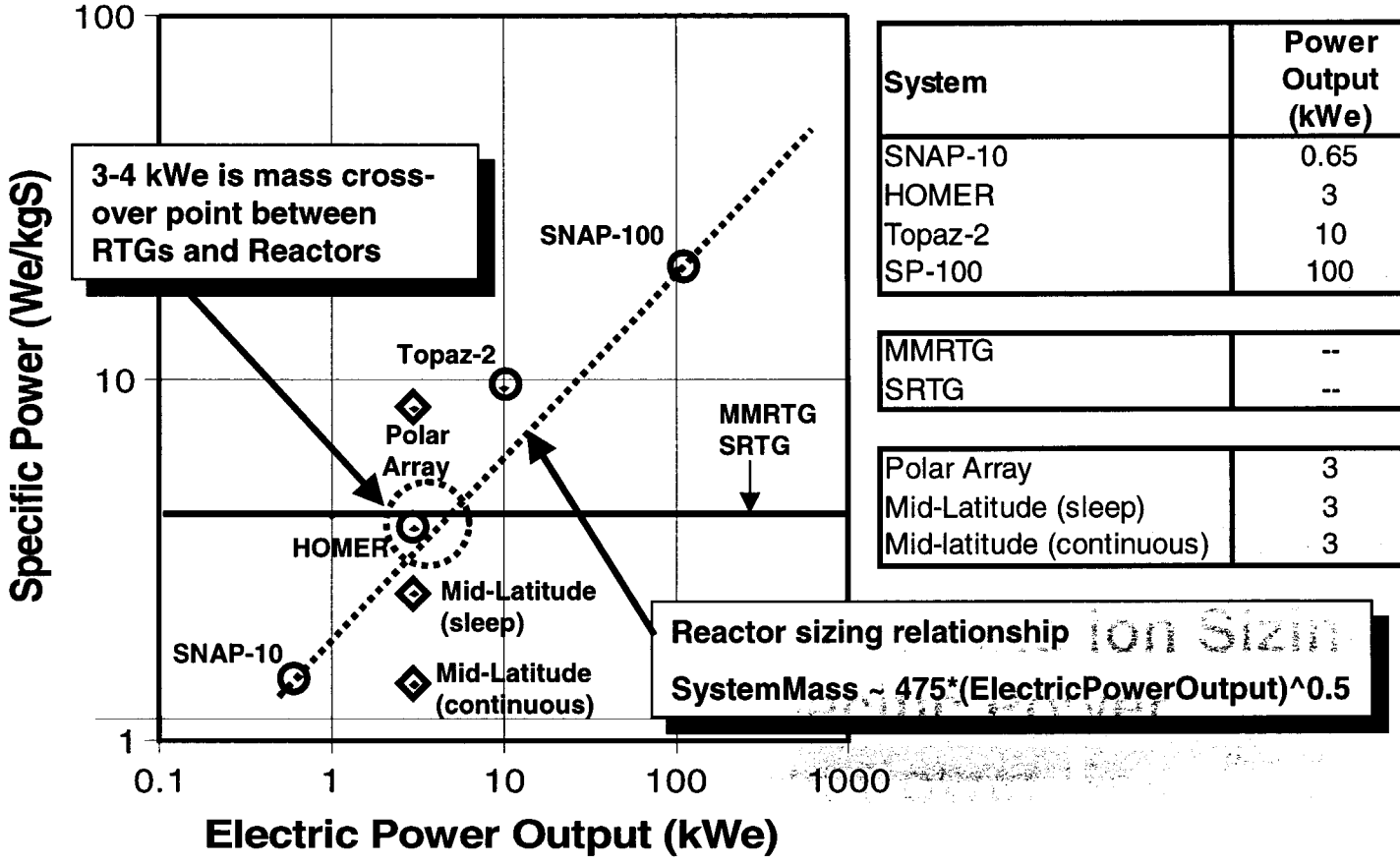
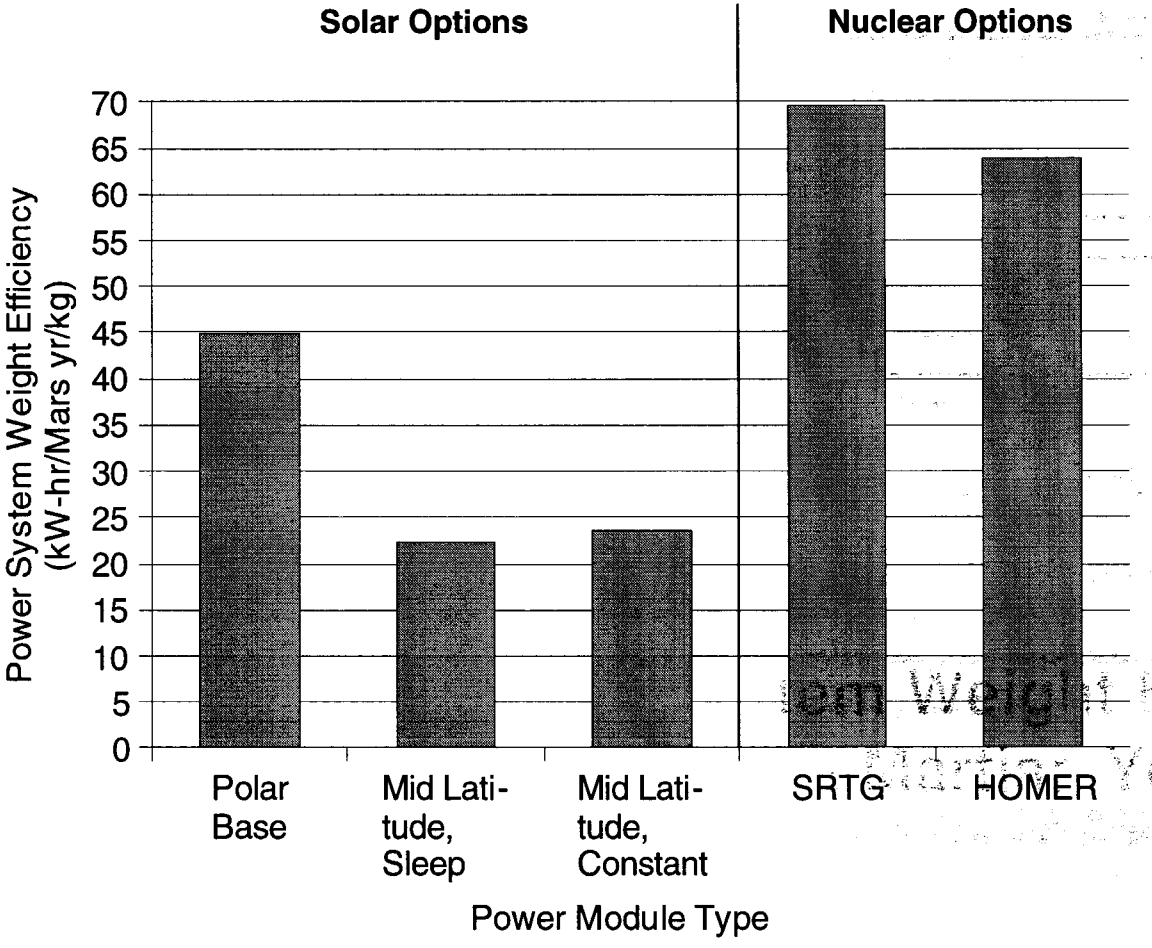
Nuclear Power Station Sizing
Specific Power



System	Power Output (kWe)	System Mass (kgS)	Specific Power (We/kgS)
SNAP-10	0.65	435	1.49
HOMER	3	775	3.87
Topaz-2	10	1060	9.43
SP-100	100	5000	20
MMRTG	--	--	4.12
SRTG	--	--	4.22
Polar Array	3	363	8.26
Mid-Latitude (sleep)	3	1177	2.55
Mid-latitude (continuous)	3	2095	1.43

Power System Weight Efficiency Over a Martian Year



Values are for total power production over a Martian year

Values will change if only daylight power is of interest

Nuclear Power Options are more weight efficient than solar power when diurnal and seasonal variations are accounted for

Comparison of 3 kWe Power Options for Robotic Outpost

	Polar Solar Module	Mid-Latitude (sleep mode)	Mid-Latitude (continuous power)	SRTG	Reactor (HOMER-based)
System Mass (3 kWe load)	363 kg	1,177 kg	1,815 kg	711 kg	775 kg
Specific Power	8.26 We/kg	2.55 We/kg	1.65 We/kg	4.22 We/kg	3.87 We/kg
Power Weight Efficency over Martian Year	44.82 kW-hr/kg	22.36 kW-hr/kg	27.24 kW-hr/kg	69.54 kW-hr/kg	63.79 kW-hr/kg
Benefits	Available Technology Modular			Low risk/existing technology Modular	Better HEDS support (growth to higher power levels)
Constraints	Dust management Structural stiffness (vertical array) No operation during eclipse		Oversized for summer	Plutonium Availability	Requires large development (NRE + risk)